TURKISH FORESTRY RESEARCHES IN THE PERSPECTIVE OF CLIMATE CHANGE

Editors

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Chapter 1

The European Climate Law and Forestry

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Forests are not merely static collections of trees; they are dynamic ecosystems vital to the health of our planet. They serve as carbon sinks, absorbing carbon dioxide from the atmosphere and storing it in biomass and soil, playing a crucial role in mitigating climate change. Moreover, forest carbon produced under alternative scenarios contributes positively to the emissions balance. It also contributes to mitigating climate change (Toksoy et. al., 2020; ; Almansouri et. al., 2020; Bayramoğlu & Seyhan, 2022; Yıldızbaş et al., 2023). The importance given to the planning, protection and sustainable management of the environment and natural resources is increasing in national and international platforms (Erdem and Aydın Coşkun, 2009; Bayramoğlu, & Küçükbekir, 2022).). The increasing global awareness of climate change and its impacts underscores the critical role of international agreements and national legislation in promoting sustainable forest management (Coşkun and Gençay, 2011; Bayramoğlu & Seyhan, 2019). European forests, for instance, capture approximately 155 million tons of carbon annually, offsetting around 10% of the EU's annual greenhouse gas emissions. Forests are not merely static collections of trees; they are dynamic ecosystems vital to the health of our planet (Botkin, 1993; Kimmins, 2004; Perry et al., 2008; Küçükbekir and Bayramoğlu, 2022). They serve as carbon sinks, absorbing carbon dioxide from the atmosphere and storing it in biomass and soil, playing a crucial role in mitigating climate change (Alemu, 2014; Ussiri & Lal, 2017). Recent studies have estimated that European forests sequester approximately 569 Mt tons of carbon dioxide annually, representing a significant contribution to the EU's climate mitigation efforts (Nabuurs, Verkerk, et al., 2018). Moreover, research has highlighted the importance of sustainable forest management (SFM) in maximizing the carbon sequestration potential of forests and ensuring their long-term contribution to achieving the Paris Agreement goals (Lier et al., 2022; Ontl et al., 2020).

Recognizing this, the European Union (EU) has implemented the European Climate Law, an ambitious legal framework aimed at achieving climate neutrality by 2050 (Erbach, 2021; Peeters & Misonne, 2022; Przyborowicz, 2021). This law has significant implications for forestry practices and policies across the EU, setting targets for emissions reduction and promoting sustainable forest management (Lier et al., 2022; Stubenrauch, Garske, et al., 2022). The European Climate Law is not just an environmental regulation; it is a recognition of the interconnectedness of human society and the natural world (Boyd, 2010; Plater et al., 2016; Szyrski, 2023; Woerdman et al., 2021). Society's perception of forests directly influences the sustainability of these resources and their availability for future generations (Birben et al., 2018; Ünal et al., 2021). Forests provide essential ecosystem services, support biodiversity, ensure the continuity of water resources that form the basis of the hydrological cycle, and are integral to the livelihoods of many communities (Thompson et al., 2011; Jenkins & Schaap, 2018; Aydın et al., 2018, Güneş Şen & Aydın, 2024). By protecting and managing forests sustainably, we not only contribute to mitigating climate change but also safeguard these vital resources for future generations. It is of the utmost importance to observe the conservation-utilisation balance at this juncture (Aydin & Yildizbas, 2023). To ensure the continued vital role of forests in combating climate change, robust legal frameworks are necessary to guide sustainable forestry practices and land use (Velioğlu, 2024).

However, the challenge lies in balancing economic needs with environmental goals (El-Ashry, 1993; Poveda, 2017; Tulukcu Yıldızbaş & Elvan, 2024). The forestry sector faces pressure from various sources, including illegal logging, unsustainable harvesting practices, and conversion of forest land for other uses (Schroeder-Wildberg & Carius, 2003; Tacconi, 2012). This is where the European Climate Law comes in, providing a legal framework to guide sustainable forestry practices and incentivize responsible forest management (Aggestam, 2024; Pandit, 2024; Romppanen, 2020). The implications of this law are far-reaching, necessitating a shift towards close-to-nature forestry, reduced impact logging, longer rotation periods, and protection of old-growth forests (Pokorny, 2019; Stubenrauch, Garske, et al., 2022). It is a call for a paradigm shift in how we view and interact with forests, recognizing their intrinsic value and their vital role in a healthy planet (Du Plessis & Brandon, 2015; Watson et al., 2018).

The European Climate Law: Key Provisions and Targets

The consequence of warming projection corresponds to various climate change scenarios at regional level (Serengil et al. 2011). Upon this, The European Climate Law, adopted in 2021, sets a legally binding target of net-zero greenhouse gas emissions by 2050 (Bäckstrand, 2022; de las Heras, 2021; Erbach, 2021). This ambitious goal, enshrined in legislation, aims to guide the European Union towards a climate-neutral future, aligning with scientific recommendations and international commitments such as the Paris Agreement (Delbeke, 2024; Rimšaitė, 2024; Türker and Aydın, 2024; Wachsmuth et al., 2022). To achieve this overarching objective, the European Climate Law establishes an intermediate target of reducing greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels (Rivas et al., 2021; Schlacke et al., 2022). This intermediate target not only provides a clear milestone for the Union's climate action but also necessitates a transformation across various sectors, including forestry (Dinerstein et al., 2019; Dormido et al., 2022).

Forests play a crucial role in climate change mitigation and adaptation by acting as carbon sinks and providing various ecosystem services (Calfapietra et al., 2015; Pandey, 2002). The European Climate Law recognizes the importance of forests in achieving climate neutrality and emphasizes the need for SFM practices (Farrell et al., 2000; Stubenrauch & Garske, 2023).

The Land Use, Land-Use Change, and Forestry (LULUCF) Regulation, which is part of the European Climate Law, sets out rules for accounting for greenhouse gas emissions and removals from the LULUCF sector (Nabuurs, Arets, et al., 2018; Romppanen, 2020; Sasso, 2023). This regulation aims to ensure that the LULUCF sector contributes to the EU's climate targets by promoting SFM and enhancing carbon sequestration (Romppanen, 2020; Vizzarri et al., 2022).

The European Climate Law also necessitates a transformation in the forestry sector, promoting SFM, bioeconomy, and the use of renewable energy sources (Liobikienė & Miceikienė, 2023; Wolfslehner et al., 2020). This transformation is essential to ensure that the forestry sector contributes to the EU's climate goals while maintaining its ecological and economic functions. In the realm of forestry (Aszalós et al., 2017; Böttcher et al.; Stanisic & Nedeljkovic, 2020), the European Climate Law mandates several actions to contribute to both climate mitigation and adaptation.

Increased afforestation and reforestation

Expanding forest cover is crucial for enhancing carbon sequestration, as forests act as carbon sinks, absorbing carbon dioxide from the atmosphere (Gorte, 2009; Raihan et al., 2019). This process plays a vital role in mitigating climate change by reducing greenhouse gas concentrations (Bessou et al., 2011; Fawzy et al., 2020). The European Climate Law promotes afforestation, the establishment of forests on land that has not been forested for a long time, and reforestation, the re-establishment of forests on deforested land (Sovilj, 2024; Verkerk et al., 2022). This focus on forest expansion aligns with the EU Biodiversity Strategy for 2030, which aims to plant at least 3 billion additional trees by 2030, focusing on areas with low forest cover and high carbon sequestration potential (Gregor et al., 2024; Lee et al., 2023; Lennan et al., 2020).

Afforestation and reforestation efforts contribute significantly to carbon sequestration, with studies indicating that afforestation can sequester substantial amounts of carbon over time (Nave et al., 2019; Trabucco et al., 2008). Moreover, these efforts enhance biodiversity by providing habitats for various plant and animal species, contributing to ecosystem resilience and the provision of ecosystem services (Kremen, 2020; Sekercioglu, 2010). Expanding forest cover also provides numerous co-benefits, such as improved water quality, soil conservation, and recreational opportunities (Kreye et al., 2014; Morgan et al., 2022; Güneş Şen, 2023). While promoting afforestation and reforestation, it is essential to consider the ecological and social impacts of these activities (Cunningham et al., 2015; Thomas et al., 2010). Careful planning and implementation are crucial to ensure that these efforts do not lead to unintended consequences, such as the displacement of local communities or the loss of biodiversity (Di Sacco et al., 2021; Pressey et al., 2017). Additionally, it is vital to prioritize the protection and restoration of existing forests, which provide invaluable ecosystem services and contribute significantly to carbon sequestration (Jenkins & Schaap, 2018; Luck et al., 2009).

Sustainable Forest Management (SFM)

The European Climate Law promotes SFM practices that maintain and enhance the health, productivity, and resilience of forests (Sotirov et al., 2015; Von Gadow et al., 2012). This approach recognizes that forests are dynamic ecosystems that provide a multitude of benefits, including carbon sequestration, biodiversity conservation, and timber production (Brockerhoff et al., 2017; Lorenz, 2010; Thompson et al., 2011). Sustainable forest management ensures the long-term carbon storage capacity of forests while safeguarding their biodiversity and ecological integrity (Mishra & Agarwal, 2024; Watson et al., 2018).

The law encourages practices such as close-to-nature forestry, which emulates natural processes to create diverse and resilient forest ecosystems (Kalapodis & Sakkas, 2024; Kuuluvainen et al., 2021; O'Hara, 2016). This approach prioritizes the use of natural regeneration, minimizes the use of chemicals, and promotes the retention of deadwood and old trees, which are essential for biodiversity (Bače et al., 2019; Vítková et al., 2018). Additionally, the law encourages reduced-impact logging, which minimizes damage to the forest during harvesting operations. This includes techniques such as selective logging and the use of cable logging systems, which reduce soil disturbance and protect remaining trees (Carmona et al., 2023; Safta & Popescu, 2024).

Several EU member states have implemented national forest programmes that promote SFM practices (Linser & Wolfslehner, 2022; Pirlot et al., 2018). These programmes often include measures such as extending rotation periods, which allows trees to grow larger and store more carbon (MacDicken, 1997). They also promote the use of mixed-species stands, which are more resilient to pests, diseases, and climate change. Furthermore, many programmes prioritize the protection of old-growth forests, which are biodiversity hotspots and provide critical habitat for numerous species (Freer-Smith et al., 2019; Larsen et al., 2022; Muys et al., 2022). By promoting SFM, the European Climate Law ensures that forests can continue to play a vital role in climate change mitigation and biodiversity conservation for generations to come.

Protecting and Preserving Existing Forests

The European Climate Law emphasizes the importance of protecting existing forests from deforestation and degradation. Deforestation, the permanent conversion of forest land to other uses, releases stored carbon into the atmosphere, contributing significantly to climate change (Gorte & Sheikh, 2010; Malhi et al., 2002; Gençay et al, 2018; Psistaki et al., 2024). Forest degradation, the reduction of forest quality and carbon storage capacity through unsustainable logging, fires, and other disturbances, also undermines climate mitigation efforts (Sunderland & Rowland, 2019; Smith et al., 2020; Gençay & Durkaya, 2023).

The law promotes measures to prevent deforestation and degradation, recognizing that preserving existing forests is often more effective in mitigating climate change than planting new trees (Gorte & Sheikh, 2010; Lyster, 2009). These measures include strengthening forest governance, combating illegal logging, and promoting sustainable land-use practices that minimize pressure on forest ecosystems (Mishra & Agarwal, 2024). Strengthening forest governance involves improving law enforcement, promoting transparency and accountability in the forest sector, and empowering local communities in forest management (De Zoysa & Makoto, 2008). Combating illegal logging requires international cooperation, stricter regulations, and innovative technologies for tracking timber and verifying its origin (Sheng et al., 2023; Tacconi et al., 2004). Promoting sustainable land-use practices involves integrating land-use planning with climate and biodiversity objectives, encouraging sustainable agriculture and agroforestry, and reducing the consumption of products that drive deforestation (Cowie et al., 2007; Nkonya et al., 2012).

Beyond preventing deforestation and degradation, the European Climate Law also emphasizes the importance of adapting to the impacts of climate change to strengthen Europe's resilience, including its vulnerable communities (Akpuokwe et al., 2024; Andrea, 2022; Dosman, 2023). This aligns with the Paris Agreement's goal of enhancing adaptive capacity, strengthening resilience, and reducing vulnerability to climate change (Cochran & Pauthier, 2019; Morgan et al., 2019).

In the context of forestry, adaptation measures are crucial to ensure that forests can withstand the increasing pressures of climate change, such as rising temperatures, altered precipitation patterns, and more frequent extreme weather events (Kolström et al., 2011; Linder, 2000). These measures may include promoting drought-resistant tree species, implementing forest fire prevention strategies, and restoring degraded forest ecosystems to improve their resilience (Chinweze, 2023; Kaur et al., 2024). Promoting drought-resistant tree species involves selecting and planting species that are better adapted to drier conditions and can withstand prolonged periods of water scarcity (Blum, 2011). Implementing forest fire prevention strategies includes reducing fuel loads through controlled burning and thinning, improving early warning systems, and strengthening firefighting capacity (Adams, 2013; Zhang, 2023). Restoring degraded forest ecosystems involves rehabilitating degraded areas to enhance their ecological functions and resilience to climate change (Arneth et al., 2021; Chaudhry et al., 2021). By integrating both mitigation and adaptation measures, the European Climate Law aims to ensure that forests can continue to provide essential ecosystem services and contribute to climate action in a changing climate (Sama, 2021; Sovilj, 2024).

Implications for Forestry Practices

The European Climate Law necessitates a shift towards more sustainable forestry practices across the EU. This includes ***Close-to-nature forestry***; managing forests in a way that emulates natural processes, promoting biodiversity and resilience. This approach prioritizes the ecological integrity of forests, recognizing their role in providing various ecosystem services and supporting biodiversity (Kalapodis & Sakkas, 2024; Triviño et al., 2023). ***Reduced impact logging***; minimizing damage to the forest during harvesting operations is crucial for maintaining forest health and productivity. This involves using techniques that reduce soil disturbance, protect water quality, and minimize damage to remaining trees (Marchi et al., 2018; Neary et al., 2009; Stupak et al., 2011). ***Longer rotation periods;*** allowing trees to grow for longer periods, maximizing carbon storage and enhancing the structural complexity of forests (Ontl et al., 2020). Longer rotation periods also promote biodiversity and contribute to the long-term resilience of forest ecosystems (Bengtsson et al., 2000; Kuuluvainen et al., 2021). ***Protection of old-growth forests***; old-growth forests, characterized by their high carbon storage capacity and unique biodiversity, are given special protection under the European Climate Law (Aggestam, 2024; Kaniecka, 2023). These forests represent a valuable carbon sink and provide essential habitat for a variety of species. Their preservation is crucial for mitigating climate change and maintaining ecological integrity (Díaz et al., 2009; Lukina et al., 2021).

Challenges and Opportunities

Implementing the European Climate Law in the forestry sector presents both challenges and opportunities.

Challenges

Balancing economic needs with environmental goals remains a significant challenge in implementing the European Climate Law, particularly within the forestry sector. While the law aims to achieve climate neutrality, it also recognizes the importance of maintaining a vibrant and economically viable forestry sector that supports rural livelihoods and provides essential resources (Connor, 2015; Stubenrauch, Ekardt, et al., 2022; Verkerk et al., 2022).

Researchers have shown that sustainable forestry practices can have positive economic impacts, such as creating new jobs in rural areas, increasing the value of forest products, and boosting tourism. For instance, SFM can create jobs in areas like ecotourism, recreation, and the production of non-timber forest products (Collins et al., 2009; Lewark, 2022). Furthermore, certification schemes like the Forest Stewardship Council (FSC) can enhance the value of timber and non-timber forest products by providing assurance of their sustainable origin (Shanley et al., 2005; Tollefson et al., 2009). However, there may also be trade-offs between economic benefits and environmental objectives, particularly in the short term. For example, extending rotation periods, while beneficial for carbon sequestration and biodiversity (Başkent & Kašpar, 2023; Thorkildsen, 2021) may lead to a temporary reduction in timber harvests, impacting the profitability of forestry operations (Duncker et al., 2012). Similarly, implementing strict conservation measures in certain areas may limit economic activities like logging. Therefore, it is crucial to develop strategies that integrate economic, social, and environmental considerations to ensure the long-term sustainability of the forestry sector (Pankivska et al., 2024; Sotirov et al., 2015). This requires a holistic approach that considers the full range of ecosystem services provided by forests, including carbon sequestration, biodiversity conservation, timber production, recreation, and water regulation (Brockerhoff et al., 2017; Ciccarese et al., 2012; Jenkins & Schaap, 2018).

Policy instruments such as payments for ecosystem services, SFM certification, and innovative financing mechanisms can help align economic incentives with environmental goals (Boscolo et al., 2010; Dubova et al., 2022). SFM certification can provide market access and price premiums for sustainably produced timber and non-timber forest products (Shanley et al., 2005). Innovative financing mechanisms, such as green bonds and impact investing, can mobilize private capital for sustainable forestry projects (Clark et al., 2018; Panayotou, 2002). By carefully considering the economic, social, and environmental dimensions of forestry, policymakers can create a framework that supports a thriving forestry sector while contributing to the EU's climate goals.

Balancing economic needs with environmental goals

The pursuit of economic benefits from forestry activities should not compromise the ecological integrity of forests or undermine their climate mitigation potential (Deal et al., 2012; Smith et al., 2022). Balancing these competing demands requires careful planning, innovative approaches, and a commitment to SFM practices that integrate economic, social, and environmental considerations (Ghajar & Najafi, 2012).

Adapting to climate change impacts on forests

Adapting to Climate change requires a proactive approach, promoting resilient forest ecosystems, implementing risk mitigation measures, and developing strategies to cope with the changing conditions. This may involve promoting drought-resistant tree species, implementing forest fire prevention strategies, and restoring degraded forest ecosystems (Kaur et al., 2024; Moreau et al., 2022).

Ensuring consistent implementation across member states

The European Union comprises a diverse range of forest ecosystems, management practices, and socioeconomic contexts. Ensuring the consistent implementation of the European Climate Law across this diversity requires clear guidelines, effective monitoring mechanisms, and a commitment to collaboration among member states (Bibi et al., 2024; Biesbroek et al., 2010; Rayner & Jordan, 2016). This includes addressing potential barriers to implementation, such as conflicting national policies, limited resources, or varying levels of awareness and capacity (Kabisch et al., 2016; Moser & Ekstrom, 2010).

Opportunities

Creating new economic opportunities in sustainable forestry

The shift towards sustainable forestry practices mandated by the European Climate Law can create new economic opportunities (Cifuentes-Faura, 2022). This includes the development of markets for sustainably produced timber and non-timber forest products, as well as opportunities in forest conservation, restoration, and recreation (Nabuurs et al., 2015). These opportunities can contribute to rural development, create jobs, and support the transition towards a climate-neutral economy.

Enhancing biodiversity and ecosystem services

Forests provide a variety of ecosystem services, such as carbon sequestration, water regulation, and biodiversity conservation (Burrascano et al., 2016; Winkel et al., 2022). The European Climate Law, by promoting sustainable forestry practices, can enhance these services, contributing to the overall health and resilience of ecosystems (Buser, 2023; Romppanen, 2020). This includes protecting and restoring forest biodiversity, which is essential for the long-term functioning of forest ecosystems and their ability to adapt to climate change (Sovilj, 2024; Verkerk et al., 2022).

Strengthening the EU's leadership in climate action

The European Union has positioned itself as a leader in global climate action. The implementation of the European Climate Law in the forestry sector can further strengthen this leadership, demonstrating the Union's commitment to achieving climate neutrality and promoting SFM practices (Aggestam, 2024; Clarke & Sahin-Dikmen, 2021; Hedemann-Robinson, 2024; Wolfslehner et al., 2020). This can inspire other countries to adopt similar policies, contributing to global efforts to mitigate climate change and protect forest ecosystems.

Conclusion

Unlike earthquakes, where individual actions and preparedness can make a difference, climate change demands a coordinated response driven primarily by state-level action, both nationally and internationally (Aydın et al., 2024). The European Climate Law sets an ambitious agenda for forestry in the EU, demanding a shift towards more sustainable practices and policies to achieve climate neutrality. By embracing this challenge, the EU can not only contribute to mitigating climate change but also enhance the health and resilience of its forests for future generations. As the EU progresses towards its 2050 climate neutrality goal, it is crucial to continue monitoring the effectiveness of the European Climate Law in the forestry sector and adapt its provisions to address emerging challenges and opportunities. Future research should focus on developing innovative forest management strategies that maximize the climate mitigation potential of forests while ensuring their long-term ecological and socioeconomic sustainability.

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Gökçe GENÇAY

Chapter 2

Sustaining Forests in the Climate Crisis: Exploring Challenges and Solutions

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Climate, in its constant interaction with natural ecosystems and humans, impacts every aspect of life, including work, nutrition, health, the economy, and overall well-being (Psistaki et al., 2024). Climate change brings about various detrimental consequences, including food insecurity, reduced access and quality of potable water, biodiversity loss, the spread of infectious diseases, damage to infrastructure, and heightened public health stress (Abbass et al., 2022). It affects forests in complex ways, including changes in temperature and precipitation patterns, increased frequency of extreme weather events, and heightened susceptibility to pests, diseases, and wildfires. These changes can reduce forest resilience, alter species composition, and disrupt ecosystem services (Allen et al., 2010). For example, warming in boreal regions accelerates permafrost thawing, altering forest structure, while tropical forests face heightened vulnerability to drought and deforestation (Bonan, 2008; Gatti et al., 2021). In recent years, as climate change mitigation and adaptation strategies have gained prominence, policymakers and the scientific community have increasingly turned their attention to nature-based solutions. These solutions encompass the conservation, restoration, and sustainable management of natural ecosystems, such as forests, wetlands, grasslands, and coastal areas (Seddon et al., 2020).

Forests cover approximately 31% of the Earth's terrestrial surface (UN, 2021; IPCC, 2021), playing a central role in addressing global environmental and societal challenges. They represent a critical link between ecological balance, economic development, and social well-being (Baumgartner, 2019; Fujimori et al., 2020; IPCC, 2021). Forests are indispensable in mitigating climate change, absorbing approximately 30% of human-induced carbon dioxide emissions annually (Friedlingstein et al., 2020). Forests can influence climate dynamics by acting as carbon sinks or carbon sources, depending on their management and degradation status (Pan et al., 2011). Beyond their impact on climate, trees and forests offer numerous additional benefits, such as biodiversity conservation, soil and water retention, reduced air and water pollution, and contributions to economic growth (Brockerhoff et al., 2017; Barrios et al., 2018). Deforestation and forest degradation collectively contribute about 10% of global greenhouse gas emissions, underscoring the pressing necessity for sustainable forest management to prevent further losses (Harris et al., 2021).

The interaction between forests and climate change represents a critical area for research and action, as addressing these challenges is essential for achieving the global climate targets outlined in the Paris Agreement. Moreover, the conservation of forest ecosystems is vital for maintaining biodiversity, supporting livelihoods, and ensuring long-term ecological sustainability. This section presents the interaction of climate change and forests in Türkiye under different headings and provides information on the current situation, developments, problem-solving, etc.

Impacts of Climate Change on Forests

While forest ecosystems have a role to play, they are also affected by the impacts of climate change. Changes in temperature due to climate change, especially drought, affect the life cycle of trees and cause structural changes in forests. As temperatures rise, the frequency of forest fires increases, and disease, insect and fungal damage increases. Climate change-related pressures on forests lead to habitat loss, fragmentation and degradation of forest ecosystems (TÜSİAD, 2023).

There is a reciprocal relationship between forests and climate change. While climate change affects forests, forests are also one of the factors that affect climate change. From this perspective, there is a need to establish a healthy connection between climate change and forests (Tolunay, 2013). The most important potential impacts of climate change on forests and forestry sector can be summarized as follows: tree species changes, structure, wealth, increment, growth changes in forests according to tree species, changes in carbon stock levels with species changes, changes in the location of forests, reductions in the growth capacity of forests if humidity decreases while temperature increases, positive developments that may be seen in plant mass increase as a result of the vegetation period prolongation as a consequence of climate change, changes in fire risks and potential fire risk areas, chemical changes in soils, insect population growth and species change, changes in the resistance of trees (Karacabey, 2023). One of the problems that climate change, which is one of the most important issues of our time, will bring to forests is that it will cause a significant increase in the intensity of forest pests (Özkazanç, 2022).

Decrease in carbon storage capacity of forests

Greenhouse gases are accumulating in the atmosphere daily. Terrestrial ecosystems and the oceans store these gases. Forest ecosystems alone account for more than 80 percent of the carbon sequestered above the soil and over 70 percent of all soil organic carbon (Jandl et al., 2007). While sustainably managed forests and forest products are an important sink, deforestation and forest degradation due to various causes, in particular forest fires, are an important source of emissions (Karacabey, 2023).

The semi-arid and arid to semi-humid climatic conditions and topographical structure of Türkiye, which covers about 65% of the country, do not provide opportunities to contribute to the realization of carbon offsets through tree planting and forest establishment to the desired extent (TÜSİAD, 2023). Türkiye's LULUCF sector, which encompasses land use, land use change, and forestry, is currently operating as a net sink. This is primarily due to the growth of wood biomass and the expansion of forests, with forest areas and processed wood products being the key sectors contributing to this net sink status (NIR, 2021). From 66.5 Mton CO2 equivalent in 1990, the annual greenhouse gas sequestration reached 77 Mton CO2 equivalent in 2014, but decreased over time to 47 Mton equivalent in 2021 according to the latest inventory figures. Due to extensive forest fires, drought-induced high wood production, and other factors, carbon sequestration in 2021 was significantly lower compared to previous years (Çevre, Şehircilik ve İklim Değişikliği Bakanlığı, 2024a). When analyzing the exposure of the carbon storage ecosystem service to drought by province, the Black Sea region stands out as it has more forest area and therefore more tree richness and increment. Exposure was also found to be high in the Mediterranean region, which has more forested areas. On the other hand, in Central Anatolia and Southeast Anatolia, the low presence of forests and low soil organic carbon stocks due to intensive agriculture have led to very low levels of exposure (Çevre, Şehircilik ve İklim Değişikliği Bakanlığı, 2024b).

Destruction of forests by extreme weather events

Climate change is evidently affecting us today, with an uptick in extreme weather events like heatwaves, heavy rainfall, floods, and droughts, both locally and globally. The primary culprit is the rapid rise in greenhouse gas emissions, primarily due to the increasing reliance on fossil fuels during the industrial revolution. While the global average temperature has risen by about 1.1°C since 1850, if this trend persists, it's projected to reach 3°C by the end of this century. Consequently, Türkiye has witnessed a substantial increase in meteorological disasters, particularly since 2018. Between 2010 and 2021, 8,274 natural disasters of a meteorological nature were reported, affecting different parts of our country to varying degrees (Çevre, Şehircilik ve İklim Değişikliği Bakanlığı, 2024a).

Extreme weather events such as storms, snow, lightning and wet landslides can cause trees to fall or break in forests (Çevre, Şehircilik ve İklim Değişikliği Bakanlığı, 2024b). In years with unusual climatic conditions, storms and snow can cause significant damage. However, this damage does not have a serious continuity. Drought-induced drying may also occur as a result of climatic conditions. Based on data from 2008-2019, the loss rates of forest areas affected by other factors are given in Figure 2 (General Directorate of Forestry (GDF), 2020a).

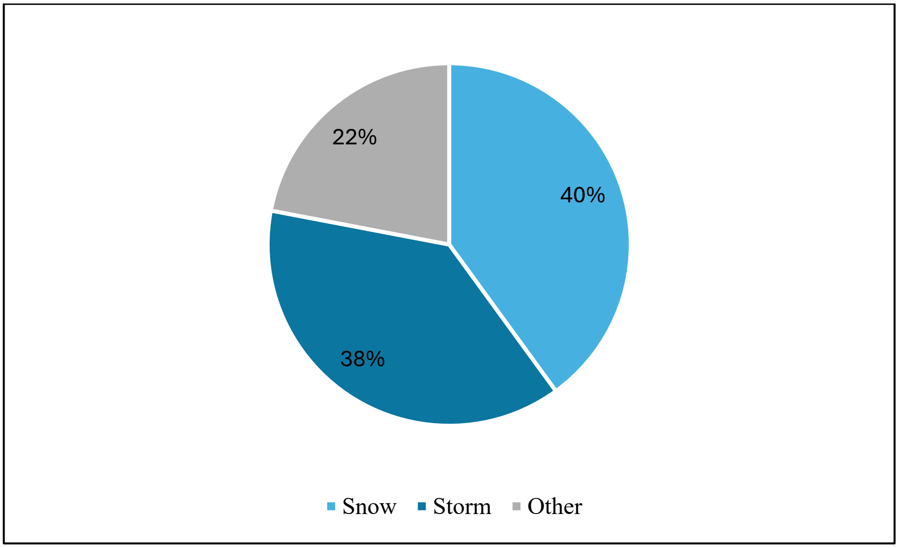

Figure 1. Loss rate in forests affected by snow, storms and other abiotic factors (2008-2019)

The effects observed in Türkiye's forests can be listed as follows (GDF, 2020b):

Due to the more frequent occurrence of extreme weather events such as storms, floods, etc., destruction is expected to be seen in some riparian, alluvial, sloping and degraded forests. According to the records of the GDF, between 2009 and 2013, more than 1 million hectares and approximately 9.7 million m3 of forest land were damaged by snow, wind, landslides, flooding and drought, decreasing forest productivity, drought, disease and insect damage are expected to increase due to water scarcity and drought observed in forests. According to the defoliation rate observations made within the scope of the 'Forest Ecosystems Monitoring Programme', the highest defoliation rate is observed in 2008, when the precipitation decrease was the highest, forest productivity is expected to increase due to the longer vegetation season in some regions without water scarcity. With the increase in temperature and change in precipitation regime, the frequency and amount of natural damages such as forest fire and pathogens increase, due to the effect of climate change, 291 176 m3 of Taurus Fir (*Abies cilicica*) dried up between 2000 and 2010 due to the increase in bark beetle population. When the records of the GDF on forest fires between 1990-2019 are analyzed, the average number of fires increases every decade. Because of climate change in Türkiye, the forest fire season has also lengthened.

Interaction between deforestation and climate change

When considered together, deforestation and climate change emerge as a global environmental problem (Hatipoğlu, 2022). With the understanding of the importance of forests in the struggle against climate change, new concepts have entered forestry literature. One such concept is deforestation. Although defined in different ways by different institutions, deforestation is the long-term conversion of forest land to other uses and is an important factor in increasing CO2 concentrations in the atmosphere (Tolunay, 2017).

In Türkiye, which initiated the planning process with annual development plans, forest inventory studies commenced in 1963. Subsequently, between 1963 and 1972, comprehensive forest management plans were prepared for the entire country. The resulting forest inventory data was published in 1980. In the same statistics, the total forest area in Türkiye has been increasing according to the inventory years since 1973 (GDF, 2020c). According to the latest statistics published by GDF for 2022, the total forest area is 23 million 245 thousand hectares. The situation is shown in Figure 2.

Large forest areas in Türkiye have been rapidly fragmented in recent years, and the risk of fire is increasing due to the growth of settlements and activities in these areas. The main reason for this fragmentation is the allocation of forests for purposes other than forestry and the sale of areas excluded from forests with 2/B to their occupants (Atmış & Akkemik, 2022). The increase of forest area in Türkiye is due to the decrease of pressure on forests in rural areas as a result of migration from rural to urban areas since the 1970s, spontaneous conversion of agricultural land from forest to woodland, cadastral surveys, etc., rather than afforestation (Atmış et al., 2022).

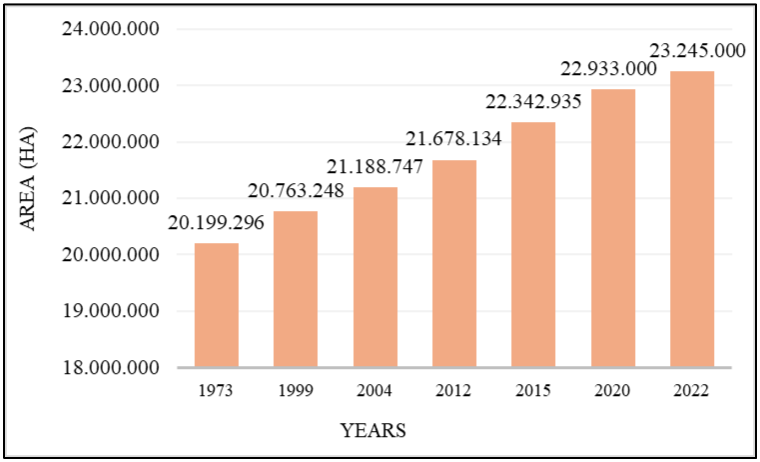

Figure 2. Changes in forest cover in Türkiye

In Search of Solutions: Sustainable Forest Management

Sustainability approach and principles

To mitigate the adverse effects of climate change on forest resources, alterations in forestry management and practices are imperative (Sousa-Silva et al., 2018). Climate change adaptation strategies can be viewed as a risk management component of sustainable forest management plans. The precautionary principle advocates for immediate action through the implementation of strategies that provide current benefits while simultaneously reducing the likelihood of catastrophic losses in the future. Forest policies must undergo evaluation to ascertain their effectiveness in promoting adaptation (Spittlehouse & Stewart, 2003).

Today, Sustainable Forest Management (SFM) has become an important concept underpinning modern forestry. This concept refers not only to the flow of goods and services, but also to the regenerative capacity of the ecosystem. Today, SFM has become an important concept underpinning modern forestry. This concept refers not only to the flow of goods and services, but also to the regenerative capacity of the ecosystem (GDF, 2020a).

The GDF Strategic Plan (2010-2014) outlined seven primary objectives for sustainable forest management in Türkiye. Each objective was directly or indirectly linked to climate change adaptation goals (Çevre ve Şehircilik Bakanlığı, 2012). These objectives included protecting forests, designated forest areas, and biodiversity within those areas from various biotic and abiotic pests. The plan also aimed to develop existing forests, enhance their productivity, and expand their areas. Additionally, it sought to establish ecosystem-based and multi-purpose forest management plans that adhered to the principles of sustainable forest management. Furthermore, the plan emphasized meeting society's evolving and changing expectations for the goods and services provided by forests at the highest level while utilizing forests in a diverse and sustainable manner. Lastly, the plan aimed to develop institutional capacity to provide sustainable forest management and deliver prompt, high-quality services. It also sought to enhance the GDF's national and international image.

Standardization of data is an issue that requires sensitivity in order to be able to monitor the realization of the strategies, targets and actions determined for the management of natural resources on a common level between institutions and to compare them with international data when necessary. In this framework, it is important to establish a holistic and sustainable data transfer mechanism between the institutions authorized by various legislations to collect and process data that will be an input for the formulation of policies on the sustainable management of forests to ensure effective implementation (GDF, 2020a).

Nature-based solutions (NbS)

The NbS concept has attracted attention in both research and related policy and practice since the late 2000s (Başsüllü et al., 2023). Nature-based solutions basically include practices that aim to protect and enhance urban resilience and ecosystem services. In other words, the concept of nature-based solutions is based on and supports other closely related concepts such as ecosystem approach, ecosystem services, ecosystem-based adaptation/mitigation and green-blue infrastructure (Urban Green UP, 2018).

NbS cover a wide range of actions that protect and restore landscapes, seascapes, watersheds and urban corridors in ways that maximize the social services they provide. NbS, such as forest habitat restoration and sustainable watershed management, are being implemented at different scales in different regions and sectors around the world (WWF, 2021).

Following the ratification of the Paris Climate Agreement, which was opened for signature in 2016, by the Turkish Grand National Assembly on 6 October 2021, Türkiye has entered a new phase in its fight against the climate crisis. In this phase, it has become important not only to eliminate the consumption of fossil fuels, but also to protect and increase the presence of forests, which are one of the key carbon sinks (Atmış & Akkemik, 2022).

As the population in rural areas is rapidly declining and there are few opportunities to intervene in urban areas, priority in land use studies should be given to semi-urban areas, where cities merge with the countryside and tend to concretise rapidly. In these areas, architectural and landscaping designs should be promoted that predominantly use low-rise timber materials (Serengil, 2019).

Policy and legal framework

Türkiye joined the United Nations Framework Convention on Climate Change (UNFCCC) in 2004 and the Kyoto Protocol in 2009. The Paris Agreement, adopted on December 12, 2015, within the framework of the Convention and entering into force on November 4, 2016, marked a significant milestone. Türkiye formally accepted the Paris Agreement in 2015 and signed the Agreement on April 22, 2016, underscoring its status as a developing country (Çevre, Şehircilik ve İklim Değişikliği Bakanlığı, 2024a).

Although climate change is a globally recognized fact, complementary policies and actions are needed to adapt to its impacts. This situation clearly shows that adapting to the impacts of climate change is as important as reducing emissions. In fact, activities to adapt to the impacts of climate change are increasing day by day all over the world, and adaptation policies have been included as an important title along with mitigation policies in international agreements (Paris Agreement, Article 7) (Çevre, Şehircilik ve İklim Değişikliği Bakanlığı, 2024a). According to the GDF (2020b), Türkiye's climate change policy is structured through a combination of cross-sectoral and sectoral policies, strategies, and action plans that are aligned with national legislation in relevant sectors. The primary policy documents specifically focused on climate change are the National Climate Change Strategy (2010-2023), the National Climate Change Action Plan (2011-2023), and the National Climate Change Adaptation Strategy and Action Plan (2011-2023).

In Türkiye's Climate Change Strategy 2010-2023, the national vision is to transform into a country that seamlessly integrates climate change policy with development initiatives. This involves widespread adoption of energy efficiency measures, increased reliance on clean and renewable energy sources, and active participation in combating climate change within the context of its unique circumstances. The ultimate goal is to provide a high quality of life and well-being to all citizens while minimizing carbon emissions. (Çevre ve Şehircilik Bakanlığı, 2012).

Recently, Türkiye has been devising its policies in line with sustainable development principles across almost all domains of combating climate change. It is also on the path of developing its legal, institutional, and economic systems in the context of the emerging climate economy. In the international arena, collaborative efforts against climate change are particularly noteworthy (T.C.

Tarım ve Orman Bakanlığı, 2021). It is possible to categorize the forestry policies related to climate change in Türkiye into 3 strategies (Figure 3) (Sıvacıoğlu & Öner, 2010):

Expansion of existing sink areas

envisaged approaches for the strategy

- Afforestation inside and outside forests
- Development of mixed systems (agroforestry, silvopastoral, agro-silvopastoral)
- Development of urban forests

Protecting existing sinks and increasing their carbon sequestration potential

envisaged approaches for the strategy

- Protection of existing forests against fire, illegal and irregular cutting, insect and fungal damage,
- Silvicultural operations suitable for the biology of forests,
- Operation of forests in accordance with sustainable forestry principles

Delaying the return of carbon bound in biomass to the atmosphere

envisaged approaches for the strategy

- To expand forest areas by afforesting vacant treasury lands
- Improving biomass production performance by rejuvenating very old forests
- Using fast-growing tree species with high production capacity in newly established forests

Figure 3. Forestry policies related to climate change in Türkiye

There is no article in the Constitution of the Republic of Türkiye that refers to climate change from the East. On the other hand, there are provisions in the constitution in some areas that are directly related to climate change (Figure 4) (Erdönmez et al., 2023)

- Article 43, which regulates the use of coasts
- Article 44 on land ownership and land protection
- Article 56 on health services and environmental protection
- Article 168, which regulates the exploration and exploitation of natural wealth and resources
- Article 169, which regulates the protection and development of forests

Figure 4. Provisions in the Constitution of the Republic of Türkiye for some areas directly related to climate change

As in international conventions, there are laws that are related to climate change in terms of their content, although they do not seem to be directly related to climate change. The most important of these are listed below according to the date of entry into force (Figure 5) (Erdönmez et al., 2023):

- Forest Law No. 6831 (1956)
- Law No. 2863 on the Protection of Cultural and Natural Assets (1983)
- Environmental Law No. 2872 (1983)
- National Parks Law No. 2873 (1983)
- Coastal Law No. 3621 (1990)
- Pasture Law No. 4342 (1998)
- Land Hunting Law No. 4915 (2003)
- Soil Conservation and Land Use Law No. 5403 (2005)

Figure 5. Laws in the Constitution of the Republic of Türkiye that are related to climate change in terms of their content

Future Perspectives

In Türkiye, the first step should be to accept the existence of deforestation and then take the necessary steps to reduce it. The first step is to review the permits issued for forest areas and to limit the scope of the permits (Tolunay, 2017). Global climate change remains one of the most pressing environmental challenges facing our society. The effects of climate change are anticipated to intensify in the forthcoming years as the delayed consequences of past and present greenhouse gas emissions, particularly on natural resources, come to light. In this context, forests in Türkiye assume a pivotal role in mitigating greenhouse gas emissions and adapting to the adverse impacts of climate change (GDF, 2021).

Türkiye's climate change policy must go beyond targets and strategies. Türkiye, which has committed to a 21% reduction in greenhouse gas emissions, has achieved a 0.5% reduction in 2018 compared to 2017. However, to achieve a 21% reduction by 2030, more mitigation policies should be pursued, as well as adaptation policies to possible impacts. This is not only the responsibility of central and local governments, but also of the whole country (Ay & Akıncı, 2020).

Identifying and monitoring the impacts of climate change on forestry activities, forest ecosystems, and species is crucial. This includes assessing the effects of rising temperatures and altered precipitation patterns caused by climate change on forest ecosystems and species. Additionally, monitoring the effects of climate change on forest fires and developing fire risk maps is essential. These maps should include necessary risk preparation and prevention measures for forest fires resulting from climate change within the context of local and regional planning studies. This approach aims to minimize the risks posed by climate change to livelihoods. To achieve this, forest villagers should diversify their livelihood activities and be prepared to switch to alternative options if necessary. It is also important to follow up on existing targets that include incorporating risk preparedness and prevention measures specifically tailored to combat forest fires caused by climate change within the scope of local and regional planning studies. (GDF, 2020a).

In Türkiye, it is also imperative to further enhance public awareness of the protective and environmental services provided by forests, including the protection of soil resources, agricultural land, protection and regulation of water resources, prevention of desertification, floods, and other natural disasters, carbon sequestration, and air purification.

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Chapter 3

The Formation of Carbon Markets: International Processes And Türkiye's Position

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The accelerated industrialization of the past century, coupled with population growth, has caused significant harm to the environment, particularly to the habitats of humans and wildlife. Consequently, climate change, desertification, biodiversity loss, disruption of the hydrological cycle, and environmental degradation are becoming increasingly severe global issues (Bayramoğlu & Seyhan, 2022; Güneş Şen, 2023). Although climate change is environmental in nature, it is a complex problem that affects all aspects of human life. It both impacts and is impacted by global challenges such as poverty, economic and sustainable development, population growth, and natural resource management. Climate change is known to have serious effects on growth and development. According to the Stern Report on the Economic Dimensions of Climate Change (2006), if collective action against climate change is not taken, the annual global cost of its adverse effects could amount to at least 5% of global GDP. Including risks and other impacts, this figure could exceed 20%. This outcome highlights the importance of global warming as a shared problem and the necessity of collective action to combat it, as emphasized in the Stern Report.

The primary cause of climate change is the significant increase in atmospheric emissions, particularly of carbon dioxide and methane gases, over the past century (Güngör & Şen, 2021). This situation has led to rising temperatures on land and in the oceans, causing climate change. Global warming, defined as an approximately 0.5°C increase in global temperatures compared to a century ago, is largely attributed to the greenhouse effect. The greenhouse effect theory identifies the increased concentrations of certain gases in the atmosphere (e.g., carbon dioxide, chlorofluorocarbons, methane, and nitrous oxides) as the cause of the problem (Sözen et al., 2017). The most effective greenhouse gases are water vapor and carbon dioxide, accounting for 95% of the total greenhouse effect (Serengil, 1995; Almansouri et al., 2020; Seyhan & Bayramoğlu, 2023).

Reducing atmospheric emissions is possible by minimizing fossil fuel use and enhancing carbon sinks, such as forests, oceans, and soils, which absorb CO2 (IPCC, 2001). In the 1980s, 25% of human-caused carbon emissions stemmed from deforestation and forest degradation. Currently, 12–20% of carbon emissions are attributed to similar activities, such as deforestation and changes in land use patterns (Başsüllü, 2014). Thus, solutions to climate change are expected to emerge from research and development efforts across all disciplines. As this is a global issue, individual actions are limited, and collective action is recognized as the only effective means to address the problem on an international scale (Çikot, 2009). The first international step in combating climate change was taken at the First World Climate Conference in 1979. Subsequently, the

Intergovernmental Panel on Climate Change (IPCC) was established in 1988 by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) to provide interdisciplinary, up-to-date, and reliable information on climate change (UNFCCC, 2006).

The United Nations Framework Convention on Climate Change (UNFCCC)

The United Nations Framework Convention on Climate Change (UNFCCC) was adopted at the Second World Climate Conference in 1992 and officially entered into force in 1994. The convention aims to "stabilize atmospheric greenhouse gas concentrations at a level that would prevent dangerous anthropogenic interference with the climate system" (UNFCCC, 1992). Türkiye joined the convention in 2004. The UNFCCC, signed by a total of 194 countries, including Türkiye, represents the first agreement of its kind.

The UNFCCC divides member countries into three groups: Annex I, Annex II, and Non-Annex countries.

- Annex I countries include those that were members of the Organisation for Economic Co-operation and Development (OECD) in 1992 and countries transitioning to market economies. Annex I countries are obligated to conserve, improve, and develop greenhouse gas sinks, limit greenhouse gas emissions, calculate these emissions, report them to the relevant secretariat, and cooperate with other countries. Türkiye was included in both Annex I and Annex II lists at the time of its acceptance into the UNFCCC. However, as Türkiye had not yet completed its industrialization process, it requested to be removed from the Annex II list, which entails financial obligations. This request was approved in 2001, and as of June 28, 2022, Türkiye remains part of the Annex I group alongside 39 other countries and the European Union (UNFCCC, 1992).
- Annex II countries have additional responsibilities beyond those of Annex I countries. These include providing financial resources to support activities in developing countries aimed at combating climate change, supplying environmentally friendly technologies, and encouraging access to these technologies and information.
- Non-Annex countries encompass developing nations, identified as being most vulnerable to the adverse effects of global warming (Çikot, 2009).

The Kyoto Protocol

The Kyoto Protocol was adopted in 1997 and came into force in 2005. Strengthening and operationalizing the UNFCCC, the Kyoto Protocol was developed to ensure that developed countries fulfill their responsibilities in combating climate change. This protocol was the result of 2.5 years of negotiations. Under the protocol, countries listed in Annex B (37 industrialized countries and the European Community) are required to adopt quantified emission limitation or reduction commitments for greenhouse gases.

- During the first commitment period (2008–2012), these countries were obligated to reduce total greenhouse gas emissions to at least 5% below 1990 levels.
- During the second commitment period (2013–2020), the reduction target was set at 18% below 1990 levels (Im, 2007).

Türkiye joined the Kyoto Protocol in 2009. However, as Türkiye was not a party to the UNFCCC at the time of the protocol's adoption in 1997, it was not included in the Annex B list, which outlines quantified emission limitation or reduction commitments. Consequently, Türkiye did not have any quantified emission reduction or limitation commitments during the first and second commitment periods of the Kyoto Protocol (UNFCCC, 2009).

Mechanisms of the Kyoto Protocol

The Kyoto Protocol introduced three flexibility mechanisms to assist Annex I parties in meeting their emission reduction targets:

1. Clean Development Mechanism (CDM)
2. Joint Implementation (JI)
3. Emissions Trading (ETS)

These mechanisms were designed to finance the low-carbon economy approach outlined by the protocol (Bayrak, 2012).

Clean Development Mechanism (CDM)

The CDM, defined in Article 12 of the Kyoto Protocol, is a project-based mechanism that allows Annex B parties with emission reduction or limitation commitments to implement emission reduction projects in developing countries. These projects generate Certified Emission Reduction (CER) units, each equivalent to one ton of CO2, which can be traded and counted towards achieving the emission reduction targets of the implementing parties (Pallav, 2008).

The CDM has two objectives:

- To assist industrialized countries in meeting their emission reduction or limitation targets.
- To help developing countries achieve sustainable development (Grubb, 2003).

CDM credits can be generated from emission reduction projects, afforestation, and reforestation (A/R) projects. However, forest-related projects under the CDM differ from energy-related CDM projects due to the temporary nature of carbon storage in forest carbon stocks.

Joint Implementation (JI)

Defined in Article 6 of the Kyoto Protocol, the JI mechanism allows an Annex I party to implement an emission reduction project in another Annex I country. The host country generates Emission Reduction Units (ERUs), equivalent to one ton of CO2, which can be transferred to the investing country. These units contribute to the emission reduction targets of the investing party.

Emissions Trading (ETS)

As a market-based mechanism described in Article 17 of the Kyoto Protocol, ETS allows Annex I countries to transfer or acquire Kyoto units from one another to meet their quantified emission limitation and reduction commitments. Countries that emit less than their allocated amounts can sell their excess units to those exceeding their targets (Dagoumas et al., 2006). Under ETS, countries can also trade units derived from land use, land-use change, and forestry (LULUCF) activities, as well as CERs from CDM projects and ERUs from JI projects (Hepburn, 2007).

The Paris Agreement

The Paris Agreement (PA), adopted in 2015 during the 21st Conference of the Parties (COP21) in Paris, outlines the framework for the climate regime post-2020. The agreement, effective since 2016, aims to limit global temperature increases to well below 2°C above pre-industrial levels and emphasizes the importance of pursuing efforts to limit the increase to 1.5°C. Türkiye became a party to the Paris Agreement in 2021. In its Intended Nationally Determined Contribution (INDC), submitted in 2015, Türkiye pledged to reduce its projected 2030 emissions by up to 21% (Talu, 2020).

Carbon Markets

Carbon markets are classified into two categories: Mandatory Carbon Markets and Voluntary Carbon Markets. These markets operate within the framework of the Kyoto Protocol and are structured as follows (ÇOB, 2008):

Mandatory Carbon Markets:

Mandatory carbon markets are established based on international obligations and regulations arising from the Kyoto Protocol. Three mechanisms are defined under these markets:

- Clean Development Mechanism (CDM)
- Joint Implementation (JI)
- Emissions Trading (ETS)

These mechanisms finance activities aimed at achieving a low-carbon economy, as emphasized in the Kyoto Protocol (Bayrak, 2012).

Voluntary Carbon Markets:

Voluntary carbon markets operate independently of legal obligations. They function based on voluntary commitments by countries, organizations, or individuals to reduce carbon emissions. Emission credits traded in these markets are referred to as Voluntary Emission Reduction (VER) Units (Hamilton et al., 2007).

Voluntary carbon markets are structured around various standards, which ensure that projects generate measurable, real, and verifiable emission reductions. These standards include:

- Verified Carbon Standard (VCS)
- The Gold Standard (GS)
- Climate Action Reserve (CAR)
- American Carbon Registry (ACR)
- ISO-14064

Projects in voluntary carbon markets primarily focus on renewable energy and energy efficiency sectors. Forestry projects, however, constitute a smaller share due to challenges related to permanence, additionality, and leakage.

Türkiye in Voluntary Carbon Markets

Türkiye has been active in voluntary carbon markets since 2005, as it doesn’t participate in the mandatory mechanisms of the Kyoto Protocol. Renewable energy projects, such as wind, solar, hydroelectric, and biomass power plants, dominate Türkiye's voluntary carbon credits (Climate Focus, 2019). Between 2007 and 2016, Türkiye generated approximately 37 MtCO2 equivalent in transactions worth over $200 million. Türkiye is recognized as the largest seller of voluntary carbon credits in Europe. The Ministry of Environment and Urbanization oversees voluntary carbon projects through regulations, such as the "Voluntary Carbon Market Project Registration Communiqué" published in 2013.

The Role of the Forestry Sector in Carbon Markets

Forest ecosystems play a critical role as carbon sinks, removing CO2 from the atmosphere through photosynthesis. Additionally, forests store carbon in trees, other woody vegetation, leaves, branches, roots, and forest soil, including both living and dead organic matter (Bayramoğlu and Toksoy, 2010a, 2010b; Başsüllü et al., 2014; Aydın et al., 2018, Güneş Şen & Aydın, 2024). However, approximately 13 million hectares of forests are destroyed annually worldwide, contributing to an estimated 18% of global emissions due to deforestation and forest degradation (FAO, 2021). Consequently, forests are vital for emission reduction efforts.

The forestry sector is supported through projects in both mandatory and voluntary carbon markets:

- In mandatory markets, forestry projects are mainly facilitated through the Clean Development Mechanism (CDM) and the Reducing Emissions from Deforestation and Forest Degradation (REDD+) initiative. These projects focus on sustainable forest management, enhancing forest carbon stocks, and reducing emissions from deforestation and forest degradation.
- Voluntary markets see greater activity in forestry projects due to the challenges faced in mandatory markets, such as permanence, accounting, and additionality requirements.

Afforestation and Reforestation (A/R) Activities

Within the scope of Land Use, Land-Use Change, and Forestry (LULUCF) activities under the CDM, forestry projects are limited to Afforestation and Reforestation (A/R) activities. Despite their potential, these projects face several barriers in both markets, including:

- Proving additionality, as projects must demonstrate that the carbon sequestration would not occur without the project.
- Addressing permanence, given that carbon stored in forests can be released back into the atmosphere due to deforestation, fires, or other disturbances.
- Avoiding leakage, where emission reductions in one area lead to increased emissions elsewhere.

As of 2023, the Forest Trends database reports a total of 262 active forestry-related carbon projects globally. However, A/R credits account for only 0.8% of all CDM credits, due to challenges in demonstrating additionality and effectiveness (Forest Trends, 2023).

The Status of Afforestation Carbon Projects in Türkiye

In Türkiye, carbon credits have largely been generated from renewable energy projects, including hydroelectric, wind, biogas, and geothermal power plants. However, the production of carbon credits from forestry projects remains limited due to various regulatory and technical barriers. For afforestation projects in Türkiye to qualify for carbon credits, they must adhere to both international certification standards and national forest legislation (Toksoy et al., 2020). The key challenges include ensuring that carbon credits are directly tied to carbon finance for new afforestation efforts, proving the additionality of the projects (i.e., demonstrating that they are carried out specifically for carbon sequestration rather than other goals), and meeting stringent management requirements to guarantee the permanence of the carbon sequestered and the sustainable use of harvested wood products. Furthermore, private afforestation on state-owned land is eligible for carbon credits only if the land was not already designated for afforestation.

Thus far, Türkiye has primarily generated carbon credits through renewable energy sectors such as hydroelectric, wind, biogas, geothermal, energy efficiency, and waste-to-energy projects (Türkiye Carbon Market, 2012). Recently, attention has turned to generating carbon credits from forestry, a sector that has gained increasing interest in recent years (Climate Focus, 2019).

Carbon credits can be generated from the forestry sector in three key ways:

1. REDD or Preventing Deforestation: This approach, more relevant to countries with high deforestation rates, focuses on reducing emissions by preventing deforestation.
2. Improved Forest Management: Forest management practices can be adapted to prioritize carbon sequestration, even if the forest was originally managed for other production goals.
3. Afforestation: This involves planting trees in areas not previously afforested, specifically for the purpose of carbon sequestration.

Constraints in Afforestation Carbon Projects in Türkiye

For afforestation projects to generate carbon credits in Türkiye, they must comply with both international certification standards and Turkish forest legislation. As outlined by Ülgen and Güneş in 2016, the following issues arise:

1. Carbon credits cannot be claimed for previously established afforestation sites unless these projects can be shown to have been implemented specifically for the purpose of carbon sequestration. This highlights the importance of additionality.

2. Additionality: For afforestation projects to qualify for carbon certification, they must demonstrate that carbon sequestration would not have occurred without the project. In other words, the afforestation must not have happened as part of regular forest management activities.

3. If afforestation is planned by institutions with afforestation goals, they must demonstrate that the project could not have been carried out without carbon finance support.

4. Harvesting of forest products: If the goal of the afforestation project is to produce goods, then carbon credits cannot be claimed.

5. Cadastre lands: Areas within forest boundaries designated as "OT" and already marked for afforestation cannot claim carbon credits, as they are legally required to be afforested.

6. Private afforestation on state-owned lands: This can qualify for carbon credits because such lands are not legally required to be afforested. However, for projects larger than 3 hectares, forest management plans must be prepared, and trees must be harvested according to the management plan once their management period ends. The critical issue here is ensuring that harvested products do not release atmospheric carbon, especially if used in products like furniture.

7. Permanence and the Zero Net Harm Policy; Permanence is an important issue for certification organizations. Once a carbon credit project ends, the land must be preserved in its forested state. In some cases, even after harvesting, the land must be replanted, and it must be guaranteed that the carbon stored in the forest products will not be released into the atmosphere. The "Zero Net Harm" policy is becoming increasingly important in carbon certification. When carbon markets were first established, it was sufficient for a project to sequester carbon. However, certification bodies now require that the project does not negatively impact the local ecology, sociology, culture, or economy.

Evaluations

Today, many countries have capitalized on their carbon stock and carbon sequestration potential through the global carbon market by generating carbon credits. However, in Türkiye, the forestry sector has not yet fully engaged in this market. The position of Türkiye in the international agreements it has signed, the relevant articles in its constitution and forestry law, and other related factors need to be reviewed and adapted to international carbon markets. To enable Türkiye to participate more actively in the growing carbon markets, it must urgently amend its regulations. Türkiye needs to make the necessary legal arrangements to be included in the forest carbon market and ensure the sustainability of its forest resources. The relevant organizations should be established under the General Directorate of Forestry and carbon credits should be integrated into forest management plans.

Türkiye’s position in international agreements, the relevant provisions in its constitution and forestry law, and many other circumstances should be reviewed to align them with international carbon market standards. For Türkiye to participate effectively in global carbon markets, immediate revisions are needed in its regulations. Necessary legal adjustments should be made to ensure Türkiye’s participation in the forest carbon market and to maintain the sustainability of its forest resources.

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Chapter 4

Applications of Artificial Intelligence in Predicting Timber Prices

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Climate change can be defined as statistically significant changes in the mean state or variability of the climate over extended periods. These changes arise due to natural processes and external forcing factors, as well as continuous human-induced alterations in atmospheric composition and land use (Türkeş, 2008; Aydın et al., 2018; Bayramoğlu & Seyhan, 2019; Güngör & Şen, 2021; Güneş Şen & Aydın, 2024). Climate change is expected to impact key environmental and societal elements such as agriculture, forests, water resources, sea levels, energy production, human health, and biodiversity (Doğan & Tüzer, 2011; Almansouri et. al., 2020; Seyhan & Bayramoğlu, 2023; Güneş Şen, 2023). Forests are considered one of the most critical natural resources in combating climate change (Pache et al., 2021). Covering approximately 30% of the Earth's land area, forests are among the most widespread terrestrial ecosystems (Raihan, 2023a). In the past, forests were used only for the production of wood raw materials, but today, as a result of the increase in social awareness, the services provided by forests have gained great importance (Küçükbekir and Bayramoğlu, 2022). Forest ecosystems play a vital role in ensuring the sustainability of our planet (Raihan, 2023b). However, climate change poses a significant threat to the structure and functionality of these ecosystems.

Due to the critical importance of forest ecosystems, their sustainable management and conservation have become necessary to address today's environmental and economic challenges. The concept of sustainable forest management provides a framework that integrates ecological, financial, and social dimensions. Within this context, the economic dimension encompasses the utilization of forest products and elements aimed at enhancing overall welfare (Kruk & Kornatowska, 2014; Güngör, 2024a). To maximize the economic potential of forest products and manage these economic factors more effectively, the adoption of innovative strategies in the forestry sector is required (Güngör, 2018). The forestry sector can benefit significantly from technology's inherent capacity to support innovation processes and enable rapid adaptation across different geographical regions and at various scales (Raihan, 2023c; Güngör, 2024b). In this context, artificial intelligence applications such as machine learning are believed to have the potential to accelerate data analysis and decision-making processes in the multidimensional management of forests, thereby contributing to sustainability goals.

In recent years, rapid advancements in technology have enabled the implementation of more innovative and effective methods in forest management (Güngör & Şen, 2024). Artificial intelligence (AI) and machine learning (ML) algorithms provide significant contributions in areas such as analyzing large datasets, developing predictive models, and managing risks (Zhao, Wang & Anderson, 2024).

When examining the history of artificial intelligence, its philosophical foundations and initial concrete steps can be traced back to the 17th century. During that period, there were efforts, particularly among the ruling and aristocratic classes, to create automata that mimicked human and animal behaviors. One of the prominent philosophers of the time, Descartes, likened humans to a machine functioning like a clock and suggested that human behavior could be imitated. In the 19th century, Charles Babbage developed the "Difference Engine," the first mechanical calculator, modeled on the workings of the human mind. In addition to performing mathematical operations, this machine possessed a memory capable of playing games, a feature that earned it a significant place in the field of artificial intelligence research (Schultz & Ellen-Schultz, 2007).

Modern artificial intelligence research began during World War II (Turing, 1950). In a 1947 lecture to the London Mathematical Society, Alan Turing described the future of machine computation as "machines that could learn through experience." This concept laid the foundation for the field of machine learning in the 1950s. Initially, computers began developing algorithms using models derived from specific datasets. To make machine learning more effective, decision trees were created, and "weights" were added to these trees to fit them optimally to the training set. These algorithms were then tested with validation sets.

Among the early significant works in the field were Donald Hebb's neural network model, which explained interactions between brain cells, and Arthur Samuel's alpha-beta pruning algorithm used in checkers. In 1957, Frank Rosenblatt designed a specialized computer by combining both models. The purpose of this computer was to focus on applications such as image recognition, but these early attempts were not successful in practical implementations (Edwards, Kaplan, & Jie, 2021).

From the late 1970s to the 1980s, a series of negative opinions about artificial intelligence led to a near standstill in AI research in many countries. This period came to be known as the "AI Winter." However, some countries, such as Japan, chose to continue their research despite these criticisms. By the late 1980s, the United Kingdom initiated its efforts to avoid falling behind Japan in this field (Öztürk & Şahin, 2018). After the 1980s, AI research began to move beyond laboratory environments, focusing on more complex applications aimed at real-world needs, a process that continues to this day (Pirim, 2006).

Machine learning (ML), a subfield of artificial intelligence (AI), enables computer systems to learn from data, developing algorithms and statistical models capable of generalizing to previously unseen data (Zhao, Wang & Anderson, 2024). The primary aim of machine learning is to train machines based on past experiences and statistical data, allowing them to efficiently perform assigned tasks to solve specific problems. Machine learning has become a critical component in addressing challenges across various sectors, including engineering, finance, and education (Peng & Sadaghiani, 2023).

Today, numerous applications of machine learning exist, including data analysis derived from historical data, voice, and facial recognition systems, and weather forecasting (Jha et al., 2019). In the financial sector, machine learning techniques are used for evaluating changing market conditions and dynamics in economic analyses, predicting demand levels in the supply processes of financial instruments, determining whether supply meets demand, and analyzing the success of supply processes based on changes in demand over time (Özgür, 2021).

Machine learning methods are also widely applied in forestry (Gomes et al., 2019). These applications include forest ecology and management, forest economics and policy, forest inventory, modeling and remote sensing, transportation, forest health and protection, soil, and hydrology. However, a review of the literature reveals that the use of machine learning techniques in forest economics is significantly less prevalent compared to other areas (Eker et al., 2023).

This study aims to increase the use of machine learning techniques in the field of forest economics, highlight the importance of data-driven decision-making processes in forestry, and contribute to the literature. By using artificial intelligence applications to predict timber prices, it is possible to enhance the efficient use of forest products, increase the economic value of forests, and promote the adoption of sustainable production methods instead of forest degradation. Given the need for proper forest management and conservation to combat climate change, it is believed that forecasting such data is of great significance.

This study aims to predict the timber prices of Black pine (Black Pine) and Scotch pine (Yellow Pine) normal-length logs in Turkey between 2014 and 2023 using machine learning algorithms, based on auction sale data. Black pine and Scotch pine species are among the most important tree species in Turkey's forests, particularly due to their high economic value in timber production. Accurately predicting the price dynamics of products from these species supports the strategic decision-making processes of businesses in the forestry sector and helps maintain market balance. However, predicting timber product prices requires the evaluation of several complex factors simultaneously. Difficulty obtaining sufficient and suitable wood raw material is a common problem of industries processing wood as a raw material (Toksoy et al., 2006). These factors include tree species, product sizes, regional market conditions, seasonal fluctuations, and macroeconomic indicators. In addition, meeting the population's demand in a sustainable manner is only possible by effectively managing natural resources (Bayramoglu and Toksoy, 2016)

In this context, machine learning models such as Linear Regression, Decision Tree, Random Forest, and XGBoost have been applied to different datasets, and their performances have been compared. The fact that the study was conducted on a broader dataset, not limited to a specific tree species or region, has enhanced the generalization capacity of the prediction models and ensured the applicability of the findings to a wider range of the forestry sector. It is believed that machine learning techniques have the potential to lead innovative applications in the forestry sector, offering more effective results compared to traditional methods. The results obtained from the study will contribute to strategic decision-making processes aimed at sustainable management of forest resources and the development of market forecasting.

Data Analysis and Application of Machine Learning Techniques

The study material consists of auction sales data from 26 Forest Regional Directorates affiliated with the General Directorate of Forestry (OGM). In this context, the datasets used include the average sale prices and quantities (m^3) of logs sold at auction every month from 2014 to 2023 for the tree species Black pine-Scotch pine, as well as the species Kızılçam, Göknar, Ladin, Sedir, Kayın, and Meşe, which are considered to have an impact on the sales price. The first two analyses focus solely on the sales data of Black pine and Scotch pine species, while the third analysis includes data from these species as well as Kızılçam, Göknar, Ladin, Sedir, Kayın, and Meşe species. These two datasets were used to comparatively analyze prediction models and evaluate the impact of different species groups on price forecasting.

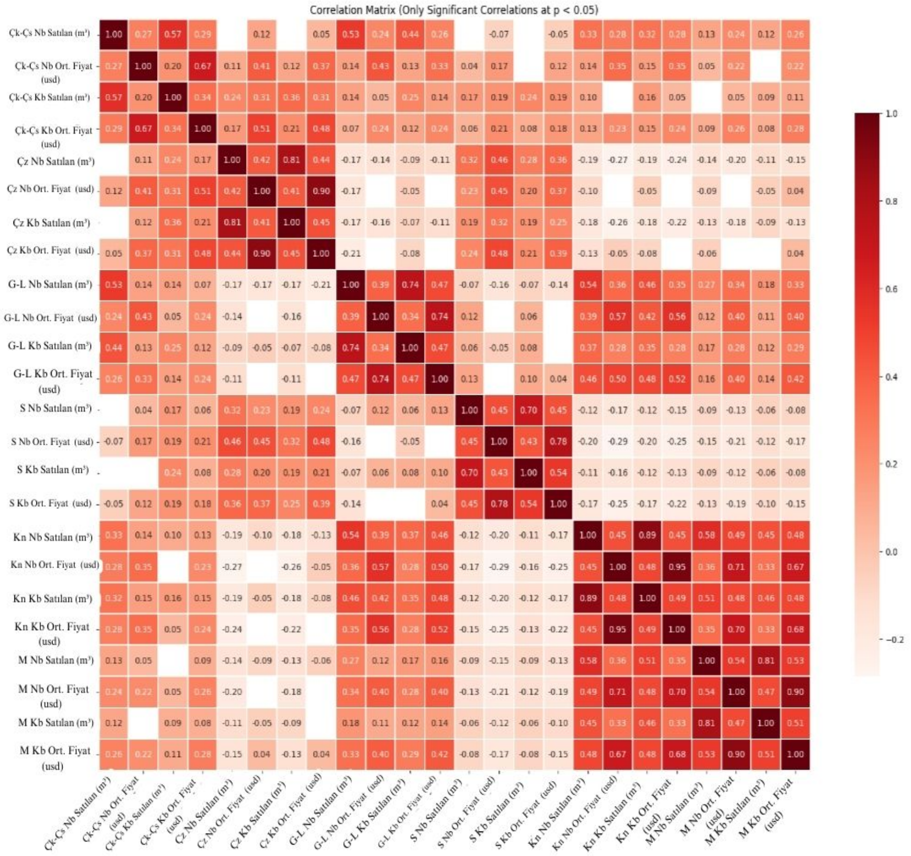
The first dataset includes the following attributes: "Black pine-Scotch pine normal-length logs sales quantities (m^3), Black pine-Scotch pine normal-length logs average price, year, month, and regional directorate."

The second dataset includes the following attributes: "Black pine-Scotch pine normal-length logs sales quantities (m^3), Black pine-Scotch pine normal-length logs average price, Black pine-Scotch pine short log sales quantities (m³), Black pine-Scotch pine short log average price, year, month, and regional directorate."

The third dataset includes the following attributes: "Black pine-Scotch pine normal-length logs sales quantities (m³), Black pine-Scotch pine normal-length logs average price, Black pine-Scotch pine short log sales quantities (m³), Black pine-Scotch pine short log average price, Kızılçam normal-length logs sales quantities (m³), Kızılçam normal-length logs average price, Kızılçam short log sales quantities (m³), Kızılçam short log average price, Göknar-Ladin normal-length logs sales quantities (m³), Göknar-Ladin normal-length logs average price, Göknar-Ladin short log sales quantities (m³), Göknar-Ladin short log average price, Sedir normal-length logs sales quantities (m³), Sedir normal-length logs average price, Sedir short log sales quantities (m³), Sedir short log average price, Kayın normal-length logs sales quantities (m³), Kayın normal-length logs average price, Kayın short log sales quantities (m³), Kayın short log average price, Meşe normal-length logs sales quantities (m³), Meşe normal-length logs average price, Meşe short log sales quantities (m³), Meşe short log average price, year, month, and regional directorate."

The average prices in the datasets are in Turkish Lira (TL), and for the purposes of this study, these prices have been converted to United States Dollars (USD) by considering the exchange rates for the relevant period.

Correlation analysis has been performed to determine the relationship levels between the variables. The correlation matrix is provided in Figure1.



	Çk-Çs Nb Satılan (m³)	Çk-Çs Nb Ort. Fiyat (usd)	Çk-Çs Kb Satılan (m³)	Çk-Çs Kb Ort. Fiyat (usd)	Çz Nb Satılan (m³)	Çz Nb Ort. Fiyat (usd)	Çz Kb Satılan (m³)	Çz Kb Ort. Fiyat (usd)	G-L Nb Satılan (m³)	G-L Nb Ort. Fiyat (usd)	G-L Kb Satılan (m³)	G-L Kb Ort. Fiyat (usd)	S Nb Satılan (m³)	S Nb Ort. Fiyat (usd)	S Kb Satılan (m³)	S Kb Ort. Fiyat (usd)	Kn Nb Satılan (m³)	Kn Nb Ort. Fiyat (usd)	Kn Kb Satılan (m³)	Kn Kb Ort. Fiyat (usd)	M Nb Satılan (m³)	M Nb Ort. Fiyat (usd)	M Kb Satılan (m³)	M Kb Ort. Fiyat (usd)
Çk-Çs Nb Satılan (m³)	1.00	0.27	0.57	0.29		0.12		0.05	0.53	0.24	0.44	0.26		-0.07		-0.05	0.33	0.28	0.32	0.28	0.13	0.24	0.12	0.26
Çk-Çs Nb Ort. Fiyat (usd)	0.27	1.00	0.20	0.67	0.11	0.41	0.12	0.37	0.14	0.43	0.13	0.33	0.04	0.17		0.12	0.14	0.35	0.15	0.35	0.05	0.22		0.22
Çk-Çs Kb Satılan (m³)	0.57	0.20	1.00	0.34	0.24	0.31	0.36	0.31	0.14	0.05	0.25	0.14	0.17	0.19	0.24	0.19	0.10		0.16	0.05		0.05	0.09	0.11
Çk-Çs Kb Ort. Fiyat (usd)	0.29	0.67	0.34	1.00	0.17	0.51	0.21	0.48	0.07	0.24	0.12	0.24	0.06	0.21	0.08	0.18	0.13	0.23	0.15	0.24	0.09	0.26	0.08	0.28
Çz Nb Satılan (m³)		0.11	0.24	0.17	1.00	0.42	0.81	0.44	-0.17	-0.14	-0.09	-0.11	0.32	0.46	0.28	0.36	-0.19	-0.27	-0.19	-0.24	-0.14	-0.20	-0.11	-0.15
Çz Nb Ort. Fiyat (usd)	0.12	0.41	0.31	0.51	0.42	1.00	0.41	0.90	-0.17		-0.05		0.23	0.45	0.20	0.37	-0.10		-0.05		-0.09		-0.05	0.04
Çz Kb Satılan (m³)		0.12	0.36	0.21	0.81	0.41	1.00	0.45	-0.17	-0.16	-0.07	-0.11	0.19	0.32	0.19	0.25	-0.18	-0.26	-0.18	-0.22	-0.13	-0.18	-0.09	-0.13
Çz Kb Ort. Fiyat (usd)	0.05	0.37	0.31	0.48	0.44	0.90	0.45	1.00	-0.21		-0.08		0.24	0.48	0.21	0.39	-0.13	-0.05	-0.08		-0.06			0.04
G-L Nb Satılan (m³)	0.53	0.14	0.14	0.07	-0.17	-0.17	-0.17	-0.21	1.00	0.39	0.74	0.47	-0.07	-0.16	-0.07	-0.14	0.54	0.36	0.46	0.35	0.27	0.34	0.18	0.33
G-L Nb Ort. Fiyat (usd)	0.24	0.43	0.05	0.24	-0.14		-0.16		0.39	1.00	0.34	0.74	0.12		0.06		0.39	0.57	0.42	0.56	0.12	0.40	0.11	0.40
G-L Kb Satılan (m³)	0.44	0.13	0.25	0.12	-0.09	-0.05	-0.07	-0.08	0.74	0.34	1.00	0.47	0.06	-0.05	0.08		0.37	0.28	0.35	0.28	0.17	0.28	0.12	0.29
G-L Kb Ort. Fiyat (usd)	0.26	0.33	0.14	0.24	-0.11		-0.11		0.47	0.74	0.47	1.00	0.13		0.10	0.04	0.46	0.50	0.48	0.52	0.16	0.40	0.14	0.42
S Nb Satılan (m³)		0.04	0.17	0.06	0.32	0.23	0.19	0.24	-0.07	0.12	0.06	0.13	1.00	0.45	0.70	0.45	-0.12	-0.17	-0.12	-0.15	-0.09	-0.13	-0.06	-0.08
S Nb Ort. Fiyat (usd)	-0.07	0.17	0.19	0.21	0.46	0.45	0.32	0.48	-0.16		-0.05		0.45	1.00	0.43	0.78	-0.20	-0.29	-0.20	-0.25	-0.15	-0.21	-0.12	-0.17
S Kb Satılan (m³)			0.24	0.08	0.28	0.20	0.19	0.21	-0.07	0.06	0.08	0.10	0.70	0.43	1.00	0.54	-0.11	-0.16	-0.12	-0.13	-0.09	-0.12	-0.06	-0.08
S Kb Ort. Fiyat (usd)	-0.05	0.12	0.19	0.18	0.36	0.37	0.25	0.39	-0.14			0.04	0.45	0.78	0.54	1.00	-0.17	-0.25	-0.17	-0.22	-0.13	-0.19	-0.10	-0.15
Kn Nb Satılan (m³)	0.33	0.14	0.10	0.13	-0.19	-0.10	-0.18	-0.13	0.54	0.39	0.37	0.46	-0.12	-0.20	-0.11	-0.17	1.00	0.45	0.89	0.45	0.58	0.49	0.45	0.48
Kn Nb Ort. Fiyat (usd)	0.28	0.35		0.23	-0.27		-0.26	-0.05	0.36	0.57	0.28	0.50	-0.17	-0.29	-0.16	-0.25	0.45	1.00	0.48	0.95	0.36	0.71	0.33	0.67
Kn Kb Satılan (m³)	0.32	0.15	0.16	0.15	-0.19	-0.05	-0.18	-0.08	0.46	0.42	0.35	0.48	-0.12	-0.20	-0.12	-0.17	0.89	0.48	1.00	0.49	0.51	0.48	0.46	0.48
Kn Kb Ort. Fiyat (usd)	0.28	0.35	0.05	0.24	-0.24		-0.22		0.35	0.56	0.28	0.52	-0.15	-0.25	-0.13	-0.22	0.45	0.95	0.49	1.00	0.35	0.70	0.33	0.68
M Nb Satılan (m³)	0.13	0.05		0.09	-0.14	-0.09	-0.13	-0.06	0.27	0.12	0.17	0.16	-0.09	-0.15	-0.09	-0.13	0.58	0.36	0.51	0.35	1.00	0.54	0.81	0.53
M Nb Ort. Fiyat (usd)	0.24	0.22	0.05	0.26	-0.20		-0.18		0.34	0.40	0.28	0.40	-0.13	-0.21	-0.12	-0.19	0.49	0.71	0.48	0.70	0.54	1.00	0.47	0.90
M Kb Satılan (m³)	0.12		0.09	0.08	-0.11	-0.05	-0.09		0.18	0.11	0.12	0.14	-0.06	-0.12	-0.06	-0.10	0.45	0.33	0.46	0.33	0.81	0.47	1.00	0.51
M Kb Ort. Fiyat (usd)	0.26	0.22	0.11	0.28	-0.15	0.04	-0.13	0.04	0.33	0.40	0.29	0.42	-0.08	-0.17	-0.08	-0.15	0.48	0.67	0.48	0.68	0.53	0.90	0.51	1.00

Figure 1. Correlation Matrix

The correlation matrix shown in Figure 1 only includes statistically significant relationships ($p < 0.05$). The results reveal both positive and negative relationships between the sales volumes and average prices of different tree species.

Machine learning algorithms have been used as the methodology in this study. Four different machine learning models, namely Linear Regression, Decision Tree, Random Forest, and XGBoost were employed for price prediction, and their performance was compared. The selection of these models was based on their distinct advantages and predictive capabilities.

Linear Regression: It is a statistical method used to determine the cause-and-effect relationship between a dependent variable and one or more independent variables (Korkmaz et al., 2022). The mathematical formula for the Linear Regression model is provided below.

$$Y_i = \beta_0 + \beta_1 X_i + \varepsilon_i \tag{1}$$

Here:

- y_i = Dependent variable (desired outcome), prediction
- β_0 = Constant value, also the point where it intersects the y-axis
- β_1 = Coefficient, the slope of the line to be drawn
- x_i = independent variable
- ε_i = error prediction

This formula represents the linear relationship between the dependent variable and the independent variable, while also accounting for the error margin that affects this relationship.

Decision Tree: Decision trees are a method within tree-based learning algorithms, used to divide large datasets into smaller subsets through a series of decision rules. This method provides ease of interpretation and can handle both categorical and numerical data (Ray, 2019). The decision tree algorithm is shown in Figure 2.

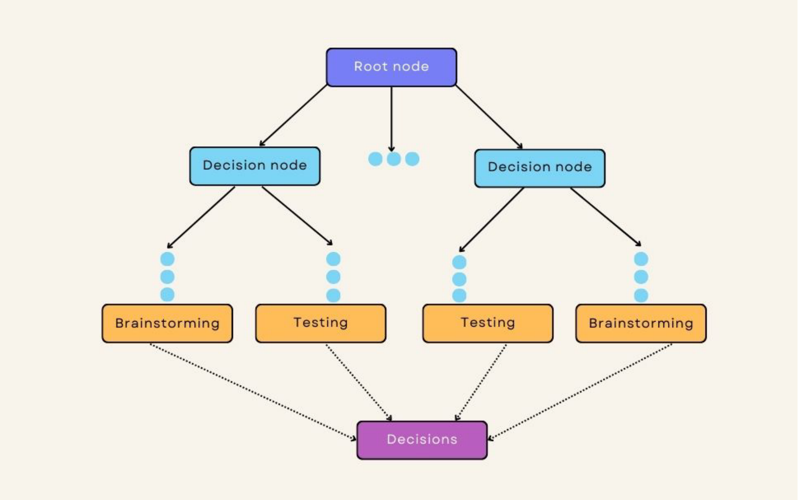


Figure 2. Decision Tree Algorithm

As seen in Figure 2:

- **Root node:** This is the starting point of the decision tree and represents the first split in the data.
- **Decision nodes:** These are intermediate nodes that follow the root node, where the data is split into branches based on a specific feature.

- **Leaf nodes:** These are the final points of the decision process, with each leaf representing a specific decision or classification outcome.

As a result, the decisions from the leaf nodes form the classification or prediction outcomes (Gültepe, 2019).

Random Forest: A random forest is an ensemble of decision trees, each based on a random sample of the training data with the same distribution, where the individual trees are independent of one another (Breiman, 2001). This method is based on training multiple decision trees and determining the most suitable class through majority voting based on the predictions of each tree (Lorena et al., 2011). The Random Forest algorithm is shown in Figure 3.

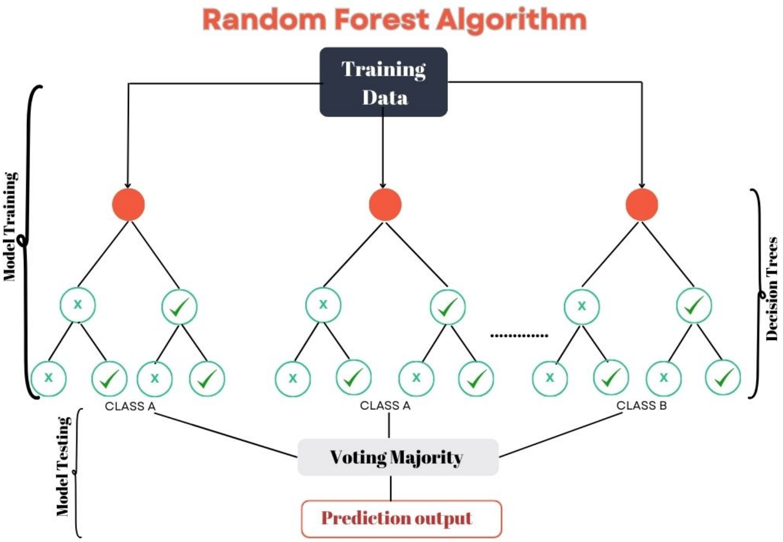


Figure 3. Random Forest Algorithm

XGBoost: XGBoost is a decision tree-based machine learning algorithm. The model includes various objective functions, such as classification, regression, and ranking (Pathy, Meher, & Balasubramanian, 2020). The XGBoost algorithm is shown in Figure 4.

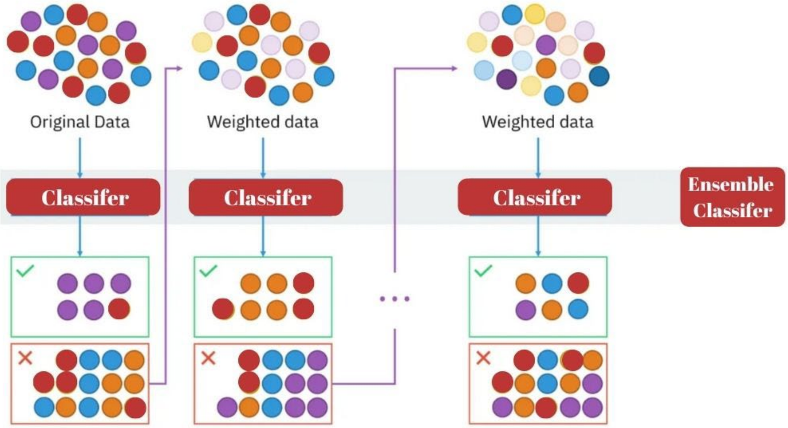


Figure 4. XGBoost Algorithm

In the study, modeling was performed with three different datasets to predict the sales prices of Black pine and Scotch pine species. Initially, only the sales data of Black pine and Scotch pine species were analyzed, and machine learning models were developed based on these data.

After the analysis of the Black pine and Scotch pine species, a new dataset was created by including sales data from other tree species (Kızılçam, Sedir, Göknar, Ladin, Kayın, and Meşe) in addition to Black pine and Scotch pine. Considering that the free market may influence the sales quantities and prices of Black pine and Scotch pine species, detailed analyses were conducted for these species, and machine learning models were developed using these data. In the application of these analyses, the structure and content of all three datasets were first examined through a general analysis. In this context, the size, shape, and variable types of the datasets were reviewed, and missing data was analyzed. To detect missing data, the 'is null ()' and 'sum()' functions from the Pandas library were used to calculate the number of missing observations for each variable. According to the results, no missing data was found in the two datasets. The clean and complete nature of the datasets contributes to generating healthier results for the model. The analyses and modeling process performed on the data was carried out using Python 3.10 programming language. Subsequently, the "forest regional directorate" variable, containing 26 different observation units, was considered a categorical variable and converted into numerical values using the Label Encoding method so that machine learning algorithms could process it. The Label

Encoding method converts each categorical variable into a numerical form starting from zero (Hosni, 2023). In Table 1, the numerical values corresponding to the categorical values of the 'month' variable after encoding are provided, while in Table 2, the numerical values corresponding to the categorical values of the "forest regional directorate" variable after encoding are shown.

Table 1. Values Obtained After Encoding the 'Month' Variable

Months	Numerical Value	Months	Numerical Value
January	9	July	11
February	10	August	0
March	6	September	3
April	8	October	2
May	7	November	5
June	4	December	1

Table 2. Values Obtained After Encoding the 'Forest District Directorate' Variable

No.	Forest Regional Directorate	Encoding Value	No.	Forest Regional Directorate	Encoding Value
1	Adana	0	14	Isparta	13
2	Amasya	1	15	İstanbul	14
3	Ankara	2	16	İzmir	15
4	Antalya	3	17	Kahramanmaraş	16
5	Artvin	4	18	Kastamonu	17
6	Balıkesir	5	19	Kayseri	18
7	Bolu	6	20	Konya	19
8	Bursa	7	21	Kütahya	20
9	Denizli	8	22	Mersin	21
10	Elazığ	9	23	Muğla	22
11	Erzurum	10	24	Sakarya	23
12	Eskişehir	11	25	Trabzon	24
13	Giresun	12	26	Zonguldak	25

The average sales price and sales quantity (m^3) variables have been normalized using the Standard Scaler to eliminate scale differences between the data in the models. The mathematical formula of the Standard Scaler method is provided below.

$$Standart\ Scaler = \frac{x_i - x_{average}}{\text{Standard Deviation}} \tag{2}$$

In the Standard Scaler method, the mean value of each feature is subtracted, and then it is divided by the standard deviation. This process ensures that the data is rescaled so that the mean becomes 0 and the standard deviation becomes 1, bringing the data closer to a standard normal distribution.

The analyses were carried out using the machine learning models mentioned above. During the analysis process, the data was split into 80% training and 20% test sets, and the models were evaluated based on this data split. Hyperparameter optimization was performed for the model that showed the best performance. This process was carried out using the GridSearchCV method. The Grid Search method is a technique that systematically optimizes hyperparameter settings to improve the performance of machine learning models (Jiang & Xu, 2022). This process aims to find the optimal values for certain important parameters, such as learning rate, number of trees (n_estimators), and maximum depth (max_depth), to enhance the model's performance. Then, cross-validation was used to test different parameter combinations of the model and achieve the best results. Cross-validation is a fundamental data resampling method used to reliably evaluate the model's performance on new data, adjust hyperparameters, and prevent overfitting (Berrar, 2019).

The performance of the models was evaluated using R^2 (coefficient of determination), MSE (mean squared error), and RMSE (root mean squared error) metrics on both the training and test datasets.

The coefficient of determination (R^2), as an extended version of the coefficient of determination defined in the context of linear regression, is a commonly used criterion to evaluate and compare the effectiveness of mathematical models based on a specific experimental dataset (Hernandez, n.d.). The formula for the coefficient of determination is given in Formula 3.

$$R^2 = 1 - \frac{(y_{i_{real}} - y_{i_{prediction}})^2}{(y_{i_{real}} - average(y_{real}))^2} \tag{3}$$

Mean Squared Error (MSE) is defined as a commonly accepted metric in the context of control and quality (Köksoy, 2006). The formula for Mean Squared Error is provided in Formula 4.

$$MSE = \frac{1}{N}\sum_{i=1}^{N}(y_i - \hat{y}_i)^2 \tag{4}$$

Root Mean Squared Error (RMSE) is a performance metric calculated by taking the square root of the Mean Squared Error (MSE). It typically represents values that are considered standard errors for errors with a normal distribution (Hodson, 2022). The formula for Root Mean Squared Error is provided in Formula 5.

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{(\hat{y}_i \ldots - y_i)^2}{n}} \tag{5}$$

Evaluation of Model Performance

In this study, the performance of models containing sales data for Black pine and Scotch pine species, as well as models containing sales data for Black pine, Scotch pine, Kızılçam, Sedir, Göknar, Ladin, Kayın, and Meşe species, has been evaluated. The findings obtained from this evaluation are summarized below.

The training and test set performances of the models containing data from the first dataset are presented in Table 3.

Table 3. Training and test set performances of the models for the first dataset

Model	Training set performance			Test set performance		
	R^2	MSE	RMSE	R^2	MSE	RMSE
Linear Regression	0.099	1907.430	43.674	0.101	1836.913	42.859
Decision Tree	1.0	0.0	0.0	0.932	139.037	11.791
Random Forest	0.995	10.307	3.210	0.963	75.511	8.689
XGBoost	0.858	299.557	17.307	0.838	330.962	18.192

When Table 3 is examined:

- The Linear Regression model shows a low performance with $R^2=0.099$, MSE=1907.430, and RMSE=43.674 on the training set. The values of $R^2=0.101$, MSE=1836.913, and RMSE=42.859 on the test set further indicate that the model's ability to predict the target variable is insufficient.

- The Random Forest model demonstrates a good fit with R^2=0.995, MSE=10.307, and RMSE=3.210 on the training set. However, the values of R^2=0.963, MSE=75.511, and RMSE=8.689 on the test set show a decrease in performance, suggesting that the model is prone to overfitting on the training data.
- The Decision Tree model achieves perfect fit with R^2=1.000 on the training set, and both MSE and RMSE values are zero, indicating no prediction error on the training data. However, the values of R^2=0.932, MSE=139.037, and RMSE=11.791 on the test set indicate that the model makes considerable errors on the test data due to overfitting.
- The XGBoost model provides a balanced performance with R^2=0.858, MSE=299.557, and RMSE=17.307 on the training set. The values of R^2=0.838, MSE=330.962, and RMSE=18.192 on the test set demonstrate the model's better generalization ability compared to other models. The model shows low overfitting risk, offering consistent performance across both training and test sets.

In Table 4, the test results of the best XGBoost model obtained after hyperparameter optimization and cross-validation are presented.

Table 4. Performance of the XGBoost Model After Hyperparameter Optimization and Cross-Validation

Model	R^2	MSE	RMSE
XGBoost	0.966	68.234	8.260

When Table 4 is examined, it can be seen that after hyperparameter optimization and cross-validation, the best XGBoost model achieved $R^2 = 0.966$, MSE = 68.234, and RMSE = 8.260 on the test set, indicating a significant reduction in the prediction errors on the test data. Based on this finding, it can be concluded that the XGBoost model is the most suitable model for this dataset.

The performance of the models for the 2nd dataset, based on the analysis results, is presented in Table 5 for both the training and test sets.

Table 5. Model Performances Containing Data for Black pine-Scotch pine Species

Model	Training set performance			Test set performance		
	R^2	MSE	RMSE	R^2	MSE	RMSE
Linear Regression	0.473	1114.469	33.383	0.477	1068.624	32.689
Decision Tree	1.0	0.0	0.0	0.934	133.096	11.536
Random Forest	0.994	11.093	3.330	0.962	77.620	8.810
XGBoost	0.895	220.967	14.864	0.866	272.179	16.497

When examining Table 5:

- The Linear Regression model showed performance with $R^2=0.473$, MSE=1114.469, and RMSE=33.383 on the training set. The values of $R^2=0.477$, MSE=1068.624, and RMSE=32.689 on the test set indicate that the model has limited generalization ability.
- The Random Forest model demonstrated excellent fit with $R^2=0.994$, MSE=11.093, and RMSE=3.330 on the training set. However, the values of $R^2=0.962$, MSE=77.620, and RMSE=8.810 on the test set show a decline in the model's performance on the test data. These findings suggest that the model is at risk of overfitting to the training data.
- The Decision Tree model achieved a perfect fit with $R^2=1.000$, and its MSE and RMSE values are zero, indicating no prediction errors in the training data. However, on the test set, $R^2=0.934$, MSE=133.096, and RMSE=11.536 values show that the model has made significant errors on the test data due to overfitting.
- The XGBoost model showed strong performance with $R^2=0.895$, MSE=220.967, and RMSE=14.864 on the training set. On the test set, $R^2=0.866$, MSE=272.179, and RMSE=16.497 indicate that the model has a sufficient generalization capacity.

In Table 6, the test results of the best XGBoost model obtained after hyperparameter optimization and cross-validation for the second dataset are shown.

Table 6. Performance of the XGBoost Model After Hyperparameter Optimization and Cross-Validation

Model	**R^2**	**MSE**	**RMSE**
XGBoost	0.967	66.193	8.135

When examining Table 6, the test set results of the best XGBoost model obtained after hyperparameter optimization and cross-validation show $R^2 = 0.967$, MSE = 66.193, and RMSE = 8.135. These values indicate that the model has captured complex data relationships more effectively and significantly reduced prediction errors on the test data. This suggests that the XGBoost model is the most suitable model for this dataset.

The analysis of the models applied to the 3rd dataset and the resulting training and test set performances are shown in Table 7.

Table 7. Model Performance Containing Data for Black pine-Scotch pine, Kızılçam, Sedir, Göknar, Ladin, Kayın, and Meşe Species.

Model	Training set performance			Test set performance		
	R^2	MSE	RMSE	R^2	MSE	RMSE
Linear Regression	0.578	892.962	29.882	0.561	896.573	29.942
Decision Tree	1.0	0.0	0.0	0.94	122.035	11.046
Random Forest	0.995	9.99	3.16	0.968	65.016	8.063
XGBoost	0.975	51.423	7.171	0.926	149.324	12.219

When Table 7 is examined:

- The Linear Regression model shows R^2=0.578, MSE=892.962, and RMSE=29.882 on the training set, indicating reasonable performance. However, it demonstrates relatively low generalization ability on the test set with R^2=0.561, MSE=896.573, and RMSE=29.942. These results suggest that the Linear Regression model fails to capture the complex relationships within the dataset, indicating that the linear model is insufficient for understanding the intricate data structure.
- The Random Forest model achieves high performance on the training set with R^2=0.995, MSE=9.99, and RMSE=3.16, but shows a more modest performance on the test set with R^2=0.968, MSE=65.016, and RMSE=8.063. Despite the model's high performance on the training data, its ability to generalize to the test data is limited, which suggests overfitting.
- The Decision Tree model shows perfect fit on the training set with R^2=1.0, MSE=0.0, and RMSE=0.0, indicating complete overfitting and exact fit to the training data. However, its performance on the test set is lower with R^2=0.94, MSE=122.035, and RMSE=11.046. These results indicate that the

Decision Tree model has overfitted the training data and has a limited capacity to generalize to the test data. The findings suggest that Decision Trees may not be sufficiently flexible to handle complex data structures.

- The XGBoost model performs well on both the training and test sets, with R^2=0.975, MSE=51.423, and RMSE=7.171 on the training set, and R^2=0.926, MSE=149.324, and RMSE=12.219 on the test set. XGBoost shows high performance on the training set and also demonstrates an acceptable error rate on the test set. These results indicate that the XGBoost model has better control over overfitting compared to other models and has improved generalization capacity. Its ability to capture the complex relationships in the dataset and generalize to new data is superior to that of the other models.

Therefore, the XGBoost model has been considered the most successful model in this study due to the balance and performance it achieved on both the training and test data. At this stage, cross-validation and hyperparameter optimization techniques were applied to further improve the performance of the XGBoost model. Table 8 presents the model performance results after applying cross-validation and hyperparameter optimization.

Table 8. Hyperparameter Optimization and Cross-Validation After XGBoost Model Performance

Model	**R^2**	**MSE**	**RMSE**
XGBoost	0.973	54.344	7.371

As seen in Table 8, after applying cross-validation and hyperparameter optimization, the performance of the XGBoost model on the test data achieved R^2 = 0.973, MSE = 54.344, and RMSE = 7.371. These findings indicate that the model's accuracy has improved, and the error rate has decreased.

In conclusion, based on the experiments conducted with machine learning models developed on different datasets, the XGBoost model is considered the most successful model in this study due to its superior performance on the test data after hyperparameter optimization. These findings demonstrate that the XGBoost model possesses strong predictive power on the dataset.

To test the accuracy of the analysis results, the Black pine-Scotch pine sales prices for the year 2024 were predicted. These predictions were made for the first six months of 2024 for six different regional directorates. In this context, predictions of Black pine-Scotch pine auction sales prices for these dates were made and compared with the actual values to test their accuracy. Table 9 shows the price predictions determined using three different approaches, along with the actual price values.

Table 9. Predicted Values and Actual Values

Region directorate	Date (Year 2024)	The average sales price prediction obtained from the analysis of the first dataset (USD)	The average sales price prediction obtained from the analysis of the second dataset (USD)	The average sales price prediction obtained from the analysis of the third dataset (USD)	Actual auction sales value	Closeness of the predicted value from the first dataset to the actual value	Closeness of the predicted value from the second dataset to the actual value	Closeness of the predicted value from the third dataset to the actual value
Kastamonu	Jan.	137,04	129,41	123,41	120,58	16,46	8,83	2,83
Bolu	Feb.	146,54	130,32	125,14	123,08	23,46	7,24	2,06
Kütahya	March	150,83	120,61	125,76	126,98	23,85	-6,37	-1,22
Bursa	April	157,36	142,04	139,52	131,43	25,93	10,61	8,09
Muğla	May	140,13	138,71	130,33	123,01	17,12	15,7	7,32
İzmir	June	143,21	109,54	113,86	112,67	30,54	-3,13	1,19

Positive(+) proximity values indicate that the predicted value is higher than the actual value, while negative (-) proximity values indicate that the predicted value is lower than the actual value.

When examining Table 9, it is observed that the model which includes all tree species demonstrates higher performance in terms of prediction accuracy for the Black pine-Scotch pine normal-length log prices. Including all species has enhanced the consistency of the predictions, providing more reliable results. Specifically, the reduction in prediction deviations observed across various months and regional directorates suggests that data from other species can contribute valuable information to the price predictions for Black pine-Scotch pine. This finding indicates that incorporating data from other tree species and using a more comprehensive dataset can improve the performance of prediction models for estimating the average sale prices of Black pine-Scotch pine.

In this study, data obtained from 26 forest regional directorates across Turkey between 2014 and 2023 were used to predict the normal-length log prices of Black pine and Scotch pine tree species using machine learning algorithms.

Linear Regression, Decision Tree, Random Forest, and XGBoost models were applied to three different datasets used in the study. As a result of comparing the performance of these models, the XGBoost algorithm demonstrated the highest performance across all datasets, with prediction accuracy increasing as the dataset size and scope expanded. The findings highlight the significant potential of machine learning models in better managing the economic value of forest products.

In this study, the hyperparameters of the XGBoost model were carefully optimized. This process balanced the model's tendency for overfitting and provided high accuracy on the test set. Through hyperparameter optimization, the model exhibited consistent performance on both the training and test sets. Additionally, the optimization accelerated the prediction process and enabled the models to operate with higher accuracy. Unlike traditional statistical models, machine learning algorithms not only learn nonlinear relationships but also uncover meaningful patterns from large datasets.

With the increasing computational power of computers, data science and machine learning have become important fields of study and are integrated with modern applications across many disciplines. In forestry, where information-based decision-making processes are critical, these technologies offer a highly suitable area of application (Eker et al., 2023). The results of this study contribute to the development of data-driven strategies in forest management, providing a foundation for the adoption of innovative approaches in the sector.

The integration of artificial intelligence and machine learning methods in economic forecasting for strategic decision-making processes is becoming a critical necessity for the sustainable management of forest resources. The use of these methods will contribute to supporting a sustainable market structure. Future studies are recommended to include macroeconomic variables, such as energy costs and inflation rates, as well as other factors influencing timber prices, to improve the model's performance and forecasting accuracy.

In the context of combating climate change, it is expected that such data-driven predictions will contribute to more efficient and sustainable forest management. In the future, the ability to predict the impact of climate conditions on forest production will play a critical role in developing long-term strategies. AI-based forecasting models not only predict timber prices but can also be utilized to manage forest resources more efficiently. Developing such models to predict the effects of factors such as forest fires or ecosystem degradation holds significant potential for the future of forest management.

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Büşra ERGÜN KARAK

Chapter 5

Inventory-Based Carbon Determınatıon For Sustaınable Forestry

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Global climate change, which affects the whole world, has various generally accepted causes. One of these human-induced causes is the increase in the use of fossil fuels due to the increasing population and the destruction of ecosystems leading to deforestation with land use change. Forest ecosystems are the places where carbon, the most important greenhouse gas shown as the cause of climate change, is stored. More than 80 per cent of the carbon stored in terrestrial ecosystems is sequestered by forest ecosystems (Jandl vd., 2007). It is known that all green plants store the carbon taken from the atmosphere through photosynthesis, and the most basic feature that distinguishes forest ecosystems from grassland and pasture ecosystems is that they are perennial. In this way, they have the ability to store the carbon they have bound in their bodies for many years. In the forest ecosystem, carbon is stored above and below ground in the stand, in dead wood, dead cover and soil.

The Good Practice Guidelines for Land Use Change and Forestry (GPG LULUCF) and the Agriculture, Forestry and Other Land Use Guidelines (AFOLU) emphasise that countries should calculate their emissions, carbon stocks and changes in carbon stocks using the most appropriate methods (IPCC, 2003; IPCC, 2006). By determining the exact and accurate amount of carbon stored in forest areas, it will be possible to report more accurately in national declarations prepared in accordance with international agreements to which we are a party. Since the carbon stored in forest areas is considered to be approximately half of the biyomass (IPCC, 2003), it is important to determine the biyomass of forest trees as a priority. In order to make the most accurate estimation, biomass studies are needed. Two generally accepted methods are used to determine the biomass, which is the basis for carbon calculation in the forest ecosystem; The first method is the Biomass Expansion Factors (BEF) or Biomass Conversion and Expansion Factors (BCEF) method (Blujdea vd., 2012, Aholoukpe, 2013, Dutca vd., 2010, Neumann vd., 2016, Mahmood vd.,2020, Kocaman ve Durkaya 2020). In this method, the above-ground biomass value is obtained by multiplying the tree volume by the BEF coefficient and the wood density value (for conifers; V x 0.446 x 1.21 and for broadleaves; V x 0.541 x 1.3) (OGM,2014). Due to the low sensitivity when using the method (Poorter et al., 2015; Neumann et al., 2016), it is recommended that the coefficients to be used by the countries be updated by paying attention to the growing environment conditions, site index and tree species, so that errors can be reduced (Jalkanen vd., 2005; Teobaldelli vd., 2009; Petersson vd., 2012).

The second method is the Allometric Biomass Equations (ABD) Method. This method is based on allometry (Gower et al., 1999; Niklas and Enquist, 2001;

Niklas, 2005), which is a relationship that aims to reach a more difficult biomass by using easily measurable values such as breast diameter, tree height, crown diameter, breast surface of a single tree. It is preferred due to its higher accuracy rate compared to BEF (Chave et al., 2014; Paul et al., 2016, Durkaya et al., 2014, Durkaya et al., 2017). In linear or non-linear mathematical equations, the diameter at breast height (d1,30) and tree height (h) are most commonly used (Wang, 2006; Porte vd., 2002, Durkaya vd., 2009, Durkaya vd.,2010,Durkaya vd., 2013). Among the important tree species in Turkey; for beech (Saraçoğlu, 1998), for oak (Durkaya, 1998; Özdemir et al., 2019), for red pine (Durkaya et al., 2009), for scotch pine (Durkaya et al., 2010a), for black pine (Durkaya et al., 2010b, Durkaya et al. 2019), for black pine plantations (Güner and Güner, 2021), for cedar (Durkaya et al., 2013) a), for cedar plantations (Karataş et al., 2017), for young scotch pine (Durkaya et al., 2016), for fir (Durkaya et al., 2013b), for Kazdağı fir (Güner, 2019), for chestnut (İkinci, 2000) allometric biomass equations have been developed. By diversifying these studies for different tree species and for different growing environment conditions of the same species, more accurate and reliable biomass calculations will be possible.

In Turkish forestry, the BEF coefficients recommended by the Intergovernmental Panel on Climate Change (IPCC) Guidelines on Land Use and Land Use Change and Forestry (GPG LULUCF) were first used to calculate biomass and carbon from biomass. However, since the IPCC report suggested that it would be more accurate for countries to use their own coefficients, the first BEF coefficients for Turkey were developed by Asan (1995). Afterwards, Tolunay and Çömez (2008) and Tolunay (2011, 2012) proposed to make calculations using the BEF coefficients developed by Tolunay (2011, 2012). In the Forest Management Plans used in the management of forest areas in Turkey, carbon calculations have been made using the BEF method since 2008. The ABD method (Chave et al., 2014; Paul et al., 2016, Durkaya et al., 2017, Gençay et.al.2018; Gençay and Durkaya, 2023) is recommended for determining the amount of carbon stock in the forest, especially in the stand, as the accuracy rate is calculated higher than the BEF. The starting point of the study is the thesis that the calculations made by the ABD method for tree species are closer to reality and more accurate. In the literature, there are various studies in which carbon comparisons are made with BEF and ABD method using the data in the management plans. Durkaya et al. (2014) determined that the calculations made with the BEF method gave a 17% lower value compared to the calculations made with the ABD method. In another study conducted for Bartın-Kurucaşile Forests, the amount of carbon calculated with the BEF method was calculated as 13% less than the ABD method (Durkaya et al., 2017). Kocaman and Durkaya (2020) determined the temporal (1986-1995 and 2009-2018 plan periods) carbon change in Bolu Aladağ/Demirciler. In the first plan period, while 103.20 tonnes/ha carbon value was determined by the ABD method in coniferous stands, it was determined as 92.18 tonnes/ha by the BEF method. In the second plan period, 127.63 tonnes/ha carbon was determined with the ABD method and 122.43 tonnes/ha carbon was determined with the BEF method. For the calculations made in these literatures, the data in the stand description tables were used. In the stand description tables, the number of trees in diameter classes and tree volume values are given for each tree species. However, it is not known exactly which tree in the stand has how many cm diameter at breast height. This may cause a statistical error in the calculations. The difference of this study from the studies in the literature is the use of actual diameter values instead of average diameter values. In order to realise the aim of this study, inventory data taken from the field for the preparation of forest management plans in Gördes Forest Enterprise, Izmir Regional Directorate of Forestry were used. The stand carbon was calculated by using the ABD method using the breast diameter data of the trees. For this purpose, single tree and stand biomass were calculated by using the breast diameters of the trees ($d_{1,30}$) and the biomass equation available for the relevant tree species. Then, carbon stock amounts of the stands were determined by performing carbon conversion.

In this study, data from inventory studies conducted in the field during the summer of 2021 in the Gördes Forest Enterprise Directorate of Manisa were utilized for the purpose of forest management planning (Figure 1). Tree species and breast diameter data from all sample plots within the enterprise were used in the study with permission obtained from the General Directorate of Forestry, Department of Forest Management and Planning. The study area includes black pine (Pinus nigra Arnold.), Turkish red pine (Pinus brutia Ten.), and oak species. Allometric Biomass Equations determined by Durkaya et al. (2015) for black pine (Pinus nigra Arnold.) and Turkish red pine (Pinus brutia Ten.), and by Durkaya (1998) for oak, were used in the study. Since there is no biomass equation for the pistachio pine species found in pure form and mixed with other species in the area, it is not included in the calculations.

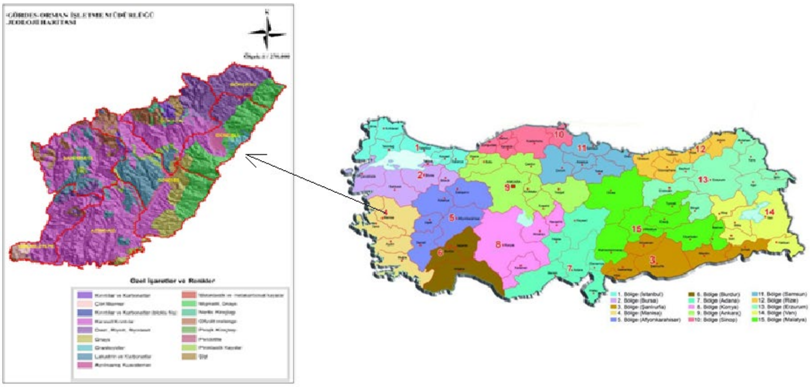

Figure 1. Study Area

Above-ground whole tree biomass was determined with the equations. After determining the above-ground whole tree biomass, the below-ground biomass was calculated by multiplying the above-ground biomass of the trees by the coefficients of 0.29 for conifers and 0.24 for broadleaves (IPCC, 2006). In the study, after determining the above-ground and below-ground biomass values, carbon calculation was started. It is reported in various sources that approximately 50% of biomass is carbon. However, in the LULUCEF guidelines, it is recommended to multiply the carbon conversion coefficient by 0.51 for coniferous trees and 0.48 for broadleaved trees in the North-Humid regions where Turkey is located (Laiho and Laine, 1997; Elias and Potvin 2003; Lamlom and Savidge, 2003; IPCC, 2006). Carbon conversions from biomass by tree species were calculated using the relevant coefficients. In this way, the biomass and carbon values of the stands in the forest areas of Manisa Gördes Management Directorate were determined. In addition, the amounts of carbon bound in different stand types and at different developmental ages were compared. Windows Excel program was used to evaluate the data.

Gördes is located in the Aegean Region, on 38° 55' north latitude, 28° 18' east longitude, in the province of Manisa and falls to the north-east of Manisa. It covers Gördes district and partially Demirci and Akhisar districts. It consists of 7 planning units, namely Azimlidağ, Gökçesu, Gökseki, Gördes, Gülmeztepe, Güneşli and Şahinkaya. The total area of the Management Directorate is 106,536.0 hectares, of which 52,600.9 hectares (49%) are open areas and 53935.1 hectares (51%) are forested areas.

Calculations were made on a plan unit basis and the biomass and carbon values of each plan unit are given below.

As can be seen in Figure 2, which was created as a result of the carbon calculations of the Azimlidağ plan unit, the stand that holds the most carbon per hectare is the Çzd$_3$ stand with 199.64 tons/ha and the stand that holds the least carbon is the Çzab$_3$ stand with 6.07 tons/ha. Although the carbon of Çfc$_2$ and Çfd$_1$ stands appear as 0 tons in the graph, these stands were not included in the calculations due to the lack of allometric biomass equation of pistachio pine and the carbon amount was not calculated. When the area of the stand in Azimlidağ plan unit is included in the calculation, it is seen that the highest carbon amount is Çzcd$_2$ stand with 106145.92 tons (Table 1).

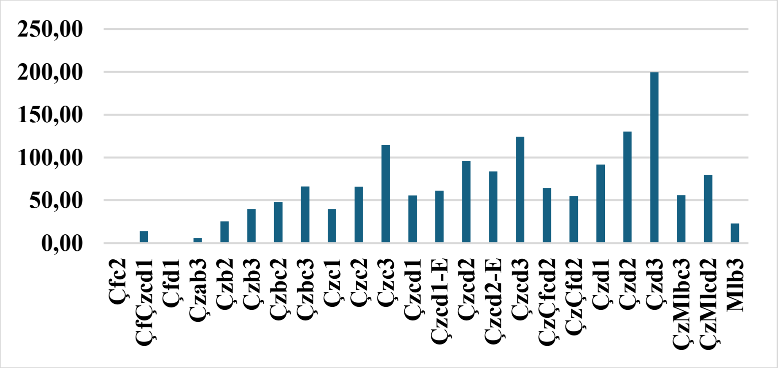

Figure 2. Stand Carbon calculation for Azimlidağ plan unit (tons/ha)

Table 1. Biomass and carbon calculations of the Azimlidağ plan unit

Stand type	**Stand Biomass (Tons)**	**Biomass (Ton/ha)**	**Carbon of the Stand (Ton)**	**Carbon (Ton/ha)**
Çfc$_2$	0,00	0,00	0,00	0,00
ÇfÇzcd$_1$	6395,02	27,38	3261,46	13,96
Çfd$_1$	0,00	0,00	0,00	0,00
Çzab$_3$	1155,62	11,90	589,37	6,07
Çzb$_2$	12766,67	49,93	6511,00	25,46
Çzb$_3$	3001,35	77,96	1530,69	39,76
Çzbc$_2$	16490,39	94,61	8410,10	48,25
Çzbc$_3$	21517,01	129,86	10973,67	66,23

Çzc$_1$	9233,24	78,05	4708,95	39,81
Çzc$_2$	68205,51	134,63	33417,33	65,96
Çzc$_3$	17234,09	224,40	8789,39	114,45
Çzcd$_1$	47359,47	109,10	24153,33	55,64
Çzcd$_1$-E	5166,59	120,15	2634,96	61,28
Çzcd$_2$	208129,25	188,27	**106145,92**	96,02
Çzcd$_2$-E	2349,02	164,27	1198,00	83,78
Çzcd$_3$	24778,61	243,88	12637,09	124,38
ÇzÇfcd$_2$	12864,50	126,12	6560,90	64,32
ÇzÇfd$_2$	5897,95	107,43	3007,95	54,79
Çzd$_1$	24629,85	180,17	12561,23	91,89
Çzd$_2$	107687,44	255,73	54920,59	130,42
Çzd$_3$	4534,24	384,26	2355,78	**199,64**
ÇzMlbc$_3$	1612,51	105,39	853,91	55,81
ÇzMlcd$_2$	2829,92	148,16	1520,04	79,58
Mlb$_3$	88,80	46,74	43,51	22,90
Total	**603927,06**	**3008,39**	**306785,18**	**1540,40**

As seen in Figure 3, the stand with the highest carbon per hectare in Gökçesu planning unit is Çkd$_3$ with 168.74 tons per hectare and the stand with the lowest carbon is Çkab$_3$ with 9.84 tons per hectare.

As can be seen in the total carbon column of the stand in the biomass and carbon table of Gökçesu planning unit, the stand with the highest amount of carbon in Gökçesu planning unit is Çkc$_3$ stand with 118475.38 tons (Table 2).

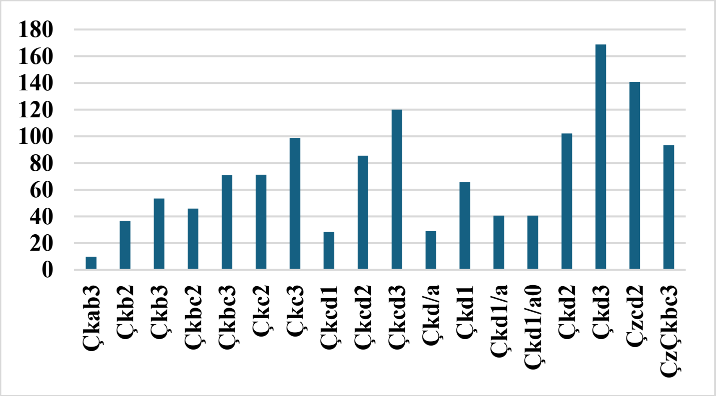

Figure 3. Stand carbon calculation for Gökçesu planning unit (tons/ha)

Table 2. Biomass and carbon calculations for Gökçesu planning unit

Stand type	Stand Biomass (Tons)	Biomass (Ton/ha)	Carbon of the Stand (Ton)	Carbon (Ton/ha)
Çkab$_3$	3411,62	19,30	1739,92	9,84
Çkb$_2$	7812,81	72,27	3984,53	36,86
Çkb$_3$	27122,60	104,76	13832,53	53,43
Çkbc$_2$	21643,08	90,10	11037,97	45,95
Çkbc$_3$	186036,91	139,09	94878,82	70,94
Çkc$_2$	63280,67	139,85	32273,14	71,32
Çkc$_3$	232304,66	193,85	**118475,38**	98,86
Çkcd$_1$	4881,95	55,79	2489,79	28,45
Çkcd$_2$	45719,09	167,71	23316,74	85,53
Çkcd$_3$	33373,50	235,19	17020,48	119,95
Çkd/a	4106,84	56,96	2094,49	29,05
Çkd$_1$	1444,34	128,96	736,62	65,77
Çkd$_1$/a	8514,97	79,65	4342,63	40,62
Çkd$_1$/a0	509,78	79,65	259,99	40,62
Çkd2	21311,71	200,30	10868,97	102,15
Çkd$_3$	30373,87	330,87	15490,67	168,74

Çzcd$_2$	7675,31	276,09	3914,41	140,81
ÇzÇkbc$_3$	16032,90	183,23	8176,78	93,45
Total	**715556,62**	**2553,64**	**364933,88**	**1302,36**

The stand with the highest carbon per hectare in Gülmeztepe planning unit was Çzd$_3$ with 191.3 tons/ha (Figure 4). The lowest carbon is in the Çfbc$_2$ stand, which is dominated by pistachio pine, followed by the Çzab$_3$ stand with 6.0 tons. Looking at the total carbon of the stand column in Table 3, it is seen that the stand with the highest carbon is Çzcd$_2$ stand with 61168.06 tons.

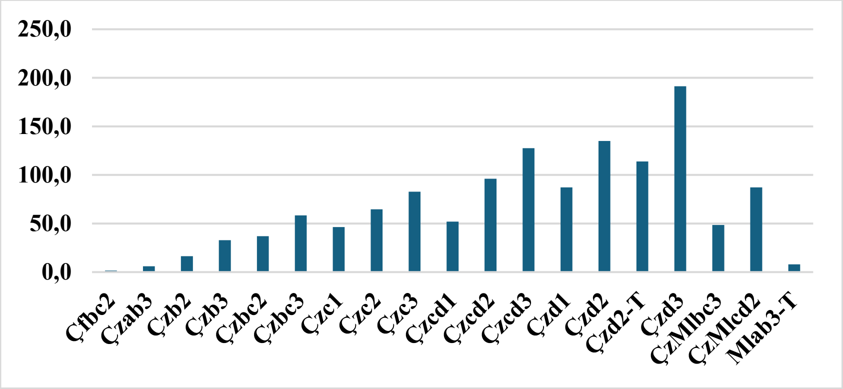

Figure 4. Stand carbon calculation for Gülmeztepe planning unit (tons/ha)

Table 3. Biomass and carbon calculations for Gülmeztepe planning unit

Stand type	**Stand Biomass (Tons)**	**Biomass (Ton/ha)**	**Carbon of the Stand (Ton)**	**Carbon (Ton/ha)**
Çfbc$_2$	127,89	3,17	65,22	1,62
Çzab$_3$	2335,48	11,80	1191,09	6,02
Çzb$_2$	2649,38	32,11	1351,19	16,38
Çzb$_3$	29976,74	64,42	15288,14	32,86
Çzbc$_2$	24960,26	72,62	12729,73	37,04
Çzbc$_3$	76611,13	114,64	39056,24	58,44
Çzc$_1$	7263,10	90,90	3704,18	46,36
Çzc$_2$	34846,59	126,90	17771,76	64,72
Çzc$_3$	25808,92	162,52	13138,06	82,73
Çzcd$_1$	36380,39	101,88	18554,00	51,96

Çzcd$_2$	119937,37	188,58	**61168,06**	96,18
Çzcd$_3$	72396,51	250,16	36922,22	127,58
Çzd$_1$	23655,21	171,04	12064,16	87,23
Çzd$_2$	119829,87	264,64	61113,23	134,97
Çzd$_2$-T	4891,26	223,35	2494,54	113,91
Çzd$_3$	26365,23	375,04	13446,27	191,27
ÇzMlbc$_3$	5655,16	96,01	2857,08	48,51
ÇzMlcd$_2$	9657,56	173,07	4867,47	87,23
Mlab$_3$-T	256,96	16,26	125,91	7,97
Total	**623605,01**	**2539,13**	**317908,55**	**1292,96**

The stand with the highest amount of carbon per hectare in Gökseki planning unit is Çzd$_3$ with 179.9 tons. The stand with the lowest carbon per hectare is the Mab$_3$-T stand with 4.0 tons (Figure 5). As can be seen when the total carbon column of the stand in Gökseki planning unit is analyzed, the stand with the highest carbon content is Çkc$_3$ stand with 63807.11 tons (Table 4).

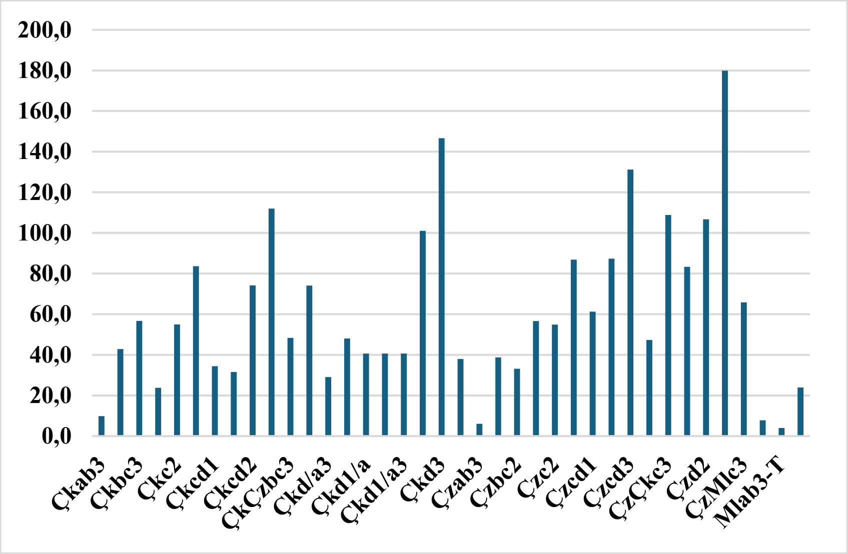

Figure 5. Stand carbon calculation for Gökseki planning unit (tons/ha)

Table 4. Biomass and carbon table for the Gökseki planning unit

Stand type	Stand Biomass (Tons)	Biomass (Ton/ha)	Carbon of the Stand (Ton)	Carbon (Ton/ha)
Çkab$_3$	623,3	19,3	317,9	9,8
Çkb$_3$	11059,6	84,0	5640,4	42,8
Çkbc$_3$	10421,1	111,2	5314,7	56,7
Çkc$_1$	1922,5	46,6	980,5	23,7
Çkc$_2$	19138,5	107,8	9760,6	55,0
Çkc$_3$	125112,0	164,0	**63807,1**	83,6
Çkcd$_1$	5985,9	67,5	3052,8	34,4
Çkcd$_1$/a	1311,8	61,9	669,0	31,6
Çkcd$_2$	81515,0	145,5	41572,6	74,2
Çkcd$_3$	116217,7	219,6	59271,0	112,0
ÇkÇzbc$_3$	1845,2	95,1	937,8	48,3
ÇkÇzc$_3$	15147,2	145,4	7725,1	74,1
Çkd/a$_3$	79,7	57,0	40,7	29,0
Çkd$_1$	4834,9	94,4	2460,6	48,1
Çkd1/a	6085,5	79,7	3103,6	40,6
Çkd$_1$/a$_0$	4452,6	79,7	2270,8	40,6
Çkd$_1$/a$_3$	1091,3	79,7	556,5	40,6
Çkd$_2$	43475,9	198,1	22172,7	101,0
Çkd$_3$	31490,3	287,6	16060,1	146,7
ÇkMlbc$_3$	1239,8	75,6	622,5	38,0
Çzab$_3$	1682,0	11,8	857,8	6,0
Çzb$_3$	5929,3	76,0	3024,0	38,8
Çzbc$_2$	6572,0	65,0	3351,7	33,2
Çzbc$_3$	8452,8	111,1	4310,9	56,6
Çzc$_2$	31239,5	107,7	15932,1	54,9
Çzc$_3$	18167,1	170,3	9265,2	86,8
Çzcd$_1$	9524,4	120,1	4857,5	61,3
Çzcd$_2$	53694,0	171,3	27383,9	87,3
Çzcd$_3$	10961,5	257,3	5590,4	131,2

ÇzÇkc$_2$	17922,4	92,8	9140,4	47,3
ÇzÇkc$_3$	11782,8	213,8	5998,4	108,9
ÇzÇkcd$_2$	19793,1	163,3	10094,5	83,3
Çzd$_2$	8723,5	209,2	4449,0	106,7
Çzd$_3$	5007,6	352,6	2553,9	179,9
ÇzMlc$_3$	3928,5	131,4	1967,5	65,8
Mlab$_3$	1000,2	16,3	480,1	7,8
Mlab$_3$-T	113,4	8,4	54,4	4,0
Mlb$_3$	569,1	49,9	273,2	24,0
Total	**698113**	**4547,626**	**355921,9**	**2314,778**

In Gördes planning unit, the stand with the highest carbon retention per hectare is Çkd$_3$ with 148.1 tons/ha. The lowest carbon holding stand is Çzab$_3$ with 5.26 tons/ha (Figure 6). Although the graph shows that stands dominated by pistachio pine have less carbon, the lack of a biomass equation for pistachio pine has reduced the carbon content of the stand and has been ignored.

When the total stand carbon column in Table 5 is examined, it can be seen that the stand with the highest amount of carbon is Çzcd$_2$ stand with 74097.742 tons.

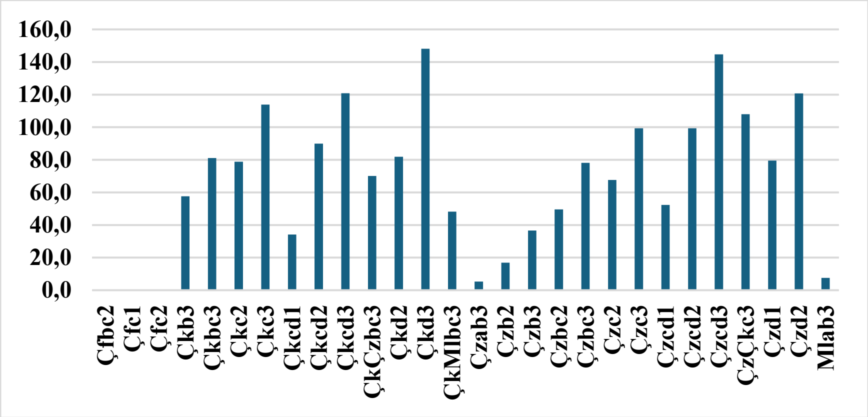

Figure 6. Stand carbon calculation of Gördes planning unit (tons/ha)

Table 5: Biomass and carbon table for Gördes planning unit

Stand type	**Stand Biomass (Tons)**	**Biomass (Ton/ha)**	**Carbon of the Stand (Ton)**	**Carbon (Ton/ha)**
Çfbc$_2$	130,6	0,853	64,0	0,418
Çfc$_1$	0,0	0,000	0,0	0,000
Çfc$_2$	0,0	0,000	0,0	0,000
Çkb$_3$	1209,6	113,045	616,9	57,653
Çkbc$_3$	906,3	159,007	462,2	81,094
Çkc$_2$	40374,7	154,574	20591,1	78,833
Çkc$_3$	35578,5	223,343	18145,1	113,905
Çkcd$_1$	140,9	67,075	71,8	34,208
Çkcd$_2$	20009,2	176,292	10204,7	89,909
Çkcd$_3$	12988,6	237,019	6624,2	120,880
ÇkÇzbc$_3$	5145,5	137,581	2622,7	70,125
Çkd$_2$	1622,8	160,677	826,7	81,851
Çkd$_3$	667,9	290,395	340,6	148,102
ÇkMlbc$_3$	4229,4	95,471	2136,1	48,220
Çzab$_3$	12,4	10,323	6,3	5,265
Çzb$_2$	4512,0	33,079	2301,1	16,870
Çzb$_3$	23962,2	71,829	12220,7	36,633
Çzbc$_2$	37563,3	97,213	19157,3	49,579
Çzbc$_3$	32916,9	153,244	16787,6	78,155
Çzc$_2$	34342,6	132,699	17514,7	67,677
Çzc$_3$	33721,1	194,807	17197,8	99,352
Çzcd$_1$	3685,0	102,647	1879,4	52,350
Çzcd$_2$	145289,7	194,811	**74097,7**	99,353
Çzcd$_3$	42247,1	283,728	21546,0	144,701
ÇzÇkc$_3$	20085,9	211,653	10243,8	107,943
Çzd$_1$	4646,5	155,921	2369,7	79,520
Çzd$_2$	35181,0	236,750	17942,3	120,742
Mlab$_3$	1468,6	19,846	561,4	7,586
Total	**444288,5**	**3713,884**	**276532,0**	**1890,922**

When the stand carbon per hectare graph of Şahinkaya planning unit is examined, it is seen that the stand with the highest carbon sequestration per hectare is Çzd$_3$ stand with 152.6 tons/ha. The lowest carbon sequestration was in the Çzab$_3$ stand with 2.6 tons/ha (Figure 7).

When the total carbon of the stand column in Table 6 is examined, it can be seen that the stand with the highest amount of carbon sequestration is Çzcd$_2$ stand with 88374.3 tons.

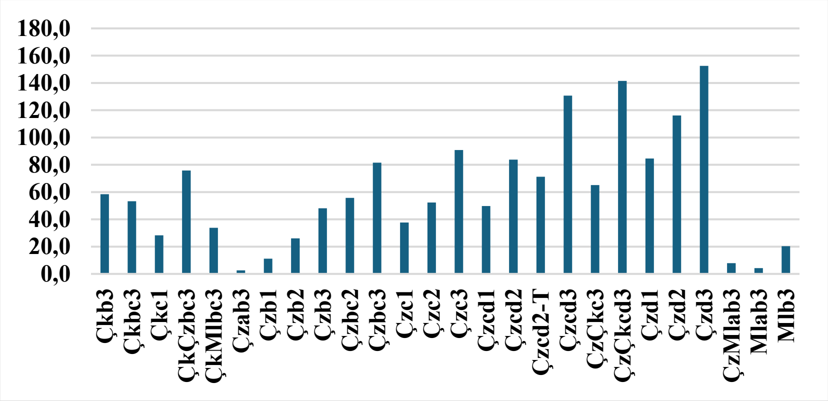

Figure 7. Stand carbon calculation for Şahinkaya planning unit (tons/ha)

Table 6. Biomass and carbon table for Şahinkaya planning unit

Stand type	**Stand Biomass (Tons)**	**Biomass (Ton/ha)**	**Carbon of the Stand (Ton)**	**Carbon (Ton/ha)**
Çkb$_3$	538,2	114,5	274,5	58,4
Çkbc$_3$	3649,9	104,6	1859,4	53,3
Çkc$_1$	6757,4	55,6	3446,3	28,3
ÇkÇzbc$_3$	3584,0	148,7	1827,0	75,8
ÇkMlbc$_3$	2163,3	67,2	1089,8	33,8
Çzab$_3$	838,7	5,2	427,8	2,6
Çzb$_1$	347,1	21,8	177,0	11,1
Çzb$_2$	5530,1	51,0	2820,3	26,0
Çzb$_3$	48828,2	94,2	24902,4	48,1
Çzbc$_2$	49618,7	109,3	25305,5	55,7
Çzbc$_3$	80422,4	160,0	41015,4	81,6
Çzc$_1$	6803,4	73,9	3469,7	37,7

Çzc$_2$	61852,6	102,6	31544,8	52,3
Çzc$_3$	45798,0	178,1	23357,0	90,8
Çzcd$_1$	27712,2	97,6	14133,2	49,8
Çzcd$_2$	173282,9	164,3	88374,3	83,8
Çzcd$_2$-T	1453,1	139,7	741,1	71,3
Çzcd$_3$	41283,4	256,3	21054,5	130,7
ÇzÇkc$_3$	7028,3	127,8	3584,4	65,2
ÇzÇkcd$_3$	23297,9	277,4	11881,9	141,5
Çzd$_1$	15582,7	165,9	7947,2	84,6
Çzd$_2$	53686,5	227,7	27380,1	116,1
Çzd$_3$	867,5	299,2	442,4	**152,6**
ÇzMlab$_3$	607,9	15,6	309,0	7,9
Mlab$_3$	486,8	8,6	238,5	4,2
Mlb$_3$	562,8	41,4	275,8	20,3
Total	**662583,8**	**3108,1**	**337879,5**	**1583,6**

The highest carbon sequestration per hectare in the Güneşli planning unit was the ÇzÇkcd$_3$ stand with 121.2 tons/ha. The lowest carbon sequestration stand is Mab$_3$ with 1.4 tons/ha after the stands dominated by pistachio pine (Figure 8).

Looking at the total stand graph in Table 7, it can be seen that the stand with the highest carbon sequestration is Çzc$_2$ with 26892.4 tons.

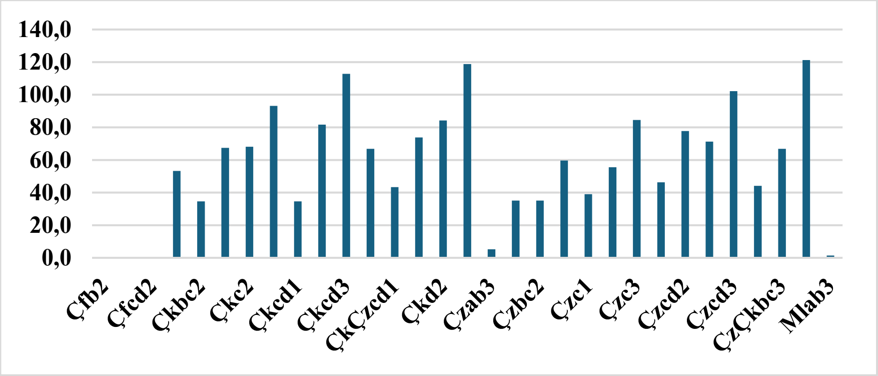

Figure 8. Stand carbon accounting for the Güneşli planning unit (tons/ha)

Table 7: Biomass and carbon table for the Güneşli planning unit

Stand type	**Stand Biomass (Tons)**	**Biomass (Ton/ha)**	**Carbon of the Stand (Ton)**	**Carbon (Ton/ha)**
Çfb$_2$	0,0	0,0	0,0	0,0
Çfc$_2$	0,0	0,0	0,0	0,0
Çfcd$_2$	0,0	0,0	0,0	0,0
Çkb$_3$	16309,2	104,5	8317,7	53,3
Çkbc$_2$	2390,7	67,9	1219,2	34,6
Çkbc$_3$	22609,4	132,1	11530,8	67,4
Çkc$_2$	3434,4	133,6	1751,6	68,2
Çkc$_3$	25965,1	182,7	13242,2	93,2
Çkcd$_1$	3294,1	67,9	1680,0	34,6
Çkcd$_2$	14275,5	160,2	7280,5	81,7
Çkcd$_3$	19193,0	221,1	9788,4	112,8
ÇkÇzc$_3$	9061,8	131,1	4621,5	66,9
ÇkÇzcd$_1$	1650,7	85,1	841,9	43,4
ÇkÇzcd$_2$	12063,4	144,6	6152,3	73,8
Çkd$_2$	5366,8	165,1	2737,1	84,2
Çkd$_3$	2375,9	232,9	1211,7	118,8
Çzab$_3$	1310,0	10,3	668,1	5,3
Çzb$_3$	4055,8	68,9	2068,4	35,1
Çzbc$_2$	1176,2	68,8	599,9	35,1
Çzbc$_3$	4325,5	116,9	2206,0	59,6
Çzc$_1$	5528,7	76,5	2819,6	39,0
Çzc$_2$	52730,2	108,9	**26892,4**	55,5
Çzc$_3$	18556,6	165,7	9463,8	84,5
Çzcd$_1$	8604,4	90,9	4388,3	46,3
Çzcd$_2$	24646,0	152,5	12569,4	77,8
Çzcd$_2$-T	8033,8	139,7	4097,2	71,3
Çzcd$_3$	7211,8	200,3	3678,0	102,2
ÇzÇfbc$_3$	6088,3	86,6	3105,0	44,2
ÇzÇkbc$_3$	6223,1	131,0	3173,8	66,8
ÇzÇkcd$_3$	3470,9	237,7	1770,2	**121,2**
Mlab$_3$	573,7	2,8	281,1	**1,4**
Total	**290524,8**	**3486,6**	**148156,2**	**1778,1**

The conclusions drawn from the research and evaluation results are presented in the following section.

Accurately determining the amount of carbon stored by forest ecosystems requires precise calculations of biomass quantities. Allometric biomass equations (ABD), developed specifically for each species and growing environment, improve the consistency of these calculations (Paul et al., 2013). However, the widely accepted method is based on using inventory data to estimate biomass by specific coefficients over stem volume. The BEF coefficients developed by Tolunay (2012) for Turkey's forests are applied within the scope of Ecosystem-Based Functional Forest Management Plans (ETFOP) and used to calculate carbon amounts, and these results are used as the basis for international carbon reporting (Durkaya et al., 2017). However, the ABD method (Chave et al., 2014; Paul et al., 2016, Durkaya et al., 2017) is recommended for determining the amount of carbon stock in the forest, especially in the stand, as the accuracy rate is calculated higher compared to BEF. The thesis that the calculations made with the US method for tree species are closer to reality and more accurate is the starting point of the study. In this study, it was aimed to determine the amount of carbon stocks in forested areas within the borders of Gördes Forest Management Directorate of Izmir Regional Directorate of Forestry. In this direction, detailed inventory data collected from the field during the preparation of forest management plans were analyzed. In this study, stand carbon was calculated using the ABD method. Based on the diameter at breast height measurements ($d_{1,30}$) of the trees included in the inventory data, biomass calculations were made first at the single tree level and then at the stand level with the help of species-specific biomass equations available in the literature for each tree species. The obtained biomass values were converted into carbon stock amounts by using appropriate carbon conversion coefficients. Thus, the carbon storage capacities of the stands in the research area were revealed in detail. The calculations obtained from the study were compared with the stand carbon calculations calculated in the Gördes Forest Management Directorate's Management Plans for the period 2022-2041 (Anon, 2022) (Figure 9).

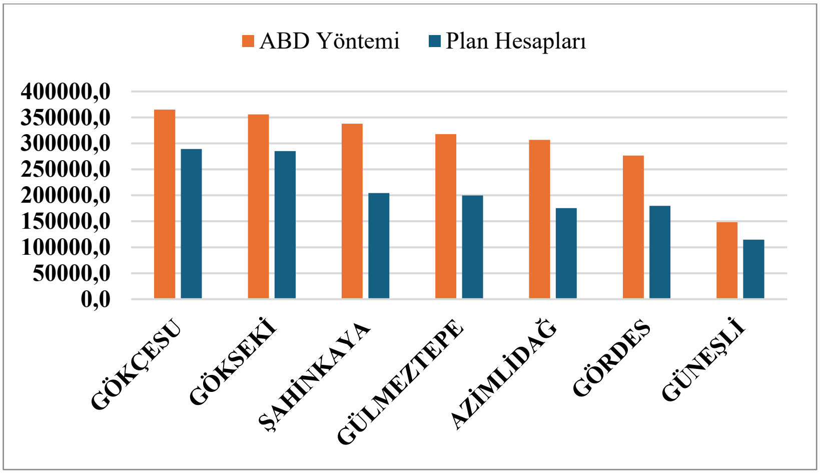

Figure 9. Gördes Forest Management Directorate Stand Carbon US method and calculations in the management plan (tons)

As can be seen in Figure 9, the stand carbon values calculated by the ABD method are higher than the stand carbon values calculated in the Management Plan. It is seen that between 20.8% and 42.8% of the stand carbon calculations were underestimated on the basis of the management directorates.

	ABD Method	Management Plan Accounts	Difference(%)
GÖKÇESU	364933,9	289159	-20,8
GÖKSEKİ	355921,9	285128	-19,9
ŞAHİNKAYA	337879,5	204331	-39,5
GÜLMEZTEPE	317908,6	199695	-37,2
AZİMLİDAĞ	306785,2	175509	-42,8
GÖRDES	276532	179757	-35,0
GÜNEŞLİ	148156,2	114545	-22,7

Table 8. Comparison of ABD method and Management Plan data

Table 8 shows the differences between the carbon stock amounts calculated by the ABD method in the chiefdoms affiliated to Gördes Forest Management Directorate and the carbon calculations in the management plans for the period 2022-2041 belonging to the management directorate. While the ABD method gives higher values for each chiefdom, the largest difference is 42.8% in Azimlidağ planning unit. The lowest difference was observed in Gökseki planning unit with 19.9%. These results show that carbon stocks are underestimated in current management plans. This difference emphasizes that the accuracy of the methods used in carbon storage calculations is critical for the effectiveness of carbon management and policies. It has been similarly demonstrated in many studies that the ABD method provides more accurate estimates (Schroerder et al. 1997, Nogueira et al. 2008). The obtained results align with the findings reported by Schroeder et al. (1997) and Nogueira et al. (2008). Schroeder and colleagues' work on improving the accuracy of biomass calculations in the United States highlights that this method yields similar results in both tropical and temperate regions (Schroeder et al., 1997). Similarly, Nogueira et al. (2008) emphasized that species-specific biomass equations in the Amazon rainforest provide more realistic carbon estimates compared to more generalized formulas.

Accordingly, the biomass calculation methods used in the preparation of management plans need to be updated. Our study shows that the lower carbon stock quantities predicted by current management plans may lead to deficiencies in carbon management and international reporting processes. The adoption of methods that provide higher accuracy is essential for accurately assessing the carbon storage capacity of forests and supporting sustainable forestry practices

In conclusion, the species-specific ABD method has proven to be a more effective tool in carbon management, and in this context, it is suggested that its use should be expanded in forest inventory studies in Turkey. Such methodological improvements will contribute to providing more reliable data for carbon cycle and climate change policies at national and international level.

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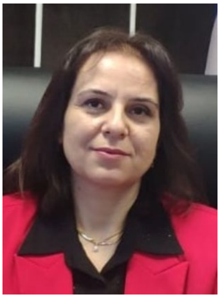

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Chapter 6

Enhancing Climate Resilience in Forestry through Artificial Neural Networks in Diameter Distribution Modeling

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Forests are increasingly subjected to profound climatic pressures, manifesting as altered growth patterns, shifts in species distributions, and reduced carbon sequestration. Addressing these impacts necessitates robust and adaptable modeling frameworks. Diameter distribution models have long served as indispensable tools for understanding forest dynamics, yet their potential is significantly expanded when integrated with Artificial Neural Networks (ANNs). These advanced methodologies provide a means to incorporate complex climatic variables—such as precipitation patterns, temperature variations, and carbon flux—into predictive modeling, enabling more precise assessments of forest resilience.

Recent research underscores the synergies between traditional probabilistic models and machine learning techniques. For instance, Liu et al. (2014) demonstrated the utility of finite mixture models (FMM) in complex forest ecosystems, while Guo et al. (2022) showed the advantages of incorporating climate-sensitive parameters into ANN frameworks. Furthermore, advances in neural network architectures have facilitated the integration of remote sensing data, expanding the potential for dynamic and adaptive forestry management. This chapter examines the transformative role of ANNs in fostering climate-resilient forestry practices, focusing on their application to diameter distribution modeling and their broader implications for sustainable forest management. Additionally, the role of forest management in global climate mitigation and biodiversity preservation further emphasizes the critical importance of adapting analytical tools to address these multifaceted challenges effectively.

Diameter distribution models have evolved significantly to address contemporary challenges in forestry, such as the need to manage mixed-species forests, adapt to climate change impacts, and optimize resource allocation in increasingly heterogeneous landscapes. These challenges demand models capable of capturing complex stand dynamics, providing accurate predictions for sustainable forest management. Studies such as those by Gorgoso-Varela et al. (2014) and Hafley et al. (1977) have highlighted the versatility of probabilistic functions, including the Weibull and Johnson's SB distributions, in modeling tree diameters across various forest stand conditions. Recent advances integrate these traditional approaches with emerging techniques, enabling a deeper understanding of forest dynamics. For instance, Liu et al. (2014) demonstrated the applicability of finite mixture models (FMM) for mixed-species stands, providing robust solutions for complex diameter distributions. Similarly, Pogoda et al. (2019) emphasized the effectiveness of percentile-based methods in enhancing the flexibility and precision of diameter modeling approaches, particularly in challenging stand conditions.

Beyond their applications in resource management, diameter distribution models contribute significantly to biodiversity conservation and ecological research. Accurate modeling enhances the ability of forest managers to schedule harvests optimally, develop sustainable strategies, and predict the ecological impacts of environmental changes. Moreover, these models are instrumental in supporting policy-making processes, as they provide robust scientific evidence for resource allocation and forest health monitoring. Recent studies have also highlighted their role in assessing forest ecosystem services and supporting global climate change mitigation efforts by accurately quantifying carbon stocks. Rio et al. (2015) emphasized the importance of integrating mixed-species stand dynamics to improve biodiversity assessments and ecosystem service evaluations.

Challenges with Traditional Methods

Traditional models, such as the Weibull and Johnson SB distributions, provide foundational tools for diameter distribution modeling. However, their efficacy diminishes when applied to ecosystems experiencing rapid climatic changes. As Hafley et al. (1977) observed, maximum likelihood estimation, often central to these models, struggles to accommodate heterogeneous stand conditions—a challenge exacerbated by climate-induced variability.

The consequences of climate change, including heightened susceptibility to pests, disease outbreaks, and disrupted growth cycles, call for innovative methodologies. Conventional models frequently fall short in integrating these dynamic influences, necessitating approaches that reflect the non-linear and multifaceted nature of modern forestry challenges. Suratman (2012) highlighted the necessity of advanced tools to address structural variability in tropical forests, further illustrating the limitations of static models under climatic duress.

Moreover, the increasing complexity of forest ecosystems under changing climatic conditions demands models capable of accounting for spatial and temporal heterogeneity. This requires moving beyond static assumptions, incorporating variables such as interspecies competition, adaptive growth patterns, and carbon flux dynamics, which are often overlooked in traditional frameworks. Recent studies, such as those by Schmidt et al. (2020), emphasize the need for continuous innovation in forestry analytics to address these challenges comprehensively. The dynamic interactions among forest components, amplified by external stressors like droughts and storms, underscore the inadequacies of traditional approaches that rely on static parameters and linear assumptions.

As climate conditions evolve, forests also experience cascading effects on ecosystem services. Carbon sequestration rates may decline, while altered species compositions can lead to reduced resilience against environmental stressors. Traditional diameter distribution models often fail to capture these broader implications, limiting their utility in comprehensive forest management strategies. Advanced methodologies must integrate long-term climatic trends, predictive variables, and adaptive capacities to address these issues holistically.

Traditional diameter distribution models, while foundational, have inherent limitations. For example, Hafley et al. (1977) noted the inadequacies of maximum likelihood estimation in heterogeneous stands, leading to suboptimal results. Fu et al. (2022) demonstrated how integrating probabilistic models with non-parametric methods, such as *k*-nearest neighbor (kNN) imputation, can enhance predictive capabilities, particularly in large-scale forest regions like Northeast China. Moreover, Podlaski (2006) analyzed different statistical distributions to highlight variability in fitting outcomes across developmental stages, suggesting the need for tailored approaches for optimal modeling.

The increasing global challenges of deforestation and climate change demand more robust and adaptable methodologies. For example, deforestation rates in tropical regions have accelerated due to agricultural expansion and logging, resulting in significant loss of biodiversity and carbon sequestration capacity. Similarly, climate change has led to shifts in species distributions and increased forest susceptibility to pests and diseases, underscoring the need for models that can adapt to rapidly changing conditions. Traditional statistical models, while valuable, often fail to address the dynamic, non-linear relationships characteristic of modern forest ecosystems. Additionally, their application is constrained by the need for extensive fieldwork, which can be both time-intensive and costly. Moreover, the lack of flexibility in these methods limits their applicability in highly heterogeneous forests, such as mixed-species or uneven-aged stands, where diameter distributions deviate significantly from standard assumptions. Addressing these limitations requires the incorporation of more dynamic and versatile methodologies that can account for varying stand conditions and external influences. Insights from Suratman (2012) highlight how structural variations in diverse tropical forests necessitate advanced modeling frameworks.

The Rise of Artificial Neural Networks (ANNs)

Artificial Neural Networks (ANNs) have emerged as groundbreaking tools in data-driven modeling, offering significant advancements over traditional statistical approaches. ANNs excel in their ability to model intricate, non-linear relationships within multidimensional datasets, making them particularly suited for forestry applications where complexity abounds. For example, ANNs are adept at handling datasets involving mixed-species stands with varying growth rates, integrating climatic variables such as precipitation and temperature, and processing remote sensing data like LiDAR to capture spatial heterogeneity within forest ecosystems. Their adaptability to diverse datasets and conditions has made them indispensable in advancing forestry analytics.

A fundamental building block of ANNs is the artificial neuron. The artificial neuron operates by summing all inputs (cumulative inputs). If the summed input values reach a specified threshold, the activation function generates an output signal. This signal, depending on the ANN architecture, moves either to a raw output or subsequent neurons. This basic unit is replicated and interconnected to form complex networks capable of modeling non-linear relationships within forestry datasets.

Figure 1 illustrates the fundamental building block of an Artificial Neural Network (ANN) -the artificial neuron. It demonstrates how input values are summed, processed through a transfer function, and transformed by an activation function to produce an output. The diagram highlights key components such as input weights, bias, and the activation process, showcasing the functionality of neurons in predicting forestry variables like diameter distributions.

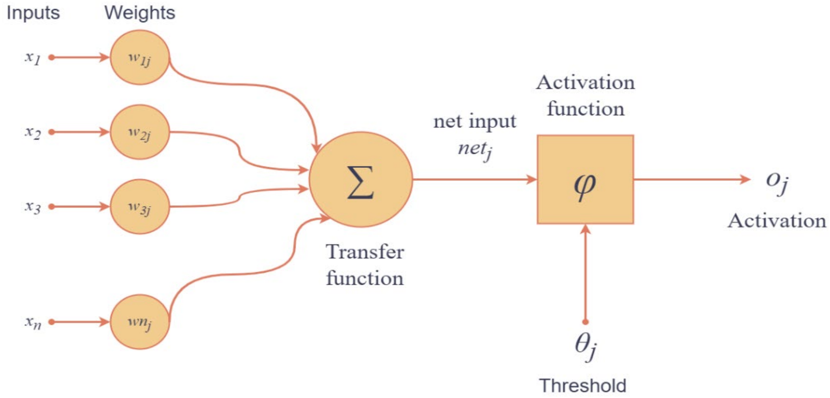

Figure 1. Basic structure of an artificial neuron, illustrating the input summation, transfer function, and activation function.

For example, in forestry applications, such a neuron can be used to predict tree diameter distributions by integrating variables like stand density and soil characteristics, showcasing the predictive power of Artificial Neural Networks.

Guo et al. (2022) introduced climate-sensitive ANN models to predict diameter distributions, incorporating variables such as precipitation and temperature to enhance accuracy under changing climatic conditions. Additionally, Ramos et al. (2014) illustrated the application of ANN methods in optimizing thinning strategies to maximize yield and diameter growth, showcasing their practical implications in forest management.

Recent research highlights that ANN models achieve higher predictive accuracy by incorporating auxiliary variables such as stand density, topographic indices, and species composition into the modeling process. The structure of feed-forward neural networks, where data flows unidirectionally from input to output layers, has proven particularly effective for forestry applications. These networks utilize backpropagation algorithms to adjust weights and minimize errors during training, ensuring that predictions align closely with observed outcomes.

Furthermore, the choice of activation functions, such as ReLU, sigmoid, or tanh, plays a critical role in determining the network's ability to model non-linear relationships within forestry datasets. These activation functions influence how well the network processes and transforms input data into meaningful predictions. Figure 2 provides visual representations of common activation functions used in ANN models, including ReLU (Rectified Linear Unit), Sigmoid, and Tanh. These functions play a pivotal role in capturing non-linear relationships within forestry datasets, influencing the model’s predictive accuracy and computational efficiency.

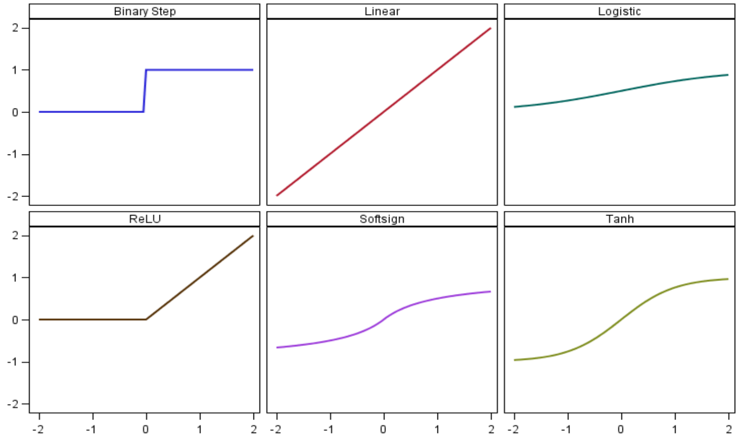

Figure 2: Common activation functions used in ANNs, including ReLU, sigmoid, and tanh.

For example, Ercanlı and Bolat (2017) demonstrated that feed-forward backpropagation networks outperformed conventional Weibull methods in predicting tree frequencies across diameter classes. Huang et al. (2010) validated the robustness of ANN frameworks in Masson pine stands, achieving up to 98% accuracy in cumulative frequency predictions.

Recent work by Vastaranta et al. (2014) has expanded the role of ANNs by integrating remote sensing data, such as TerraSAR-X stereo imagery, to enhance predictions of forest stand attributes. These applications underscore the adaptability of ANNs in combining traditional forestry data with cutting-edge remote sensing technologies.

Key advantages of ANNs include their capacity for continuous improvement through dynamic learning and their ability to integrate real-time environmental data, such as temperature, precipitation, and pest outbreak records. For instance, ANNs can use live satellite imagery and ground sensors to update predictions for tree growth and forest health, thereby offering unparalleled scalability and adaptability in forestry management. Emerging architectures, such as generative adversarial networks (GANs), provide novel approaches to simulate and predict forest structural changes, further expanding the frontiers of forest modeling. These features position ANNs as transformative tools in forestry analytics, with the potential to address both theoretical and operational challenges. Şenyurt et al. (2020) further demonstrated that ANN models could accurately predict relationships between diameter at breast height and stump diameter in Crimean pine stands, showcasing their utility in highly specific forestry applications. Ou et al. (2023) further underscored the utility of ANNs in predicting height-diameter relationships for Durango pine, utilizing resilient backpropagation techniques to outperform traditional nonlinear mixed effects models.

This chapter bridges the gap between traditional and ANN-based approaches by reviewing the theoretical foundations of conventional diameter distribution models, introducing ANN methodologies tailored to forestry applications, presenting comparative analyses and case studies that demonstrate the practical efficacy of ANNs, exploring hybrid models that integrate statistical and ANN-based techniques, and proposing future research directions focusing on scalability, interpretability, and technological integration. By pursuing these objectives, this chapter aims to highlight the transformative potential of ANN methodologies in advancing sustainable forestry management while providing actionable insights for forestry professionals seeking to adopt cutting-edge analytical tools.

Traditional Diameter Distribution Models

Statistical diameter distribution models, notably the Weibull and Johnson S_B functions, have been extensively utilized due to their computational efficiency and flexibility (e.g., Bailey & Dell, 1973; Bullock & Burkhart, 2005; Cao, 2004; Özçelik et al., 2022; Özçelik et al., 2023). The Weibull distribution, in particular, remains a staple for even-aged stands, while the Johnson S_B excels in modeling skewed distributions. Traditional parameterization methods—including maximum likelihood estimation (MLE) and the method of moments—provide reliable outputs for homogeneous stands but falter in heterogeneous conditions (Eker and Özçelik., 2017). Moreover, their univariate focus often limits their applicability in multivariate contexts. Advances in computational techniques have improved their precision, but these methods still require significant manual intervention and domain expertise. Recent developments, such as the incorporation of percentile-based estimation and Bayesian frameworks, have provided incremental improvements but continue to fall short in addressing the full complexity of modern forestry scenarios.

ANN Approaches in Forestry

Artificial Neural Networks revolutionize the field by addressing the limitations of traditional methods. Inspired by biological networks, ANNs excel in modeling complex, non-linear interactions. Key forestry applications include:

- Predicting growth trajectories and yield.
- Estimating biomass using remote sensing data.
- Modeling diameter distributions with high accuracy.

Prominent ANN architectures, such as feed-forward and recurrent networks, demonstrate varying success levels depending on data complexity. Studies indicate substantial improvements in predictive accuracy when applying ANN models to heterogeneous and mixed-species stands (e.g., Diamantopoulou et al., 2015; Duan et al., 2013). Moreover, ANNs have proven effective in incorporating ancillary data, such as climatic variables, soil characteristics, and topographical information, to enhance model robustness. Recent advancements in training algorithms, such as adaptive gradient descent and batch normalization, have further optimized ANN performance, enabling them to handle large and complex datasets with higher efficiency.

Ercanlı and Bolat (2017) demonstrated that ANN models could capture variability in stand conditions more effectively than traditional approaches, offering insights into forest dynamics that were previously unattainable. Furthermore, ANN models have shown exceptional performance in addressing challenges such as missing data and outlier detection, enhancing their utility in forestry analytics. These innovations underscore the growing role of ANNs as a cornerstone in modern forest modeling. Tang et al. (2016) highlighted the application of tree-ring analysis in combination with ANNs to model aboveground biomass dynamics, integrating historical growth data for improved predictions. Ou et al. (2023) demonstrated the application of resilient backpropagation ANNs in modeling height-diameter relationships for Durango pine species, achieving superior performance metrics compared to conventional approaches.

Hybrid Approaches

Hybrid models effectively bridge the gap between the statistical robustness of traditional methods and the adaptability of Artificial Neural Networks (ANNs). These approaches leverage the strengths of both methodologies to overcome limitations encountered when applied independently. For example, Gorgoso-Varela et al. (2021) demonstrated the efficacy of integrating LiDAR-derived forest metrics with parameter recovery approaches optimized by ANNs, which improved predictions in *Pinus halepensis* plantations. Similarly, Fu et al. (2022) highlighted the role of kNN-imputed data in refining Weibull distribution parameters, an approach further enhanced by ANN architectures that accommodated the complex relationships between tree dimensions and site-specific variables.

The hybridization of ANNs with statistical models is particularly beneficial in addressing the interpretability challenges associated with neural networks. Ou et al. (2023) emphasized this synergy in modeling height-diameter relationships for Durango pine, combining resilient backpropagation networks with traditional regression techniques to achieve both accuracy and explanatory power. Additionally, the incorporation of probabilistic frameworks, such as Bayesian parameter estimation, into ANN-based modeling has further extended their applicability.

In mixed-species forests, hybrid approaches enable the incorporation of species-specific growth dynamics, which are challenging to model with purely statistical methods. Pretzsch et al. (2014) illustrated the dynamic interplay between species interactions and size structure in mixed stands, a complexity better captured through ANN-driven hybrid models. These models accounted for nonlinear interactions, including those arising from competition and resource allocation, and provided practical insights into management strategies.

Further advancements in hybrid methodologies include the integration of remote sensing technologies, such as TerraSAR-X and LiDAR, with ANNs to enhance predictions of forest attributes. For instance, Vastaranta et al. (2014) successfully utilized TerraSAR-X imagery combined with ANN models to estimate forest biomass and canopy cover in boreal forests, demonstrating the potential of these technologies to deliver precise and scalable results. For instance, Picard et al. (2016) demonstrated how combining Liocourt's law with ANN-based hybrid approaches improved the modeling of tree diameter distributions across varying management regimes, highlighting their adaptability and precision in practical forestry applications. Picard et al. (2016) demonstrated how hybrid approaches informed by Liocourt's law effectively modeled tree diameter distributions across various management regimes. These techniques, when combined with ANNs, not only improved predictive accuracy but also offered new avenues for analyzing forest dynamics under different silvicultural interventions.

Advancing Forestry Management with Hybrid Approaches

The practical implications of hybrid models extend to forest management, where accurate diameter distribution predictions are critical for inventory planning, harvesting schedules, and ecosystem conservation. For instance, Mina et al. (2017) illustrated how hybrid models incorporating harvesting scenarios improved projections of forest dynamics in Slovenia's mountainous regions. This example highlights how these models balance ecological sustainability with productivity, providing actionable insights for forest management practices. For example, Mina et al. (2017) highlighted how incorporating harvesting scenarios into hybrid models improved projections of forest dynamics in mountainous regions of Slovenia. This approach provided actionable insights for balancing productivity with ecological sustainability.

By blending the explanatory capabilities of traditional statistical methods with the predictive power of ANNs, hybrid models represent a paradigm shift in forestry analytics. This shift mirrors past advancements such as the integration of remote sensing technologies in the 1990s and the adoption of probabilistic models in the early 2000s, which revolutionized data collection and modeling precision. Hybrid models now build on these foundations by offering scalability and flexibility, addressing modern challenges like climate variability and ecosystem heterogeneity. These methodologies offer scalable and adaptable solutions for managing forests in the face of climate change and increasing anthropogenic pressures. Future research should focus on refining these models by integrating additional data streams, such as climatic indices, soil health metrics, and biodiversity indicators, to further enhance their utility in comprehensive forest management strategies.

The conclusions drawn from the research and evaluation results are presented in the following section.

Comparative analyses reveal the diverse capabilities of diameter distribution modeling techniques. Gorgoso et al. (2012) demonstrated the effectiveness of Johnson's SB and Beta functions in specific contexts, while Fu et al. (2022) emphasized the scalability and adaptability of hybrid models in complex forest ecosystems. Similarly, Kangas and Maltamo (2000) showcased the advantages of calibration techniques in improving Weibull model accuracy, highlighting opportunities for integration with ANN methodologies. Schmidt et al. (2020) further validated the utility of parameter recovery methods for truncated Weibull distributions, aligning them with modern predictive frameworks. Together, these studies underscore the complementary strengths of traditional and ANN-driven approaches, fostering innovative solutions for advancing forestry analytics. While Gorgoso et al. (2012) identified superior fits of Johnson's SB and Beta functions in certain contexts, Fu et al. (2022) emphasized the scalability of hybrid models in complex environments. Additionally, Kangas and Maltamo (2000) compared Weibull and percentile-based methods, revealing the strengths of calibration techniques in improving model accuracy, which could complement ANN approaches. Schmidt et al. (2020) demonstrated the utility of parameter recovery methods for truncated Weibull distributions, emphasizing their compatibility with modern predictive frameworks. Comparative analyses underscore the evolving nature of diameter distribution modeling. While Gorgoso et al. (2012) identified superior fits of Johnson's SB and Beta functions in certain contexts, Fu et al. (2022) emphasized the scalability of hybrid models in complex environments. Additionally, Kangas and Maltamo (2000) compared Weibull and percentile-based methods, revealing the strengths of calibration techniques in improving model accuracy, which could complement ANN approaches. Comparative analyses underscore the evolving nature of diameter distribution modeling. While Gorgoso et al. (2012) identified superior fits of Johnson's SB and Beta functions in certain contexts, Fu et al. (2022) emphasized the scalability of hybrid models in complex environments. These findings validate the potential of ANNs and hybrid approaches in advancing forest management practices. The juxtaposition of traditional and ANN methodologies underscores their respective strengths. While traditional models excel in simplicity, ANNs offer unmatched flexibility and predictive accuracy, particularly in diverse ecosystems (e.g., Rumelhart et al., 1986). Hybrid models bridge these paradigms, creating a synergy that leverages the strengths of both approaches.

Incorporating ANNs into diameter distribution modeling represents a transformative shift in forestry analytics. Key transformative aspects include: (*i*) Enhanced predictive accuracy by modeling complex, non-linear relationships. (*ii*) Integration of real-time environmental and remote sensing data for dynamic decision-making. (*iii*) Scalability across diverse forest ecosystems, from even-aged to mixed-species stands. (*iv*) Synergy with hybrid approaches, combining statistical rigor with ANN adaptability. (*v*) Addressing operational challenges like missing data and outlier detection effectively.This review underscores the potential of ANNs and hybrid methodologies to enhance forest management strategies, paving the way for sustainable practices in a rapidly evolving environmental landscape. By embracing these innovations, forestry professionals can better navigate the complexities of modern ecosystems, ensuring resilience and productivity for generations to come. Continued inter-disciplinary collaboration and investment in advanced technologies will further cement the role of ANNs as pivotal tools in the future of forestry.

Glossary of Technical Terms

Artificial Neural Network (ANN): A computational model inspired by the structure and functioning of biological neural networks. ANNs are used to process and analyze complex data through interconnected layers of nodes.

Activation Function: A mathematical function in neural networks that determines the output of a node, helping the model capture non-linear relationships. Common examples include ReLU (Rectified Linear Unit), sigmoid, and tanh.

Backpropagation: A training algorithm used in neural networks to adjust weights by calculating and propagating the error gradient backward through the network.

Feed-Forward Neural Network: A type of ANN where data flows in one direction, from input to output layers, without cycles or feedback loops.

Generative Adversarial Network (GAN): A type of neural network composed of two sub-models (a generator and a discriminator) that compete with each other to produce increasingly accurate predictions or simulations.

Hybrid Model: A modeling approach that combines traditional statistical methods with machine learning techniques like ANNs to leverage the strengths of both methodologies.

LiDAR (Light Detection and Ranging): A remote sensing technology that uses laser pulses to measure distances and generate precise 3D information about an object or environment.

Maximum Likelihood Estimation (MLE): A statistical method for estimating model parameters by maximizing the likelihood function, ensuring that the observed data is most probable under the model.

Resilient Backpropagation (Rprop): An improved version of the backpropagation algorithm that adjusts weight updates to avoid the vanishing gradient problem.

Weibull Distribution: A statistical distribution commonly used in forestry to model diameter distributions due to its flexibility and ability to represent a wide range of shapes.

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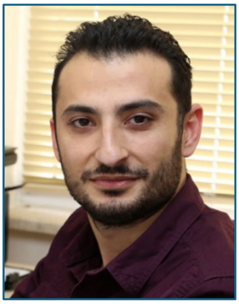

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Chapter 7

AGROFORESTRY AND TÜRKİYE IN THE FIGHT AGAINST CLIMATE CHANGE

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Agriculture is one of the oldest and primary production activities in human history, serving to meet people's basic needs, particularly in food production. Given that nutrition is humanity's fundamental need, the agricultural sector holds significant importance for the entire world. Agriculture is a branch of science that focuses on the production of plant and animal products, enhancing their quality and yield, preserving these products under suitable conditions, processing and evaluating them, and marketing them. In other words, agriculture is defined as the entirety of activities related to the care, feeding, cultivation, protection, and mechanization of all agricultural and animal products that can serve as human food and possess economic value, along with all fishing activities conducted in stagnant waters or designated areas (Direk, 2012). Moreover, the agricultural sector offers economic, environmental, and social benefits that extend beyond mere food production.

The rapid increase in the global population has led to a growing need for more land for food production, coupled with rising food prices and environmental issues, which necessitates the adoption of alternative agricultural practices (Güngör & Sever, 2022).

The increasing and diversifying human needs place land (soil) in a position of being a scarce resource that is difficult to increase in a short time. Furthermore, it is a production factor that many sectors compete for and share problems over. This competition is also evident in the agricultural and forestry sectors. Therefore, sustainable practices that allow competing sectors to share the same piece of land are noteworthy as realistic solutions. Among the serious proposals developed for the sustainable use of resources, both globally and in our country, agricultural forestry practices are at the forefront (Toksoy and Bayramoğlu, 2020).

The increasing world population, coupled with decreasing agricultural areas, raises global food security concerns. According to the Intergovernmental Panel on Climate Change (IPCC, 2021), if the global average temperature rises by 1.5°C, it is predicted that the decline in food productivity, which has already decreased by 20% since the onset of climate change, will accelerate and suffer significant damage. Additionally, it is anticipated that the global economy will lose 10% of its value by 2050. If the average temperature were to rise by 2°C, in addition to the current situation, it is estimated that another 180 million people will face hunger, and more than 410 million people living in urban areas will experience water scarcity due to severe droughts (Aydın et al., 2018, Güneş Şen & Aydın, 2024). Overall, it is expected that the global Gross Domestic Product (GDP) will decline by 11% annually.

Agriculture is a critical sector in promoting economic growth and reducing poverty (Coulibaly et al., 2017). The need to produce more food in the face of a growing population and limited agricultural land positions agroforestry as an important strategy to address issues such as low productivity, environmental degradation, and climate change (Antle & Diagana, 2003). The Food and Agriculture Organization of the United Nations (FAO) has developed the concept of agroforestry to improve the economic conditions of rural populations in less developed and developing countries. These systems have the potential to mitigate the effects of climate change, increase agricultural productivity, and contribute to food security (Mbow et al., 2014). Furthermore, the World Agroforestry Centre (ICRAF) has stated that agroforestry is a significant strategy for combating hunger, poverty, disease, ignorance, environmental degradation, and discrimination against women (Garrity, 2004).

In Türkiye, there is a growing trend of decreasing agricultural land size. Agricultural lands are important for crop production, while pastures, summer grazing, and winter pastures are vital for the development of livestock and nature conservation. According to the 2021 data from the Turkish Statistical Institute (TÜİK), the total agricultural area in Türkiye, including pastures and meadows, is 38,063,000 hectares. Of this total agricultural area, 52.2% consists of cultivated lands, 9.4% consists of lands under perennial crops (such as fruit orchards), and 38.4% consists of permanent meadows and grazing areas. With the increase in Türkiye's population and the corresponding decrease in total agricultural land, per capita agricultural land has diminished. Between 1990 and 2018, while Türkiye's population increased by approximately 45.2%, the contraction of per capita agricultural land during the same period was 39.3%. The per capita total agricultural land, which was 0.76 hectares in 1990, declined to 0.45 hectares by 2021. As of 2021, considering the total arable land of 23,446,000 hectares, there is only 0.28 hectares of land per capita. According to 2020 data, the global per capita cultivated agricultural land is 0.18 hectares, while in the European Union, it is 0.22 hectares (URL-1, 2022). Additionally, recent mass migrations to Türkiye from neighboring countries have further diminished these values.

Türkiye possesses a significant amount of land that should fall within the forest regime but is currently utilized for agriculture and livestock. Besides this land, there are also large areas used for agriculture and livestock. The addition of suitable tree species to all these areas will positively impact the total quantity of products and services while also contributing to rural development and environmental improvements. Therefore, agricultural forestry practices should be considered in terms of national policy (Güngör et al., 2018; Toksoy and Bayramoğlu, 2020).

Concept of Agroforestry

The definition of agroforestry was established in 1978 by the International Centre for Research in Agroforestry (ICRAF) as "a land management system that combines tree management (forest and/or other trees) with agriculture and/or livestock management, either simultaneously or in rotation, in a manner that can compete with traditional local practices, enhances land productivity, and is suitable for the production of sustainable, multifunctional products and services." Toksoy and Bayramoğlu (2020) described agroforestry as "an integrated land management system that increases the quantity and diversity of products and ecosystem services by utilizing the biological interactions resulting from the combination of forest trees with agricultural crops and/or animals." Over the years, agroforestry systems have led to significant research at local, regional, and global scales regarding their environmental impacts and their social and economic aspects (Murthy et al., 2016; Ayaz & Güngör, 2019). Agroforestry, which serves multiple functions, has been defined differently by various scientists according to different disciplines.

According to Batt (1999), the functions of agroforestry can be categorized into two groups:

Macro functions: These involve large-scale effects aimed at improving rural development levels, creating employment, preventing population growth in cities, increasing national foreign trade, reducing agricultural product prices, ensuring soil and forest protection, preventing desertification, and mitigating floods and water runoff, as well as extending their economic lifespan.

Micro functions: These refer to smaller-scale effects such as enhancing the productivity of degraded lands to restore them to their former condition, increasing product diversity, augmenting income, improving employment opportunities, reducing overall costs, increasing land value, and enhancing production and quality while improving ecological conditions.

Agroforestry systems and benefits

Agroforestry systems vary based on land structure, the objectives of landowners, traditional and cultural characteristics, and market needs. Generally, agroforestry is classified under three main systems: silvopastoral, agrosilvopastoral, and agro-silvicultural systems (Toksoy and Bayramoğlu, 2020).

1. *Silvopastoral Systems:* These systems combine tree cultivation and livestock activities. Typically, they involve trees planted in clusters along wide spaces or pastures (Grebner et al., 2021).
2. *Agrosilvopastoral Systems:* This system integrates crops, pasture, livestock, and woody perennials into the same agricultural system (Nair, 1989).
3. *Agro-silvicultural Systems:* This agroforestry practice is characterized by the simultaneous presence of trees and crops on the same plot of land (each component occupies a separate area, but both are present at the same time) or in succession (one component rotates to replace the other) (Nair, 1985).

In addition to these systems, various others have emerged due to advancing technology and changing needs. These systems are classified as apiculture (beekeeping), aquaforestry (combination of woody species and aquaculture), agrosilvofishery (combination of trees, fish, and agricultural crops), silvomedical (integration of trees and agricultural plants for medical benefits), and agrosilvomedical (production of medicinal products using trees and agricultural crops) (Zou and Sanford, 1990).

Agroforestry is a practice that simultaneously supports both forest conservation and the establishment of productive lands suitable for agriculture. This practice can play a significant role in creating a sustainable future by increasing farmers' incomes while protecting the environment. Initially, agroforestry practices were used to maximize product and yield from a unit of land. However, it has later been recognized that, beyond the economic benefits of obtaining more products, there are significant environmental and socioeconomic advantages on a global scale (Mazlum, 2023).

Agroforestry practices provide various benefits by enhancing food security. These systems offer product diversity, thus reducing the risk of food shortages and facilitating access to a variety of foods while improving soil quality and reducing the need for chemical fertilizers. This situation particularly benefits farmers economically and environmentally. The trees used in agroforestry systems protect the soil, prevent erosion, support natural pest control, thereby reducing pesticide use, and protect water resources, minimizing the risk of pollutants (Mazlum, 2023; Güneş Şen, 2023).

Agroforestry practices contribute positively to biodiversity conservation. Additionally, due to their carbon storage capacity, they play an important role in combating climate change. Tree plantations offer a low-cost alternative to help balance greenhouse gas emissions (Schlamadinger and Marland, 2000; Van Kooten et al., 1999; Richards & Stokes, 2004; Lee, 2007).

Agroforestry systems provide economic advantages to producers by allowing the simultaneous cultivation of multiple products. In cases of disasters or crop losses, other products within the systems can compensate for losses.

Clımate Change and Agroforestry

Climate change is a complex problem that is rapidly advancing due to human activities and is affecting all areas of life. Global warming has increased by 10 degrees compared to a century ago, and the rise in greenhouse gases is triggering this situation (Toksoy, 2021). Climate change encompasses not only rising temperatures but also rising sea levels, an increase in extreme weather events, and the melting of glaciers. These changes threaten coastal areas, adversely affect agriculture and water resources, and result in alterations in ecosystems and habitats of species (WMO, 2021).

The most effective tools in combating climate change are agriculture, livestock, and forestry, which are fundamental components of agroforestry systems. Reducing emissions and increasing forest cover are essential strategies against climate change (Toksoy, 2021). However, as demands on forests increase, their conservation becomes more challenging. The agricultural sector is significantly affected by climate change, with sudden rainfall, extreme temperatures, and drought negatively impacting agricultural production, which in turn has adverse effects on inflation and the current account balance (Öziş et al., 2013). In livestock farming, industrial systems are used to meet the demands of a growing population, but these systems have much higher greenhouse gas emissions than traditional methods (Verge et al., 2007). Additionally, climate change can negatively affect the productivity, reproductive physiology, and immune systems of animals (Nardone, 2002).

In this context, agroforestry emerges as a significant strategy to enhance environmental quality and ensure food security. Agroforestry systems have a greater carbon storage capacity and can be implemented in various regions, helping to mitigate the negative impacts of climate change (Toppo & Raj, 2018). These systems store carbon in plant biomass and soil while increasing the potential for carbon retention through the enhancement of tree numbers in agricultural areas (Toksoy & Bayramoğlu, 2020).

Biodiversity in agroforestry

Biodiversity refers to the variety of plant, animal, and microorganism species and plays a direct and influential role in the sustainability of food resources and the functioning of ecosystems. Agroforestry is an important strategy for the conservation and sustainable use of biodiversity. This practice contributes to maintaining healthy ecosystems by protecting plant and animal species and restoring habitats (McNeely and Schroth, 2006).

The growing interest in agroforestry in recent years emphasizes the importance of this practice in the conservation of biodiversity (McNeely and Schroth, 2006; Buck et al., 2004). Agroforestry plays five fundamental roles in the context of biodiversity: (1) providing habitats for species sensitive to environmental conditions, (2) conserving genetic resources of vulnerable species, (3) reducing natural habitat conversion, (4) facilitating connectivity by creating habitat corridors, and (5) preventing environmental degradation and habitat loss (Pimm et al., 1995).

Research shows that agroforestry has positive effects on biodiversity. Agroforestry practices offer 60% more taxonomic richness compared to forests and play an essential role in biodiversity conservation (Bhagwat et al., 2008; Steffan-Dewenter et al., 2007). However, due to intensive management, agroforestry practices may often host fewer endemic species (Noble and Dirzo, 1997).

The conservation of biodiversity is critical for improving ecosystem services. Biodiversity provides both material and spiritual benefits to society, contributing to agriculture through pest control and pollination, and enhancing resilience against environmental changes (Hooper et al., 2005; Gallai et al., 2009). In this context, agroforestry practices are viewed as important tools for supporting ecosystem services and conserving biodiversity.

Carbon in agroforestry systems

Agroforestry systems play a significant role in carbon storage capacity. These systems store carbon through organic matter in the soil, wood products, and root biomass. Plants absorb carbon from the air through photosynthesis and store this carbon in long-lived carbon pools such as the stem (above-ground biomass) and roots (below-ground biomass) (Schoeneberger, 2009; Kumar & Nair, 2011; Almansouri et al., 2020). Moreover, carbon pools in agroforestry systems also include fruits, soil microorganisms, and both organic and inorganic forms of carbon. The increasing biomass associated with growing plants enhances the amount of stored carbon and, consequently, the carbon sequestration potential of agroforestry systems (Schoeneberger, 2009; Kumar & Nair, 2011).

In Sri Lanka, in regions where agroforestry is widely promoted, CO2 emissions account for less than 0.1% of the global total. The establishment of forests and vegetation on non-forested land has led to a reduction in emissions. The transition from grasslands and other low-biomass land use systems to agroforestry has resulted in a net gain in carbon stocks by sequestering more carbon within the biomass (Roshetko et al., 2007).

The carbon storage capacity of agroforestry systems can reach up to 50 Mg C ha^-1 in humid regions. In tropical areas, small group agroforestry systems can sequester between 1.5 and 3.5 Mg C ha^-1 per year (Montagnini & Nair, 2004). The carbon storage potential of tropical agroforestry systems averages 95 Mg C ha^-1, with a range of 12 to 228 Mg C ha^-1 (Albrecht & Kandji, 2003). In humid tropical regions, these systems have the potential to sequester over 70 Mg C ha^-1 in plant biomass and can store up to 25 Mg C ha^-1 of carbon in the top 20 centimeters of soil (Mutuo et al., 2005).

In agroforestry systems in Costa Rica, the carbon storage potential of above-ground components is estimated at 2.1 × 10^9 Mg C per year. Additionally, an agroforestry system managed with 10-year-old *Erythrina poeppigiana* can sequester 0.4 Mg C ha^-1 per year in coarse roots and 0.3 Mg C ha^-1 per year in tree stems (Oelbermann et al., 2004).

Agroforestry and rural development

Rural development is the effort to eliminate the disadvantages stemming from natural, socioeconomic, and infrastructural factors in rural areas, primarily by rationally utilizing the resources in these regions to enhance rural welfare (Toksoy & Bayramoğlu, 2017). In this context, agricultural and forestry activities are priority sectors for rural development. Particularly, agroforestry stands out as a significant practice by providing alternative production options on limited land.

Agroforestry is an ancient land-use system that combines trees, animals, and agricultural production. Although it has lagged behind the monoculture approaches of modern agriculture, agroforestry has begun to be recognized as a sustainable alternative in recent years. The European Union includes agroforestry in its rural development policies (Hain, 2014).

The distinguishing feature of agroforestry compared to other land-use systems is the incorporation of woody plants into the system. Economically, tree-based agricultural products can enhance economic resilience by increasing product diversity (Amare et al., 2019). The use of multifunctional trees provides alternative income sources for rural communities, as well as fodder and food during periods of scarcity (Gebru et al., 2019). For instance, teak tree systems in Indonesia contribute 12% of total household income (Roshetko et al., 2013). In West Sumatra, damar pine agroforestry accounts for up to 50% of total household income (Wollenberg & Nawir, 2005).

Agroforestry can also create new job opportunities in rural areas, such as timber harvesting and furniture making (Iskandar et al., 2016). These job opportunities can improve gender equality, particularly for women, and enhance the rural economy by preventing rural migration (Kiptot et al., 2014; Mukhlis et al., 2022). Additionally, agroforestry contributes to improving food security. A study in Indonesia demonstrated that agroforestry was associated with increased consumption of legumes and vitamin A-rich fruits and vegetables (Ickowitz et al., 2016). Low-income farmers receiving agroforestry training have shown increased food productivity and diversity, which has enhanced food availability (Pratiwi & Suzuki, 2019).

Agroforestry can also promote socio-cultural activities. Farmer communities can gather to discuss topics such as tree species, product diversity, and fertilizer management. Among small forest communities in Thailand, knowledge sharing and problem-solving have been seen as part of a cultural practice (Mungmachon, 2012).

Agroforestry in Türkiye

In Türkiye, the subsystems of agroforestry are categorized under the heading of agrisilvicultural systems, which include alley cropping, multilayered orchards, the cultivation of multipurpose trees in agricultural lands, rural home gardening methods, soil conservation afforestation, and windbreaks. Within the subsystems of silvopastoral systems, the cultivation of trees in pasture and rangeland, producing fodder leaves from trees, and growing and grazing herbaceous plants under trees are included. Agrosilvopastoral systems encompass rural home gardens for livestock, beekeeping using tree and forest resources, fish production from forest resources, and multipurpose protection forests (Tolunay et al., 2007).

Agroforestry practices in Türkiye are commonly carried out in an unplanned and unconscious manner, relying on traditional knowledge passed down through generations. Traditional practices such as grazing in forested areas exemplify silvopastoral systems, while cultivating agricultural crops among forest trees or shrubs in home gardens is an example of agrosilvicultural systems. In Türkiye, agroforestry practices are generally conducted with agrosilvopastoral and agrisilvicultural systems aimed at growing fodder or agricultural crops under forest trees. Some notable examples of these and other systems implemented in the country include:

In the provinces of Izmit, Adapazarı, and Yozgat, crops such as beans, beet, sunflowers, maize, melons, watermelons, tomatoes, and fodder plants are grown under rows of poplar trees. In Şanlıurfa, agroforestry practices have been carried out under species such as Aleppo pine, cypress, false acacia, and black poplar, with the cultivation of forage plants including common clover, smooth brome, white clover, meadow foxtail, pigweed, pasture foxtail, and red clover. In Düzce, hazelnut cultivation has been observed under poplar trees. In the Bergama district of İzmir, vetch and fodder production for livestock, as well as beekeeping and viticulture, are conducted under stone pine. In Rize, linden trees are cultivated around agricultural plants by local people. The Amasya Regional Directorate of Forestry has grown soybeans, maize, watermelons, and melons under poplar trees within the first four years of poplar plantation areas. After developing tree canopy in poplar plantations, herbs such as St. John's wort, lemon balm, mint, thyme, parsley, and catnip have also been planted for shadow farming (Büyükşahin, 2010).

In the Göller Region, known for its lakes, fishing and agriculture coexist in Eğirdir, Hoyran, and Kovada lakes in the vicinity of Isparta and Burdur. In addition, carp and trout are cultivated in rivers and streams within the forests. Beekeeping activities are conducted under red pine in the upper watersheds of the Western Mediterranean region. Moreover, areas where flowering plants and false acacia grow are preferred for beekeeping (Tolunay et al., 2007).

Agroforestry studies in Türkiye have seen only limited attempts and production continues through traditional methods. Due to the land structure, climate conditions, and the reliance on agricultural activities for livelihoods in certain regions, Türkiye possesses significant agroforestry potential. For agroforestry to gain acceptance and become widespread in Türkiye, it is essential for official institutions, cooperatives, and non-governmental organizations to carry out initiatives. Promoting agroforestry and its subsystems to producers, providing education, offering support through tools and seeds, and establishing demonstration plots to implement region-specific systems are vital steps for facilitating the transition of local communities to agroforestry. This transition can enable agricultural workers to increase their economic gains while also achieving ecological benefits through agroforestry systems.

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Reha MAZLUM

Chapter 8

Bryophytes and Climate Change: Ecological Roles and Strategic Approaches

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Forests are regarded as a conservation priority due to their ecosystem integrity, structural complexity, natural richness, and continuity. The defining criteria for this purpose remain under deliberation; nonetheless, it is underscored that the new concepts must accurately reflect forest integrity and be more readily quantifiable than current standards. Bryophytes serve as indicator species in forest ecosystems due to their essential role in forest integrity and their sensitivity to particular forest management practices (Frego, 2007).

Overall Impacts of Climate Change on Ecosystems

Climate change is a multifaceted phenomenon that significantly impacts the composition and operation of ecosystems. Factors including elevated temperatures, altered precipitation patterns, and rising sea levels jeopardize biodiversity by disturbing ecosystem equilibrium. The rise in extreme weather events constrains the adaptive ability of ecosystems and endangers several species with extinction (Türkeş, 2008).

The primary driver of climate change is the heightened emission of carbon dioxide (CO_2), methane (CH_4), and other greenhouse gases into the atmosphere due to anthropogenic activity. The concentration of these gases in the atmosphere disturbs the Earth's natural temperature equilibrium, resulting in global warming. The primary contributors to this growth include energy use, industrial operations, deforestation, and agriculture (Türkeş et al., 2000). This process presents a significant risk to ecosystems and living organisms, not only due to rising temperatures but also as a result of alterations in precipitation patterns, heightened drought, and extreme weather events (Ursavaş and Ediş, 2024).

Global warming immediately impacts the habitats of flora and fauna, prompting species to relocate to higher latitudes or elevations (Tavşanoğlu, 2018). This affects interspecies relationships within ecosystems, resulting in disturbances in food chains and a decline in ecological functioning. Aquatic ecosystems, in particular, are subjected to consequences including rising water temperatures and ocean acidification. Coral reefs, as sensitive ecosystems, are significantly impacted by these changes and face the threat of extinction (Green et al., 2003).

The effects of climate change on forest ecosystems in Turkey are concerning. Rising temperatures and diminishing precipitation elevate the incidence and intensity of forest fires, hence diminishing carbon storage capacity. Moreover, the growth and regeneration processes of certain tree species are adversely impacted (Altürk, 2017). This circumstance jeopardizes the sustainability of forest ecosystems and impedes the continuity of ecological activities.

Comprehending the effects of climate change on plant species is crucial for biodiversity conservation and sustainable ecosystem management. Nevertheless, a significant portion of the current research in these domains has concentrated on tracheophytes, which are plants possessing specific conductive tissues (xylem and phloem) that facilitate the transfer of water and nutrients throughout the organism, including vascular plants. Conversely, research on bryophytes, which possess a more ancient evolutionary lineage, is significantly restricted (He et al., 2016). Bryophytes exhibit a significant reliance on their external environment, employing a poikilohydric approach for the acquisition of water and nutrients. This disparity indicates that findings from vascular plant studies cannot be extrapolated to bryophytes.

In conclusion, climate change has multifaceted and complex impacts on ecosystems. A better understanding of these impacts and taking the necessary measures are critical for the sustainability of ecosystems and the conservation of biodiversity.

Role and Significance of Bryophytes in Ecosystems

Bryophytes are among the most ancient plants in terrestrial ecosystems and are distinguished by their reliance on water for their life cycles. This assemblage of mosses, liverworts, and hornworts plays significant ecological roles in ecosystems, notwithstanding their little size. They promote ecosystem health, particularly through processes including carbon sequestration, hydrological management, and microhabitat formation (Ursavaş and Öran, 2021).

Bryophytes, particularly Sphagnum species, facilitate peatland formation by sequestering substantial quantities of carbon via photosynthesis. Peatlands are essential for mitigating atmospheric carbon dioxide levels and controlling the carbon cycle (Gorham, 1991). Moreover, due to their ability to retain water, they sustain moisture equilibrium in microhabitats, aid in soil stabilization, and mitigate erosion (Proctor, 2000). These features substantially contribute to the preservation of water equilibrium in ecosystems during drought conditions.

The survival and reproductive strategies of bryophytes demonstrate their capacity to adapt to environmental conditions. Their poikilohydric composition, resistance to cellular desiccation, and capacity to sustain functionality during wet-dry fluctuations render them adaptable to climate change (Proctor, 2009). Nonetheless, these characteristics also heighten their sensitivity to external environmental fluctuations.

Thus, bryophytes are a crucial element for ecological sustainability. They greatly contribute to ecosystem health and play a crucial role in mitigating climate change through several functions, including water management, carbon storage, and soil stabilization.

Ecological Functions of Bryophytes

Water retention capacity

Bryophytes, particularly mosses and Sphagnum species, significantly contribute to ecosystems through their water retention abilities. Due to the gaps in their cellular architecture and their significant absorption capacity, these plants can retain substantial quantities of water. Bryophytes, through these characteristics, aid in the preservation of water resources during arid conditions and maintain the hydrological equilibrium in moist environments (Ursavaş and Tuttu, 2020). The water retention ability of bryophytes influences ecosystems in the following ways:

Establishment of microhabitats: Their moisture-retentive characteristics foster appropriate environments for diminutive organisms. These microhabitats facilitate the survival of aquatic-dependent species.

Regulating the hydrological cycle: Bryophytes facilitate uniform water distribution in the soil and mitigate erosion by diminishing surface runoff.

The function of water storage in peat ecosystems: Sphagnum species serve as the primary regulators of water in peatlands. These species can retain 20-40 times their own weight in water, hence sustaining the moisture equilibrium in these regions (Turetsky, 2003).

The gradual breakdown characteristics of bryophytes facilitate humus formation, hence enhancing the soil's capacity to retain water and nutrients. They additionally encourage rooting activities at the junction of the humus layer and fine tree roots (Longton, 1984; Weetman, 1968). These characteristics demonstrate that water retention capacity is a crucial factor in maintaining ecosystem integrity.

Bryophytes function in nutrient cycles

Bryophytes are essential to the nutrient cycling within ecosystems. Their role in organic matter generation, soil interactions, and nitrogen cycling directly underpins ecological stability. The roles of bryophytes in nutrient cycles are as follows:

Bryophytes generate organic materials as primary producers. This organic debris decomposes, enhancing soil nitrogen levels and promoting soil fertility (Abay et al., 2014).

Interactions occurring above and below the ground: Bryophytes, securely anchored to the soil by their rhizoids, modulate the mineral composition of the soil and augment organic matter through their decaying material (Abay et al., 2014).

Bryophyte species enhance soil nitrogen levels through associations with nitrogen-fixing symbiotic bacteria. They are recognized for their ability to sequester carbon in peatland ecosystems and significantly contribute to the carbon cycle (Gorham, 1991).

These roles in nutrient cycling allow bryophytes to mitigate environmental changes and enhance ecosystem functionality.

Bryophytes function in habitat development

Bryophytes provide a distinctive role in habitat formation and the facilitation of ecological activities. They actively participate in various ecological processes, including soil stabilization and microhabitat formation.

Soil stabilization:

Bryophytes mitigate erosion by securely anchoring to the soil surface via their delicate rhizoids. This is especially apparent on exposed and disturbed soil surfaces. Bryophytes contribute to soil stabilization in the following ways:

Erosion control: Mitigates flow following precipitation and inhibits soil displacement (Turetsky, 2003).

Facilitation of soil formation: Expedites soil formation processes by the accumulation of organic elements over time. This is significant on newly exposed rock surfaces or in places affected by fire.

Initiating vegetative restoration: Due to its ability to store water and nutrients, it aids in the rooting of other plants and fosters vegetation regeneration.

Microhabitat Formation:

Bryophytes serve as microhabitat producers in ecosystems, offering appropriate environments for small plants, animals, and microbes.

Their microhabitat generation functions can be delineated as follows:

Ensuring a humid environment: The water retention ability of bryophytes facilitates the survival of hydrophilic species by establishing a moist microenvironment (Glime, 2007).

Invertebrate refuge: Numerous insects, mollusks, and mites inhabit the wet and sheltered environments offered by bryophytes (Ursavaş and Ören, 2021).

Bryophytes enhance seed germination rates by providing a protective cover for seeds on the soil surface, hence removing barriers to germination.

Epiphyte environments: Bryophytes create habitats for epiphytic species by colonizing tree trunks, stones, or other surfaces (Bates, 2000).

Ecological and climatic significance:

Bryophytes play a crucial role in soil stabilization and the formation of microhabitats, which are essential for preserving ecosystem biodiversity and enhancing resistance to environmental stressors. These attributes facilitate the broader application of bryophytes in the regeneration of degraded landscapes and forestry initiatives (Abay et al., 2014).

Climate Change and Bryophytes

Comprehending the responses of plant species to climate change is a significant problem in biodiversity conservation and sustainable ecosystem management. However, current study has predominantly concentrated on tracheophytes, namely vascular plants. Despite bryophytes being an evolutionarily ancient category, research on these plants is constrained. Bryophytes, which satisfy their water and nutrient requirements via a poikilohydric approach, exhibit significant sensitivity to environmental fluctuations, with their survival and reproductive activities heavily reliant on these conditions (He et al., 2016).

Effects of climate change on bryophytes

Recent research indicates that climate change significantly affects the quantity and species composition of bryophyte ecosystems (Walker et al., 2006; Lang et al., 2009; Elmendorf et al., 2012). Temperature elevation, moisture reduction, and habitat alterations directly influence several attributes of bryophytes, encompassing their metabolic functions and geographical dispersion.

Elevation of temperature:

Bryophytes are flora adapted to chilly and moist environments. Consequently, rising temperatures present significant risks to numerous species under this category.

Equilibrium of photosynthesis and respiration: Elevated temperatures can diminish the photosynthetic rate in bryophytes while augmenting the respiratory rate. This imbalance diminishes energy efficiency and interferes with metabolic activities (Proctor, 2000).

Contraction of geographical distribution: Species susceptible to elevated temperatures may be compelled to relocate from lower elevations to cooler, higher altitudes or polar regions. The conjunction of this mechanism and habitat loss can elevate the danger of species extinction (Gignac, 2001).

Reduction of moisture:

The life cycle of bryophytes is significantly reliant on the availability of water. Consequently, reduced humidity and heightened drought conditions can significantly affect bryophyte ecosystems.

Cycle of hydration and desiccation: Bryophytes possess the capability to suspend their metabolic processes in response to dehydration. Prolonged droughts compel this adaptive mechanism, endangering species viability (Glime, 2007).

Drought resilience: While several species can endure brief droughts, extended droughts may result in population reductions (Turetsky, 2003).

Alterations in habitat:

Climate change impacts the natural habitats of bryophytes in both direct and indirect manners.

Habitat degradation: Ecosystems characterized by dense bryophyte populations, such as tundra and peatlands, are diminishing due to rising temperatures and dry conditions (Gorham, 1991).

Limited dispersal potential: Bryophytes reproduce by spores, constraining their ability to adapt to fluctuating environmental conditions. This hinders their ability to disseminate and acclimatize to novel environments (Ursavaş and Çetin, 2014).

Alterations in soil and microhabitat: Alterations in soil structure and moisture content resulting from climate change might adversely impact the rooting and habitat formation abilities of bryophytes (Bates, 2000).

Bryophytes are particularly responsive to environmental alterations induced by climate change. Elevated temperatures, moisture depletion, and habitat deterioration heighten the extinction risk for numerous species. Nonetheless, the persistence and adaptability of certain bryophyte species indicate their potential response to forthcoming environmental changes (Ursavaş and Öztürk, 2016).

Mechanisms of bryophyte adaptation to climate change

Bryophytes are resilient plants capable of adapting to environmental fluctuations. This flexibility relies on diverse physiological, genetic, and ecological systems that facilitate survival in harsh environments.

Characteristics of tolerance:

Desiccation tolerance: Bryophytes can suspend their metabolic processes during dehydration and promptly reactivate them upon rehydration. This trait enables their survival during drought conditions (Glime, 2007; Proctor, 2000).

Rapid moisture absorption capability: They can fulfill their hydration requirements by extracting moisture from the atmosphere. This renders them beneficial in areas with limited water resources.

Bryophytes mitigate cellular damage by synthesizing stress proteins in response to drought and thermal stress (Glime, 2007).

Photosynthetic plasticity: Bryophytes possess the ability to modulate their photosynthetic rate in response to environmental variables. This facilitates the preservation of carbon fixation even in conditions of low light and humidity (Turetsky, 2003).

Genetic variation:

Genetic variability: Due to their extensive genetic diversity, bryophytes possess the capacity to adapt to various environmental situations (Bates, 2000).

The haplo-diploid life cycle, encompassing both haploid and diploid phases, enhances genetic variety and fortifies adaptive potential (Ursavaş and Keçeli, 2021).

Epigenetic adaptations: Bryophytes can respond to environmental challenges via transient alterations in gene expression.

Ecological adaptations:

Habitat versatility: Bryophytes can inhabit various substrates, including soil, rock, and bark. This adaptability enhances their resilience to habitat degradation (Ursavaş and Öztürk, 2016).

Colonization capability: They can swiftly inhabit freshly disturbed regions and aid in the restoration processes of ecosystems (Abay et al., 2014).

The adaptive mechanisms of bryophytes render them adaptable to environmental fluctuations. Nonetheless, the constraints of these processes may hinder species' survival during catastrophic climatic events. A comprehensive study of the adaptation mechanisms of bryophytes is essential for this plant group and for formulating effective strategies to address climate change.

The Function of Bryophytes in Mitigating Climate Change

Carbon sequestration capabilities

Bryophytes play a crucial role in combating climate change, particularly in relation to the carbon cycle. Through photosynthesis, they sequester carbon dioxide (CO_2) in the atmosphere as organic carbon, so mitigating the impact of greenhouse gasses and sustaining the carbon equilibrium of ecosystems. Sphagnum species, particularly prevalent in peatland environments, are critical contributors to this process (Ursavaş and Çetin, 2013).

Bryophytes sequester carbon via photosynthesis and provide long-term carbon storage due to their minimal breakdown rate (Gorham, 1991). This phenomenon is most evident in habitats characterized by extensive bryophyte coverage, such as peatlands.

Sphagnum mosses constitute the foundation of peatland ecosystems and sequester around 30% of global carbon, rendering them significant carbon repositories (Turetsky, 2003). These attributes render peatlands distinctive regarding carbon sequestration.

The slow breakdown rate of bryophytes facilitates the long-term sequestration of atmospheric carbon and retards its re-release into the atmosphere.

Bryophytes contribute to methane sequestration. Certain bryophyte species in peatland ecosystems harbor bacteria that inhibit methane generation, hence contributing to the reduction of atmospheric methane levels (Frolking and Roulet, 2007).

Contributions to the hydrological cycle

Bryophytes are essential for controlling the hydrological cycle and sustaining the moisture equilibrium of ecosystems. Their potential to retain water, regulate moisture, and facilitate evaporation processes enhances ecosystem sustainability, particularly in the context of drought and climate change.

Bryophytes possess a significant water retention capacity inside their cellular structure, facilitating uniform water distribution across microhabitats. Sphagnum mosses can hold 20-40 times their weight in water, maintaining moisture equilibrium during dry conditions (Turetsky, 2003).

Hydrological equilibrium: Bryophytes assist in sustaining groundwater levels through the absorption of precipitation. They mitigate surface runoff, hence preventing soil erosion and enhancing the productivity of water resources (Glime, 2007).

Minimization of evaporation: The water retention capabilities of bryophytes regulate atmospheric evaporation, preserving microclimates and enhancing soil moisture (Proctor, 2000).

Due to these characteristics, bryophytes facilitate the sustainability of the water cycle and serve as an effective means to mitigate water scarcity resulting from climate change.

Application of bryophytes in habitat enhancement

Bryophytes are essential for the restoration of degraded ecosystems and the enhancement of habitats. They facilitate ecosystem rejuvenation by their ability to retain water, stabilize soil, and create microhabitats (Abay et al., 2014).

Soil stabilization:

Bryophytes mitigate erosion by securely anchoring themselves to the soil via their rhizoids. This is most apparent on exposed surfaces or regions of disrupted soil:

Soil erosion mitigation: It mitigates surface runoff, hence preventing soil erosion and preserving soil structure (Turetsky, 2003).

Role in soil development: Bryophytes expedite soil formation by accumulating organic material over time. This is significant in regions affected by wildfires or agricultural practices (Abay et al., 2014).

Biodiversity and microhabitats:

Bryophytes make environments more diverse by giving other plants, microorganisms, and animals a place to live:

Creating an area that is damp: Due to their ability to hold water, they help water-dependent species stay alive by making damp places to live (Glime, 2007).

Getting seeds to grow: The moist environment that bryophytes provide helps other plant species germinate and grow roots faster.

Recovery and long-term success:

Because they don't cost much and last a long time, bryophytes are perfect for restoring ecosystems:

Bringing back to life-damaged areas: As Ursavaş and Birben (2023) say, bryophytes are used to restore damaged areas because they control water flow and keep the earth stable.

Revitalizing peatlands: Species of Sphagnum can be used to make peatlands better at storing carbon. This is a long-term defense against climate change (Gorham, 1991).

Many people see bryophytes as a useful way to fight climate change because they can store carbon, help the water cycle, and make habitats better. Because of these traits, they are necessary for managing ecosystems and restoring damaged ones. In the fight against climate change, it should be a top concern to protect ecosystems like peatlands and bring more attention to the ecological services that bryophytes provide.

Research Gaps and Outlooks for the Future

Review of previous research

Although bryophytes are very important for the health of ecosystems, they have not been studied as much as other plant groups, both in Türkiye and other countries. This makes it hard to figure out what part bryophytes play in climate change and ecosystem services. Here's a list of the important research gaps that need to be filled:

Not enough research on ecological services:

Scientists haven't investigated how bryophytes affect the carbon cycle or their part in bog ecosystems enough. We need to learn more about how much carbon Sphagnum species can store on a world and regional scale (Gorham, 1991; Birben, et al., 2014).

We all know that bryophytes play a role in controlling water levels and soil wetness, but it's still important to go into more detail about how they work in different types of ecosystems (Glime, 2007).

Possessing the capacity to manage and adjust to climate change:

Genetic variety and adaptive mechanisms: Limited knowledge exists regarding the genetic diversity of bryophytes and their adaptive processes in the context of climate change. Further research in this domain may yield novel methods to enhance the resilience of bryophytes against natural stressors (Gignac, 2001).

Resilience to extreme conditions: Further investigation is required about the responses of bryophytes to drought, elevated temperatures, and environmental alterations, as well as the varying reactions of different species in these scenarios (Proctor, 2000).

Inadequacies in restoration project applications:

Application in restoration strategies: Research on the effective application of bryophytes in the restoration of degraded ecosystems is scarce. They can be easily used especially in the restoration of mining sites in Turkey, but there are few studies on this subject. A comprehensive investigation of bryophytes is essential, particularly in the context of peatland restoration and carbon sequestration initiatives (Turetsky, 2003).

Prolonged observational research: Insufficient research exists regarding the long-term effects of bryophytes employed in restoration initiatives. This weakness results in a shortfall in evaluating ecological sustainability (Ursavaş, 2015).

Incorporation into climate policies:

Strategies for policy and management: The contribution of bryophytes to mitigating climate change has not been well included into forestry and water management programs. Policy decision-makers require more information regarding the ecosystem services supplied by bryophytes (Bates, 2000).

Atmospheric contamination and ecological surveillance: Bryophytes serve as significant markers of air pollution and environmental alterations. Nonetheless, the incorporation of these studies into environmental management policy is constrained.

Although current research has established a significant foundation for comprehending the ecological and climatic functions of bryophytes, it is essential to solve knowledge deficiencies in this domain to fully harness their potential in mitigating climate change (Ursavaş and Ören, 2014).

The role of bryophytes in climate change policies

Bryophytes, despite their essential contribution to ecosystem services, have not been sufficiently incorporated into climate change policies. Given their sensitivity to environmental stressors and their roles in carbon storage and water regulation, there are considerable opportunities to incorporate bryophytes into these policies (Birben et al., 2014).

Function in forestry policies:

Bryophytes adhere firmly to the soil surface, mitigating erosion and controlling water discharge. These attributes are essential for enhancing the sustainability of forestry initiatives (Glime, 2007).

Ecosystem restoration: Bryophytes serve as an efficient means for rehabilitating regions adversely affected by forest fires, agricultural, or mining operations. Their propensity to retain water and quick growth facilitates the rejuvenation of forest ecosystems (Proctor, 2000).

Promoting biodiversity: Bryophytes' ability to produce microhabitats significantly enhances biodiversity in forest ecosystems (Bates, 2000).

Function in climate change policy:

The carbon sequestration potential of Sphagnum mosses in peatlands enhances the significance of bryophytes in addressing climate change. Safeguarding these habitats constitutes a vital approach for mitigating carbon emissions (Gorham, 1991).

Strategies for natural solutions: The ecosystem services provided by bryophytes, including water regulation, moisture control, and habitat construction, might be regarded as nature-based solutions. These strategies are effective means to alleviate the effects of climate change (Turetsky, 2003).

Environmental surveillance and metrics: Bryophytes' sensitivity to environmental stressors can serve as an instrument for the early detection of alterations resulting from climate change (Gignac, 2001).

Recommendations for policy integration:

Conservation efforts must be implemented in regions with significant bryophyte populations, including peatlands, forest floors, and moist environments (Birben et al., 2014).

Investigation and data acquisition: Further investigation into the ecological services and adaptive strategies of bryophytes should be undertaken and included in forestry and climate policies.

Community-oriented methodologies: Residents ought to be informed about the significance of bryophytes in ecosystem health and engaged in their conservation efforts.

Incorporating bryophytes into forestry and climate policies presents significant opportunities for sustainable ecosystem management and climate change mitigation measures. This integration will facilitate more efficient use of the ecological services offered by bryophytes (Birben et al., 2014).

Conclusion and Recommendations

Comprehensive assessment

Bryophytes, despite their simplicity, are essential to ecosystem functionality and climate change mitigation. Their capability for water retention, carbon sequestration, soil stabilization, and creation of microhabitats renders them a vital element of ecological processes (Glime, 2007).

Significance in ecology:

The ability of bryophytes to absorb and retain water is essential for regulating the water cycle and sustaining ecosystem water balance. These attributes mitigate pressures such as drought and severe water depletion (Proctor, 2000).

Soil stabilization: Their rhizoids mitigate erosion by anchoring the soil surface and serve as a crucial instrument in the rehabilitation of degraded environments (Turetsky, 2003).

Bryophytes enhance ecosystem biodiversity by offering refuge and breeding habitats for many creatures (Bates, 2000).

Significance of climate:

Sphagnum species specifically enhance carbon storage capacity by sequestering substantial quantities of carbon in peatlands, hence mitigating the effects of greenhouse gases (Gorham, 1991).

Climate regulation: Bryophytes significantly influence the water cycle, manage microclimatic conditions, and contribute to the carbon cycle, all of which are crucial in addressing climate change (Turetsky, 2003).

International viewpoint: The ecosystem services provided by bryophytes have become increasingly vital due to the escalating effects of climate change. Nonetheless, the significance of these plants is inadequately highlighted in forestry and climate change policy. The conservation of bryophytes must be a strategic priority for ecosystem management and sustainability.

The ecological and climatic roles of bryophytes have significant promise for promoting ecosystem sustainability and addressing climate change. A more profound comprehension and application of the functions of this group of plants presents a significant potential to attain global environmental objectives.

Recommendations for Implementation

Strategies utilizing bryophytes provide economical, sustainable, and efficient options to address climate change. The subsequent proposals provide techniques for the more effective utilization of bryophytes in this challenge:

Conservation and restoration of peatlands:

Enhancing carbon sequestration zones: Peatlands are carbon-dense ecosystems characterized by a high prevalence of bryophytes. The conservation and restoration of these regions is a crucial method for enhancing their carbon sequestration potential (Turetsky, 2003).

Regulations pertaining to legal and managerial practices: Management plans and legislative rules must be established to safeguard peatlands from draining and overexploitation (Gorham, 1991).

Restoration initiatives utilizing bryophytes:

Bryophytes, due to their quick growth and water retention capabilities, serve as an excellent restoration tool for degraded areas such as post-mining sites, erosion-prone soils, and fire-damaged regions (Glime, 2007; Ursavaş, 2015).

Bryophytes facilitate ecosystem regeneration by establishing micro-habitats that promote the roots of additional plant species (Ursavaş, 2015).

Application in natural therapeutic approaches:

Carbon-neutral solutions: Bryophytes may serve as an economical technique for carbon sequestration. Advocating for bryophytes in non-agricultural regions and forest understory’s can enhance their carbon sequestration potential (Bates, 2000).

The water retention capabilities of bryophytes can be employed to establish microhabitats that mitigate water loss in arid environments (Proctor, 2000).

Environmental surveillance and educational initiatives:

Monitoring of air quality and environmental conditions: Bryophytes' sensitivity to environmental stressors serves as a biological indicator for assessing the effects of climate change and pollution (Gignac, 2001).

Programs for education based in the community: Educational initiatives must be established for local communities to enhance understanding regarding the significance of bryophytes in ecosystem health and their role in mitigating climate change.

Investigations and technological advancements:

Further investigation is warranted into the adaptive mechanisms of bryophytes, their genetic diversity, and their contributions to ecosystem services. This will facilitate the incorporation of bryophytes into climate change plans (Glime, 2007).

Artificial peatland systems designed to replicate carbon sequestration and hydrological management may enhance the utilization of bryophytes.

The gathering of bryophytes from Turkey's forest habitats is authorized under forestry regulations. Bryophytes have been gathered in varying quantities and at different dates from the Regional Directorates of Forestry in Adana, Antalya, Balıkesir, Bolu, Bursa, Çanakkale, Denizli, İstanbul, İzmir, Isparta, Kütahya, Kastamonu, Mersin, Muğla, Sinop, and Zonguldak. The bryophyte specimens gathered to know have been employed domestically. No international sales were conducted for business purposes (Ursavaş and Söyler, 2015). Annually, around 184 tons of bryophytes are harvested from Turkey's forest ecosystem for diverse applications, according to government data. The excessive extraction of bryophytes from the forest environment, conducted without proper inventory, will undoubtedly yield detrimental effects.

Bryophytes provide sustainable and efficient methods to address climate change. Their enhanced application in ecosystem management, restoration initiatives, and environmental monitoring can significantly contribute to climate policies at both local and global levels. Nevertheless, the diversity and ecological roles of bryophytes are presently significantly impacted by worldwide environmental changes.

The conservation of bryophytes in biodiversity-rich regions, like the Mediterranean, boreal forests, and alpine biomes, is essential for this plant group, as well as for carbon sequestration and ecological sustainability. The sensitivity of bryophytes to environmental alterations renders them indicators of climate change and integral to mitigation methods.

Investigating the physiological and ecological traits of bryophytes will facilitate their conservation and enhance their application in mitigating climate change. Bryophytes, characterized by their poikilohydric structure and remarkable flexibility, play a crucial role in ecosystem activities, providing significant solutions in rapidly changing environmental situations.

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Chapter 9

Skidding Roads for Opening-up of Managed Forest Stands

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General negative impacts such as climate change due to human population growth and human activities bring the importance and value of forest ecosystems to the forefront. Although the expectations of human beings to both protect and utilize forests create contradictions, it is essential to maintain the functions of forests by developing sustainable solutions. According to the principles of sustainable forestry, wood raw material production in forests managed with economic function and forestry operations for this purpose are already being carried out in the world and in Türkiye. Against the destructive effects of climate change, erosion and desertification, loss of biodiversity, etc., it is necessary to achieve bearable results by carrying out the interventions applied to forests in a planned and controlled manner. One of the forestry operations that have lasting impacts on the forest ecosystem is the construction of roads (which are dug and filled using various tools on the forest floor).

Forest roads constitute the main element of the transport infrastructure, especially in the optimal opening-up of forests managed with the production function. Forest roads designed and constructed in accordance with forest road network plans (primary and secondary forest roads for trucks) enable the transportation of forest products by trucks, but they alone are not sufficient to open forests for operation. The capacity of forest roads to opening-up forest areas for extraction depends on their spacing and density to penetrate into the forest and shorten the skidding distance. In general, forest roads such as valley, slope and ridge roads are used to opening-up forests for extraction, but in places where the skidding distance is very high, low-quality and low-cost roads and lanes that are not suitable for truck traffic but allow off-road vehicles to travel empty and loaded are used in order to carry out only the removal and thus open the stand or stands for extraction. Bringing the product harvested and processed in the stand to the roadside can be carried out by harvesting machinery such as tractors designed and manufactured to move on the land and/or by cable lines developed for this purposes.

In stands where forest road density is low, road spacing is high, skidding distance is long and skidding costs are high, tertiary skidding roads (spur roads or skidding/skid roads or logging roads) and/or tractors roads or skid trails, which have relatively low geometric characteristics and are simple to construct, can be used to avoid the construction and maintenance costs of forest roads and to reduce forest area loss due to road construction (Tavşanoğlu, 1971; Bayoğlu, 1996; Erdaş, 1997; Eker, 2020). These roads are constructed for the purpose of hauling (pulling the load partially or completely in contact with the ground) and/or transporting (loading the load completely onto a carrier and taking it away) the wood-based forest products in the stand to the nearest forest road by various vehicles.

Since the harvesting machines that can travel in the field and carry out transportation within the forest are heavy, expensive and have low speeds, their transportation costs per unit woody product are very high compared to truck transportation (Eker et al., 2024a). Therefore, it is necessary to reduce the skidding distances with these vehicles and reduce the total transportation costs to the optimal level by increasing the road density. However, the increase in the construction costs of forest roads, especially in mountainous terrain, depending on the slope and soil structure, does not allow the density of these roads to exceed certain limits in economic terms. In the face of this situation, forest road networks should be supported by roads with lower construction costs such as skidding roads in order to ensure that skidding machines can operate within economic distances on the one hand and to keep the total road construction and repair costs at an optimal level on the other hand (Erdaş et al., 2014). For this purpose, skidding roads that are suitable for the traffic of harvesting machines can be constructed by earthworks on the slope land in order for agricultural and forestry tractors, tractor trailers (forwarders), rubber-wheeled or tracked skidders and drag animals to be able to move and to carry out the extraction works (Eker, 2020).

In general, the functionality of skidding roads is centered on the application of an extraction technique that protects the stand and the product being hauled, reducing extraction costs, avoiding the hazards and risks of occupational accidents, even if indirectly, and ergonomically reducing the strain on forest workers. These facilities are often placed in the forest in a planned and organized manner for medium and long-term use. They are connected to forest roads such as valley, slope and ridge roads, or to tractor roads and each other to form a network of roads within the forest, thus improve opening-up capacity.

Despite their technical and economic importance in terms of opening up forests for extraction and carrying out skidding operations, skidding roads, like forest roads, have potential negative impacts on the forest ecosystem depending on the presence of roads per unit area. This is because secondary and tertiary roads for logging and transportation are directly linked to various negative ecological impacts, including forest fragmentation (Forman, 1995; Acar & Şentürk, 1996; Forman & Deblinger, 2000; Gucinski et al., 2001; Trombulak & Frisell, 2000; Alkan & Eker, 2005; Eker & Acar, 2005; Coffin, 2007; Eker et al., 2010; Eker & Çoban, 2010). During skidding operations, various damages occur on stands, soil and water resources (Görcelioğlu, 2004; Makineci et al., 2007; Akay et al., 2014). At the scale of landscape integrity, the most important ecological impact of the road network is the disruption of the landscape integrity process and structure (Harris et al., 1996). Roads within forests are recognized as an element of habitat fragmentation (Mader et al., 1990; Noss, 1995; Reed et al., 1996). The road network divides a large holistic landscape, leading to habitat fragmentation, area reduction and attrition (Forman, 1995). Therefore, special care should be taken in the design and construction of skidding road routes to ensure that stands are not damaged and remain in a condition suitable for nature. In principle, only vehicles capable of working in the field are expected to utilize drag roads. Stands with slopes higher than 50% slope are not economically and ecologically suitable for the construction and use of skidding roads. Likewise, slopes and terrains with landslides are very problematic terrains for skid roads. Therefore, skidding roads are more suitable for lands that do not pose difficulties in terms of construction technique.

Skidding roads are considered to be permanent facilities that are expected to serve the logging of forest products for a long time. This expectation implies that, depending on the age of stand development, skidding roads can be used for 2-3 maintenance and utilization interventions. However, the skidding roads' economics become more problematic the more expensive they are to build and the less forest products are taken out of the compartment. Skidding roads should therefore be planned and built with the following considerations: i) the terrain should be easy to create; ii) it should not be swampy or wet; and iii) it should be utilized as a retaining strip in regions that are accessible to tractors and for extraction purposes.

There have been increasing debates recently about how much skidding road should be constructed for the transport of forest products in a harvesting unit and how much road density can be kept. In the logging operations of wood-based forest products, skidding roads are becoming important in transport facilities due to logistical reasons such as increasing the use of machinery (agricultural tractors) and encouraging this (as required by legislation), the spread of industrial plantations, the increase in standing tree sales practices, facilitating transportation works and increasing the commissioning rate in parallel with the trends in the transportation of logging residue (Eker et al., 2010; Eker et al., 2011) and stump woods (Eker & Eryılmaz, 2023; Eker et al., 2024b).

Today, the increasing importance of forest areas and tree wealth within the scope of combating climate change requires sensitive behavior in all kinds of forestry practices due to their negative effects on the forest ecosystem. While dealing with forest transport facilities, it is seen that skidding roads are kept in the background in technical, economic and environmental evaluations. According to the current legislation, skidding roads are planned and implemented by making additions in the communiqués numbered 292 (GDF, 2008) and 310 (GDF, 2019). However, it is observed that the density of the skidding roads has increased excessively in terms of shortening the skidding distance, the technical rules are not sufficiently understood and there are implementation problems. In addition, both in theory and in practice, skidding roads are confused with tractor roads and skid trails (tracks), they are used interchangeably in nomenclature and sometimes cannot be distinguished from each other in proposals for solving transport problems and there is confusion in terms of the description of these facilities. When looking at the stand after harvest operations; tertiary roads, which are connected to forest roads and distributed on the slope terrain and supported the extraction capacity, and which are narrower and shorter than forest roads in terms of shape and are often seen as taut, can be characterized as skidding roads.

The lack of an good practice guideline compiling the procedures and principles of “skidding roads” in order to plan (design) and implement technically, economically and ecologically feasible skidding roads for the application of mechanization (agricultural and/or forestry tractors, skidders, forwarders, etc.) in the activities of wood extraction in mountainous and high slope (steep and very steep; slope is higher than 30%) forest land demonstrates that there is a deficiency on the subject. Despite the technical, economic and ecological status of skidding roads, it is acknowledged that they are not sufficiently understood by both theoreticians and practitioners in the field of forest engineering. In order to protect the forest ecosystem, prevent area loss, reduce erosion risks and prevent the destruction of vegetation, the amount and construction of skidding roads should be decided in a planned manner. In this context, it has become necessary to present the planning, construction, utilization and supervision conditions related to the terminological, geometric and implementation legislation related to skid roads. For this purpose, it is aimed to create a guideline. In order to support the elimination of the lack of information on this subject, this book chapter was needed. The aim of this study is; 1) to describe the roads, 2) to explain the general characteristics of skidding roads (general principles, planning principles, technical principles and construction principles) and 3) to evaluate the roads in terms of current conditions. In this context, the concepts of the roads have been identified, the technical principles have been determined and the proposals have developed on application procedures related to skidding roads that are considered necessary for the technical and economic extraction of wood-based forest products from the stands.

The object of this book chapter is the skidding roads (constructed in necessary cases and places) which are of tertiary importance in terms of the transport logistics of forest products. In order to create the section, first of all, the legislation on forest roads and wood harvesting in Türkiye were used as material and the directives on skidding and tractor roads were examined. A literature search on skidding roads was conducted and information on the definition, characteristics, principles and differences of skidding roads from other roads in forestry was compiled. By taking into account the potential ecological effects of skidding roads by using previous studies, the principles on planning and implementing skidding roads without damaging the forest ecosystem were tried to be reviewed. In order to determine the problems caused by skidding roads in practice, information was obtained from the relevant units in state forest administration and forest engineers through personal communication. With the help of literature, legislation and documentation on the subject, the general and technical characteristics of skidding roads were described theoretically. Then, an evaluation was made on skidding roads by considering the current and future trends on the subject (at the scale of Turkish forestry).

General Features of Skidding Roads

Skidding roads can be described as a typical forest road specific to mountain forests (Tavşanoğlu, 1971). Skidding roads are in-stand operation facilities that are separated from the forest roads in valleys, slopes or ridges suitable for all year round traffic of rubber-wheeled vehicles and enter interior of the stands, and are used by off-road skid vehicles, and are constructed at low costs, as well. Skidding roads are called as tertiary roads that are simple to build, inexpensive, and have low technical and geometric standards. The roads are used to opening-up the forest stands for logging, where the skidding vehicles are unable to move on the stand floor (raw ground or skid trail) due to topographical factors (slope, relief, bearing capacity of the ground, etc.). Skidding roads provide services for the collection of wood raw materials by various logging techniques and for extraction (skidding, pulling or forwarding) them with different skidding vehicles. Skidding roads differ from primary and secondary forest roads, tractor roads and skid trails in terms of function, construction site, and technical characteristics (Figure 1) (Eker, 2020).

Figure 1. Ground skiddding with an agricultural tractor on the skidding road

Skidding roads are constructed using simple earthwork in areas where it is not possible for operation of rubber-tired or wheeled logging machines, such as tractors, to move around. The most important factor that distinguishes a skidding road from skid trail is that skid trails should have certain marks where traffic can be operated, provided that there are no factors that would hinder the tractor's movement (extremely steep slope, rough surface, rocky-stony ground, swamp, tall and dense saplings, etc.) on the ground of the stand where skidding is done, and that the tractor has the opportunity to move in all directions within the field. After skidding roads are built on sloping terrain, forest road - skidding road – skid tail combinations can be applied (Figure 2) by using skid trails on flat, nearly flat and smooth relief parts of the same terrrain. The aim of constructing skidding roads is to guarantee that motorized skiding vehicles, particularly tractors, travel only on approved routes, preventing them from entering the forest floor and preventing the loss of forest area, and consequently yield.

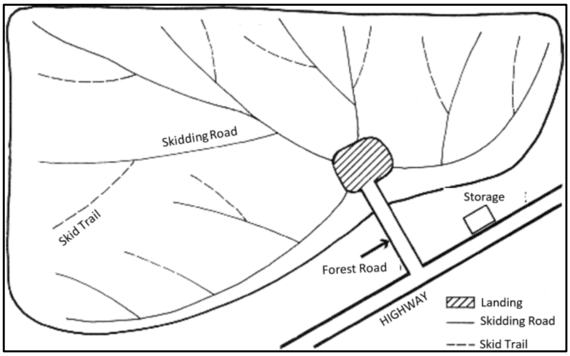

Figure 2. Combination of forest road, skid road and skid trail on slightly sloping terrain (-<30%)

Skid roads are planned and designed in a way that: i) is in stands that cannot be opened up with standard forest roads, ii) is connected to the existing forest road network, iii) is compatible with the topography of the stand terrain, iv) provides a very good level of opening up for logging, v) is on solid ground, and vi) is as tight and short as possible. Care is taken to ensure that the skidding road is compatible with the forest road network plan and, if any, the tractor road plan. Skidding roads are built to ensure that the product is skidded to the nearest standard road and/or landing in an economical, safe and aesthetic way in order to enable the use of various options such as uncontrolled gravity skidding, tractor cable pulling or short-distance sky line yarding with crane on slopes where it is not sufficient for opening-up the standard forest road for logging, the use of long distanced cable yarding is not possible or the skidding distance is too long. When determining skidding road routes, extra care is taken to ensure that the stands are not damaged and are kept in a natural state. Despite being permanent transportation facilities, skidding roads are carefully designed to be cost-effective (Bayoğlu, 1996).

As a rule, the skidding roads are only open to off-road vehicles. Vehicle traffic with heavy axle loads such as trucks etc. is not allowed on skid roads. Since skidding vehicles do not need to speed, they are built to low construction standards. Skidding roads are applied in areas where the terrain slope is between 30% and maximum 70% and the bearing capacity of the ground is moderate and good. Construction of skidding roads may be dangerous from an economic and environmental standpoint in areas with slopes greater than 50–60%. Slope lands with landslide potential are problematic areas in terms of the construction of skid roads (Bayoğlu, 1997; Erdaş et al., 2014).

In skidding roads built on slopes, considering that the extraction will be operated from the bottom up, the connection angle with the forest road and the area to be opened for logging are designed accordingly. Therefore, skidding roads are designed to ascend in the direction of descending forest roads descend while connecting to forest roads, avoiding double opening-up regions (Erdaş et al., 2014).

Planning Principles

At the planning unit (forest management unit), forest road network plans (for secondary transport) are made for opening-up forests. Facilities related to primary transport or extraction (skid road, tractor road, cable yarding, and cable traction lines, etc.) should be made after the forest road network plans and in an integrated manner with these plans.

Skidding roads may not have to be shown on the forest road network plan/map. However, in today's world where digital forestry is widespread, it is necessary to design skidding roads or transfer manufactured roads to the plan on forest information systems (ORBIS as in Türkiye) or database management systems. Because for the planning of harvest operations to be carried out in micro-scale areas such as compartments/sub-compartments (selection of the most appropriate logging method), a planning sketch should be prepared to see at least the connection of skidding roads to the forest road and openin-up zones in a stand. Considering the widespread use of digital maps and the availability of databases, a large-scale (1/5000 or larger) site plan should be prepared by manipulating 1/25000 scale base maps and showing the routes of skidding roads and their connections with forest roads. Considering the permanence of skidding roads in terms of short and medium term use, it is concluded that this process is necessary.

When planning and constructing skid roads, it should be ensured that they pass through land pieces (no rocky, steep, wet, swampy, etc. land) where construction costs will be low, skidding vehicles can operate profitably, and that will not cause problems in terms of construction technique. Care should be taken to ensure that these roads are as economical as possible in order to solve the problem of opening-up the stands.

Skidding roads should be connected to a forest road at least at one end. In skidding road that cannot be connected to a forest road at both ends, a good turning place should be planned and implemented at the remaining end.

It should not be forgotten that skidding roads built on slopes will play a very positive role in removing forest products from the bottom of the slope by pulling them upwards with a tractor winch, and the connection angle with the forest road and the area of opening to operation should be designed accordingly. Skidding roads are typically built diagonally on steep slopes and vertically on flat or uneven terrain. The route of skidding roads can generally be designed in two ways, depending on the condition of the forest roads on the field (Bayoğlu, 1988):

1. In case the forest roads have very low slopes and/or run parallel to the contour lines (probably in this kind of terrain, the slope gradient may be between 25-40%); skid roads can be planned and implemented with high gradients and diagonal the forest roads (Figure 3a).
2. In places where the slope of forest roads is high (the slope of the land is probably also high; above 40%), skiding road are designed to run parallel to the contour lines with a low slope (Figure 3b). The most negative aspects of parallel skidding road can be listed as the one-sided connection of the skid roads to the forest road, being lengthy, having the drainage problem of

rainwater and the inability to prevent the formation of wheel tracks on sensitive ground.

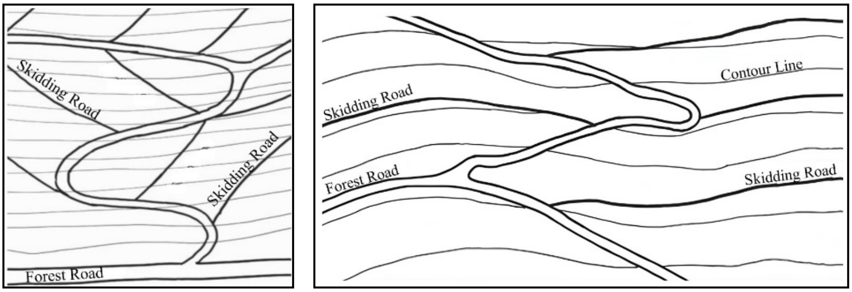

Figure 3. (a) Diagonal skidding road on low slope terrain (left); (b) Parallel skidding road on high slope terrain(right)

When planning skid roads, a route that will create a straight cross-section as much as possible should be selected in order to ensure a smooth traffic flow (in terms of skidding vehicles). However, in economical and technical terms, both vertical (reverse slope) and horizontal curves can be planned and implemented in places where negative cardinal (compulsory) points such as forest road connection points, dry stream beds, slopes, etc. must be crossed. In this case, it should not be forgotten that the harvesting method (cut-to-length, whole tree, whole trunk (Erdaş et al., 2014)) is a determining factor. Since skidding roads are skid facilities that are well adapted to the terrain or have been installed, the number of curves can increase and sometimes they can include small radius curves. In general, the radius of horizontal curves can be reduced to 8 m by considering the length and quality of the skidding vehicle, the length of the product to be skidded or carried, the location of the road, etc.

Technical Characteristics

Slope

In terms of facility types, the longitudinal slope of skidding roads that are parallel to contour lines should be at least more than 3%. In places with high rainfall capacity, intense surface water movement and wet road ground, the slope of skid road should be at least 3-5%. If it will reduce construction costs when skidding roads are applied, breaks and reverse slopes can be allowed. The reverse slope should not be more than 10%. The slope of skidding roads should not be more than 15% in fine-grained soils that are very sensitive to erosion. Longitudinal slopes of skidding roads can be increased up to 25% in skeletal and permeable soils that are resistant to erosion. In rocky and durable soils, the longitudinal slope of skidding roads can be increased above 25% (depending on the technical capacity of the skidding vehicle and the direction of skidding).

Surface water flow can be controlled by giving a 3-4% transverse slope towards the valley direction on skidding roads. However, during skidding, the possibility of the logs sliding in this direction due to the given transverse slope creates a safety problem. Therefore, skidding road platforms/surfaces that are already given a longitudinal slope can provide a safe skidding opportunity. The most commonly applied skidding road shape against the drainage problem is the shape where the cross section is flat or the slope towards the valley side is kept as low as 1-2%.

Width

The width of skidding road depends on the slope, type of soil, amount of precipitation, the kind of terrain, and width of skidding vehicles. The width of skidding road should be at least 2.5 m. In erosion-resistant soils, it may be more appropriate to take the skidding road width as 3 m. Considering the possibility of using some special and wide-axle vehicles (forwarders, special forest tractors/skidders), skid road width can be increased to 3.5 m in stands with solid ground. In erosion-sensitive soils, it may be appropriate to built an embankment on the platform of skidding road towards the filling side to prevent erosion.

Road platfom (surface)

In the construction of skidding road, it is sufficient to cut down the trees on the skid path route and level the ground (with the construction vehicles) in a way that is suitable for the movement of skidding machines such as tractors, skidders, and etc. In steep terrains, for safety reasons, the cross-section of the skidding road should be completely included in the excavation side. In rugged terrains, the cross-section should be of a mixed profile type that includes balanced excavation and filling. Here, the width of the excavation profile should be taken as the width of the building machine to be used for excavation.

The majority section of the road platform must be constructed on solid ground (on the excavation side). No stabilization material is laid on the road surface/platform and no mechanical compression is applied. Skidding road do not contain a superstructure. They are left as a dirt road facility within the stand. On the raw dirt road surface, in order to prevent drainage problems, slits (open speed bumps) can be made every 40-50 meters to ensure the drainage of water down the slope.

Road length

Within a stand opened up with the support of skidding roads, the length of the skid road is determined by local (site-specific) conditions such as; i) forest road density, ii) the opening-up area and ratio of the skidding road, iii) the amount of forest product to be harvested and transported, iv) the construction costs of both secondary forest roads and skid roads, v) the shape of the stand, and vi) the ground stability of the terrain. However, in general, it may be appropriate to use a scale as listed below:

- In places where forest road construction costs are low and forest roads are dense (25-35 m/ha), the length of the skid road can be up to 300 m.
- In areas where forest road construction costs are moderate and forest road density is also moderate (15-25 m/ha), the length of the skid road can be up to 500 m.
- In places where forest road construction costs are very high and forest road density is very low (- <10 m/ha), the length of the skidding road can be increased up to 800 m.
- Instead of skidding roads that can be longer than 800 m, either a standard forest road should be built or a combination of forest road and long-distanced mobile skyline should be considered. In places where forest road construction costs are very high and forest road density is very low, if there is no skyline in the enterprises, a skidding road longer than 800 m can be considered as a last solution.

Road density and spacing

If construction of a skidding road is unavoidable for opening-up of a forest stand, the density and spacing of the skidding road is vary depending on the some factors. These are standard forest road density and spacing, the productivity of the forest stand, road construction costs, annual allowable yield, terrain conditions, skid road construction area, average terrain slope, etc. In soils with good permeability and not sensitive to water, since the construction area is good and there is no difficulty in terms of skid road construction technique, the road density may be high in this stands. In soils with high clay content, fine grained, loose stones, since the construction area is weak and difficulties in terms of construction technique arise, the skid road density may be low and the road spacing may be high here. The distance between the skidding roads can be estimated using Table 1.

Table 1. Distances Between Skidding Roads (Bayoğlu, 1996)

Terrain Slope	Maximum Skidding Distance (m)			Oblique Distance Between Skidding Roads (m)	
	Tractor Cable Line		Sliding with Gravity	Maximum Value	Suggested Value
	Upwards	Downwards			
- < 40 %	100	50	-	150	100-120
- > 40 % (sliding not possible)	100	30	-	130	100-120
- > 40 % (sliding possible)	100	-	150	250	150-200

In mountainously forest terrain, skidding roads can open the stand sections above and below their location for logging operation. For skidding the wood products on the upper parts of the skid roads, either manual and uncontrolled sliding with gravity or ground pulling with a tractor winch or cable yarding with an skyline can be used. For pulling the products on the lower slopes to the skid path, a tractor winch with cable or skyline is also used. Therefore, the logging technique from the compartment/stand is the determining factor for skidding road spacing. In mountainous terrain, depending on the characteristics of the stand characteristics, skidding road density can be increased up to 100 m/ha together with the existing forest road density (Bayoğlu, 1996).

Construction Principles

After the reconnaissance made from the ground or air (digital map, satellite imagery or images from unmanned aerial vehicles (Durgun et al., 2022) for planning, application or site plan, the trees on the route of skid road should be cut and the obtained assets should be kept in a safe place of the field until the skidding road is built. Thus, the skidding road construction (excavation) area should be kept clean. While the trees to be cut for the construction of the skid roads to be made in the stands where the clearcutting will be applied do not cause any problems, a route that will cause very little damage to the vegetation should be followed for tending and thinning operations.

During the construction of skidding roads, care should be taken to open them as narrowly as possible, and to built them parallel to the snow and wind effects, not perpendicularly. The stumps of trees cut on the excavation side should be left slightly high. This should also be considered as a barrier against sudden trunk falls from above. Skidding paths should be constructed approximately one year before their first use. In this way, the natural stability of both the forest and the excavation and filling sides are ensured.

In mountainous terrain, skidding roads should be constructed using excavators, mini excavators, backhoes (tractors with a front shovel and a rear hydraulic digger arm) or tractor blades. Bulldozers should not be used for skid road construction on sloped terrain as much as possible. In addition to ensuring the balance of excavation and filling during construction, it should be clarified where the excavation and filling will be provided. The filling material should not be allowed to roll down and destroy the stand. During construction, the excavation machine should be operated from top to bottom. In this way, the excavation machine will work more efficiently.

In the case of skidding with tractors standing on the road to perform cable pulling from the bottom of the slope or rarely from the upper slope, it should be ensured the cable pulling lines are made from dry water bed for avoiding disruptions in the cutslope or the sidecast fill.

Guidelines for Skidding Roads

Skidding roads, which are constructed to assist in the removal of forest products from the stand in a way that will be connected to forest roads, are supporting facilities that provide solutions for the realization of transport operations and silvicultural activities in the compartment where the existing logging techniques cannot be applied. Skidding roads are designed in accordance with the natural structure of the stand terrain and can generally be used by tractors or special skidding machines, harvesting machines (such as harvesters) and other off-road vehicles (Figure 4).

Figure 4. Forwarding with grapple loader on skidding road

Skidding roads can prevent tractors or other off-road vehicles from moving randomly on the forest floor, thus preventing soil erosion and water erosion and protecting the land. They are constructed at a lower cost than standard forest roads and help reduce operating costs. If principles such as length, width and density are taken into account, they can relatively preserve the natural structure of the forest and enable harvest and transport operations.

Skidding road are distinguished from tractor roads and skid trails in terms of their technical features such as construction sites and routes, construction techniques, opening-up areas, ecological effects, etc. In practice tractor roads and skidding roads can be used interchangeably, and there is a similarity in terms of the vehicles that will move on both road types. Until recent years, skidding roads and tractor roads were addressed in different legislations in Türkiye and managed by different units of the state forestry administration. While tractor roads are included in the legislation related to primary and secondary forest roads ((Communiqué No. 292 (GDF, 2008)), skidding roads are included in the legislation related to wood harvesting (Communiqué No. 288 (GDF, 1996) and Communiqué No. 310 (GDF, 2019)). According to the current legislation (Communiqué No. 310), GDF encourages the active use of agricultural tractors in the wood extraction from compartments and the use of tractors as a scale in determining the logging costs. This situation requires the profitable use of tractors in the forest. However, it is not technically possible for tractors to move in every direction on the forest floor and it causes ecological damage. There is a need for a tractor movement route that will reduce forest area losses, soil compaction and erosion risks. Therefore, either skid trails should be determined on the forest floor or skidding roads should be built. Because building of tractor roads according to the Communiqué No. 292 cannot play a role in opening up of the whole stand and require a planning procedure. Since this situation creates a unique procedure, in practice, tractor road construction is mostly avoided and unplanned or irregular skidding roads are tried to be built in order to carry out the work of removing from the stand. However, skidding roads were included in the classification of roads without technical/geometric qualities in the circular regarding harvestin works. It is seen that the construction of skidding roads without permission, in a random and unplanned manner, causes an increase in the road density within the stand, an increase in the loss of forest area, an increase in the surface area where the mineral soil is exposed and becomes susceptible to erosion, and soil compaction due to the trips made along random routes (Makineci et al.,2007). Therefore, in recent times (today), the need to build skidding roads only in places where it is considered necessary, the necessity of doing it with machinery and the fact that this requires road construction techniques, have been included in the legislation on forest roads (Communiqué No. 292). As can be seen, since commonality has been achieved in terms of legislation, and both skidding and tractor roads are used for similar purposes and vehicles. It would be appropriate to use a single term (either skidding road or tractor road) for tertiary roads in order to change the terminology over time and to prevent confusion. When looking at the reasons for the movement of tractors within the stand; the purpose of removing forest products from the stand is more dominant. In other words, in professional terms, tractor roads are built for the purpose of being used in skidding activities. Therefore, it seems more logical to call tractor roads as skidding roads.

Accordingly, it may be appropriate to call the transport facilities as “skidding road” that i) enable the forest products accumulated in streams and on slopes to be carried to landing or roadsides in cases where secondary forest road density is not sufficient and/or skidding distance cannot be shortened, ii) can be built on streams, slopes or ridges, iii) are around 300-500 m in length under normal conditions but can be up to 800-1000 m in length, iv) are suitable for the traffic of tractors or similar vehicles by leveling the ground without requiring any superstructure and are suitable for long-term use (permanent). However, it cannot be said that a mistake would be made if this described road was called a tractor road. It is understood that the planning procedure prepared in accordance with the legislation for tractor roads (GDF, 2008) may actually be valid for skidding roads. Therefore, it may be possible to eliminate the conceptual confusion that has taken place in practice with a simple change in legislation and to determine the construction methods of skidding roads. In this context, it will be possible to regulate the construction and use of such roads in places where mechanized work is possible by eliminating the terminological, geometric, legislative and application differences between tractor and skidding roads.

However, it should not be ignored that there may be significant differences in the technical features of these types of tertiary roads, whether they are called tractor roads or skidding roads, depending on where they are built. In cases where the problem of wood extraction from a stand cannot be solved even with mechanization and mostly in streams, it is recommended to build tractor roads. In practice, tractor roads are mostly encountered in dry stream beds, along the neck lines where neighboring slopes intersect (Figure 5).

Figure 5. Tractor road in dry stream bed with slope intersection lines

On the other hand, both skidding road and tractor road are distinctly different from skidding roads. For example, in a harvesting unit where the logs will be removed from the stand by ground skidding with tractor; it can be followed the forest road, skidding and/or tractor road and skid trail, respectively, during the process of the tractor reaching the harvested logs (Figure 6).

Figure 6. A view of the secondary forest road, skid roads and skid trails together on a stand

It has been observed that some problems have arisen regarding the skid roads that have been built with the widespread use of tractors in extraction, after 2019. These are;

1. It is reported that more skidding roads and tractor roads are built within a stand than technically necessary, that the budget for skidding and tractor road construction demands for the coming years has also increased, and that applications are made in a way that is more than necessary and beyond the

purpose (Personal communication: S. Cilan; M. Aktaş; E. Öztürk). However, skid roads are not facilities that need to be built in every stand, but are tertiary level support facilities that need to be built only in places where they are needed and in proportion to the needs.

2. In making decisions on whether to build a skid road or not, the economics of extraction from the compartment (shortening the skidding distance and reducing skidding costs) are taken into consideration rather than bio-technical requirements and examination, and excessive skid roads are built in some compartments, as can be understood from the increase in skid road density when looking at satellite images (Eker, 2020).
3. It is seen that there are disagreements among the forest engineers about the amount, density and spacing of skidding roads. The skidding road length given in the legislation (instructed in addition to the main legislation) (for example, 500 m) is perceived as the length of skid road that can be built in the entire stand. Although the length of each skidding road (as a segment) within the stand varies according to the stand topography and the opening-up area, it may be appropriate not to exceed 300 m in terms of preventing both loss of area and erosion and landslide risks in stands with low site quality. Because the density of forest roads in Türkiye is increasing, skid distance is shortening, and there have been decreases in the sizes of the compartment areas and the amount of areas to be harvested at one time according to functional forest management plans. Therefore, it may be possible to keep skidding road lengths short. In this way, reverse slope, curve construction and excessive soil work are avoided.
4. Whether or not a skidding road is needed should not depend on the demands and initiatives of forest product traders, loggers, harvest workers, customers or owners of transport trucks. Especially in sales types where the standing sales method is applied, the customer or contractor who receives the products wants the length and density of skid roads to be increased in order to speed up the work, reduce logging costs and leave the field with less labor and days. Because transportation trucks are also tried to enter the forest via skidding roads. In order to prevent such arbitrariness, whether or not a skid road can be built in the stand, the possible route and length should be clearly stated before sales and/or harvest operations.
5. Similarly, it is reported that the skidding roads are built in the desired places and with the available machinery within the framework of arbitrariness. It is possible to see that the skidding road routes are not built according to certain technical principles and that excessively wide skid roads are built (Eker, 2020;

Durgun et al., 2024). Because the use of irregular excavation machines (heavy and wide track-open excavators used in mining) and the construction of skid roads by operators who are uninformed and inexperienced in road construction in the forest, wider, unbalanced and unstable skid roads are encountered. It should be noted that these types of skidding roads have a potential for negative ecological effects.

6. It is learned that in the stands where harvesting is made in the standing sales method, buyers have their skidding roads built as they wish in order to make their jobs easier, the above-mentioned sensitivities are not taken into consideration and the administration exhibits and permits approaches that will lead to the destruction of the forest cover, loss of area and erosion without sufficient research and examination on the need. In addition, it is stated that it is mostly encountered in the stands where standing tree sales are made, and that after the tree is cut, the products extracted as whole trees are desired to be skidded to the roadside without breaking the bole using powerful agricultural tractors, and skidding roads are needed to do this. Rather than the ecological, technical and economic advantages and disadvantages, a high density of forest roads or skidding roads is required for the application of this logging technique. This shows that skidding roads will have negative consequences.
7. However, as a result of the construction of skidding roads on random routes, without organization and coordination, the material flowing down the slope and the rolling stones during the creation of the filling slopes increase the risk of work accidents for the production workers working in the stand.
8. On the other hand, if unnecessary or excessive skidding road are allowed to be built in harvesting areas, it becomes difficult for the administrative staff to control these activities from an institutional perspective. In particular, it becomes difficult to control the technical characteristics of skidding roads such as incorrect or inconsistent skid road routes, longer and wider road than designed, etc.

Skidding roads are temporary and auxiliary medium-term facilities that will enable the removal of wood raw materials from the stands where the slope of the land, the ground structure area and the ground bearing capacity in terms of construction technique are suitable within the forest and at the compartment scale. The skidding roads are not suitable for transportation by truck, which described as long-distance transportation and main transportation. Skidding roads, like other interventions applied to forests, cause ecological effects such as loss of habitat area, soil compaction, increase in surface area susceptible to erosion, change in water flow regime on the slope, etc.

For these reasons, special attention should be paid to i) not building skid roads unless necessary, ii) not building skid roads for every stand, iii) keeping skid roads short, considering that skid roads can be preferred as an alternative solution in stands that cannot be opening-up with standard forest roads, iv) building them narrow, and v) keeping low road densities.

As a result, in order to eliminate the conceptual confusion in practice and to gather the principles and procedures in a single concept, especially in order to benefit from mechanization opportunities, it is possible to use only "skidding road" instead of tractor road and skid trail. However, if the disadvantages of the legislative change are put forward, the same road can also be called tractor road. The important issue here is how the geometric features of these road will be, how the length limit and construction principles will be determined. Because, in harvesting activities carried out with both traditional and standing tree sales (especially in sales extending to future years), it has been observed that scattered and dense skid roads are built since no planning and sketching is taken as a basis in skid roads built with verbal permissions of forest administrations.

These roads were made suitable for truck traffic and used in the form of secondary forest roads. It is also known that the projected road density has been reached two or three times. While the actual skidding distance has been shortened, the amount of lost forest area has increased. Because it is possible to create excavation slopes by side cutting by soil work on such roads. In this case, it is clear that such roads have been made suitable for perennial use. Due to both erosion, soil compaction and area loss, such practices cannot and should not be approved. In that case the state forest administration or forest engineers must plan the roads to be described as skidding or tractor roads or have them planned through commitment. The labor force and mechanization capabilities of the forest villagers or loggers who will do the harvesting work, harvest costs and environmental effects at the compartment scale should be taken into consideration and it should be decided whether skidding roads are necessary or not, if necessary, road length, road density, route on the field and construction technique.

In this context, the following suggestions can be made regarding the skidding road routes that are currently on the agenda both theoretically and practically. These are;

- In harvesting areas that cannot be opening-up properly with the standard type forest road network built within the scope of plans and programs and where the rate of opening-up cannot be increased above 70%, in cases where extraction cannot be achieved with mechanization possibilities and other measures in addition to the existing standard road network, then skidding roads should be preferred.

- In the sections where it is necessary to build, skid roads should be applied in places where the land structure is not too broken in terms of construction technique, where road construction can be executed with simple leveling and where the bearing capacity of the ground is suitable.
- Particular attention should be paid to the functionality, safety and aesthetics of the skidding road. In this context, traffic safety and occupational health and safety issues should be taken into consideration. Skidding roads built for tractors or similar skidding vehicles are also intended to be open to the traffic of heavy-tonnage log trucks. For this purpose, road widths, surfaces and slopes are tried to be adapted to be suitable for truck traffic. Therefore, risks that may arise in terms of occupational health and safety for loading work, loading vehicles, workers, trucks and transportation work on the skid road should be avoided.
- The maximum width of the skidding roads should not exceed 3 m. According to the information received by the state forest administration; if high-tonnage excavators with a wide track width are used both in skidding road construction and as loader, the maximum permitted skid road width of 3 m can be exceeded by considering the establishment of landing for loading operations. Considering that skidding roads cannot be opened to truck traffic, vehicles that comply with skid road standards should be preferred both as construction machinery and as loaders.
- Considering the standard forest road density, road spacing, opening-up area and ratio, skidding distance, shape of the compartment, location of the standard forest road in the compartment, cable pulling distance with the tractor, movement distance with the tractor on the ground, 40 m/ha can be accepted as the optimal density value based on unit area in compartments with average product yield for the total length of skidding roads and/or tractor roads that are the basis for extraction.
- Since machine skidding is foreseen as the skidding method for slopes of 40% and below and this method is taken into account in unit price calculations, skidding roads should be constructed up to a maximum of 250 m within a stand. In other words, the length of each skidding road segment should not exceed 250 m. Construction of road elements such as reverse slopes and curves should be avoided as much as possible.

- In areas where manual skidding is used as a method in accordance with Communiqué No. 310 in slope groups of 41% and above, skidding roads should be constructed as an exceptional solution to reduce the damage to the forest ecosystem, and the length of each skidding road should not exceed 250 m.
- When designing skidding and tractor roads, it should be taken into account that they are not transportation roads, but simple structures that will serve to perform the skidding function with a winch and cable system attached to the tractor used in skidding in case of mechanized logging.
- It should be ensured that the construction of skidding roads and tractor roads is built up with machinery and equipment belonging to the state forest administrations.
- Skidding and tractor roads should be designed within a plan and project and connected to the forest road network plan, and the necessity of construction and the function it will fulfill after construction should be clearly reported.

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Mehmet EKER

Chapter 10

Analysis of FSC Certification Principles Based on Degree of Difficulty: Multi-Criteria Decision Making with AHP

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Today, increased access to information and the widespread use of technology, especially the internet, have led companies to become more transparent to the public and their stakeholders. While this has had positive effects by increasing product, service and brand awareness, it has also led to closer scrutiny of their practices (Auld et al., 2008). While this transparency makes companies more accountable in environmental and social responsibility issues, certification programs stand out as an effective mechanism in shaping environmentally sensitive production and consumption patterns (Rex & Baumann, 2007). Humphreys (2006) notes that certification mechanisms that attempt to provide solutions to illegal logging and other forest management problems may be insufficient to achieve the environmental and social goals to which they are committed. Nevertheless, these mechanisms have attracted attention, especially voluntary environmental labels and certificates (Chappin et al., 2015; Baykalı & Şen, 2024).

NGOs and international organizations have established independent certification standards to encourage companies and landowners to practice responsible management (Cashore et al., 2003). These standards have had various impacts on the market by mobilizing companies for environmental and social responsibility. For example, programs such as ISO 14001, FSC and PEFC are widely used to improve sustainable forest management and environmental performance (Dendler, 2014; Vermeulen & Kok, 2012). However, the effective implementation of these systems entails significant costs and technical capacity requirements (Dias et al., 2015).

Forest certification has brought environmental and social benefits to the forefront in the relationship between companies and local communities (Şen, 2022). Romero et al. (2013) argue that FSC certification has impacts across multiple dimensions, such as the protection of forest ecosystems and the involvement of local communities. However, more research needs to be done on the costs, implementation challenges, and relevance of this certification to local conditions (Lehtonen & von Stedingk, 2016). For example, in implementing green strategies in the building sector, certification schemes often face high initial costs, although the long-term benefits of energy and water savings can offset the costs (Chang, 2011).

Green marketing and environmental labeling have been developed to increase the impact of certification systems (Rex & Baumann, 2007; Şen et al., 2019; Güngör & Şen, 2021). However, Yenipazarlı (2015) emphasizes that the presence of a large number of different labels in the market may have negative effects on the consumer credibility and legitimacy of these certification systems. O'Brien and Teisl (2004) state that environmental certification is used as a corporate strategy for companies, increasing market demand. Maroto et al. (2013) show that forest certification in the Mediterranean region plays a critical role in achieving various sustainable development goals such as tourism and renewable energy.

This study aims to analyze the degree of difficulty in implementing FSC certification based on expert opinions in the provinces of Amasya, Antalya and Muğla. Using Analytic Hierarchy Process (AHP) methodology, the impacts of this certification system on environmental, social and economic dimensions were evaluated. The research aims to contribute to the improvement of certification practices by filling knowledge gaps in the existing literature. In this context, the study consists of five main sections: theoretical background, methodology, findings, discussion and conclusions.

Forest Certificate

It is easy for businesses to see the impacts from social and environmental issues in their economic output. Therefore, many businesses not only fulfill the requirements of the law, but make a stronger commitment through voluntary actions. Such practices offer a variety of benefits, such as reducing production costs, increasing sales, adding value to products and increasing benefits overall.

Consumers' preference for products produced by environmentally conscious businesses gives companies that adopt sustainable practices a significant competitive advantage. In particular, the demand for forest certification increases the interest of businesses in this process. In this context, private sector policies include public awareness campaigns, information sharing and direct investments in forest sustainability. One of the most effective ways to promote sustainable forest management is to demonstrate the commitment of businesses to a forest certification (Cubbage et al. 2007; McGinley and Cubbage 2011; Vidal et al. 2005).

Forest certification is a mechanism that promotes "good forest management" practices and aims to ensure the sustainability of forests. Although the Americas have large forest areas and large producers and consumers (especially Canada and the US), less than 5% of these areas are certified (Basso et al. 2018).

Bratt et al. (2011) stated that the main objective of forest certification is to identify products from certified and monitored sources. The certification process involves adopting good practices in the managed forest area and obtaining the management forest certificate. Chain of custody certification is then carried out, which verifies that all certified materials in the supply chain are monitored and separated from uncertified or uncontrolled materials (Alves 2016).

Certification systems aim to promote the sustainable use of forests in environmental, economic and social terms (Bowyer 2008; Hansen et al. 2006; Almansouri et al., 2020; Güneş Şen, 2023). The two most widely used systems in the world are the Forest Stewardship Council (FSC) and the Programme for the Endorsement of Forest Certification (PEFC), both of which are based on principles and criteria that include social, environmental and economic aspects (Güneş Şen & Aydın, 2024).

Rametsteiner and Simula (2003) stated that forest certification is a tool used to promote sustainable forest management. This tool is in line with criteria and indicators for sustainable forest management (SFM). Criteria and indicators developed at the national level provide a basic reference for identifying and monitoring status and trends in forest management. They are also used as a basis for setting certification standards.

The methodology is organized under three headings. First, the Analytic Hierarchy Process (AHP) is described; second, the decision tree of the forest certification implementation is presented, as well as the operational instructions and the data collection tool. Third, the sample obtained in this study is presented.

Analytic Hierarchy Process (AHP) and Forest Certification: Application and Theoretical Framework

This study examines the application of the Analytic Hierarchy Process (AHP) method based on a questionnaire survey of Turkish Forestry Regional

Directorates and FSC (Forest Stewardship Council) certification experts. AHP is a method developed to address the complexity of decision-making processes and is used in this study to identify the priorities of decision-makers in sustainable forest management and certification. AHP is widely preferred because of its simplicity and efficiency in analyzing complex problems. This methodology offers the ability to calculate the relative importance of each criterion by systematically evaluating various decision criteria (Saaty, 1980).

Definition and Basic Principles of AHP Method

AHP is a method developed by Thomas L. Saaty in the 1970s that proposes solutions to multi-criteria decision making (MCDM) problems. AHP allows complex decision problems to be decomposed into more manageable sub-problems and each sub-problem to be compared. In this process, each decision criterion is ranked in a hierarchical order and the relative importance of these criteria is determined. Saaty (2012) defines AHP as "a method that provides structure to complex decision problems, making the solution more understandable". This process allows decision makers to reveal their preferences with both numerical and quantitative data, and in the later stages, it allows predictions to be made about future outcomes with the data obtained.

AHP is based on the construction of a decision tree and the relationships between each decision criterion and the alternatives are determined by pairwise comparisons. In this way, the decision maker can express the relative importance between both elements and the results can be summarized at a numerical level to create a synthesis. According to Saaty (2001), the basic components of the AHP method are the creation of a decision hierarchy and comparisons between criteria in line with this hierarchy. These comparisons are usually made on a scale from 1 to 9, and the importance of each criterion is determined relative to the others.

Forest Certification and the Role of AHP

Forest certification is a mechanism for ensuring the sustainable management of forests. Systems such as FSC and PEFC audit the environmental, social and economic dimensions of forest management and assess whether certain standards are met in these dimensions. Forest certification therefore plays an important role in the marketing of forest products. Certification is an internationally recognized standard for protecting the ecosystem services and biodiversity of forests (Bowyer, 2008).

Forest management requires an approach that adopts sustainability principles and makes decisions based on these principles. In this context, AHP is a powerful tool that helps decision makers to determine which option is more appropriate, where different criteria and alternatives are evaluated together. AHP is a very effective method in forest certification as it enables a large number of factors to be effectively analyzed and ranked relative to each other (Vaidya & Kumar, 2006). Since sustainable management of forests involves not only environmental factors but also social and economic factors, the ability of AHP to evaluate each factor independently increases the accuracy and validity of forest certification.

Using AHP for Sustainable Forest Management

AHP is also frequently used in the development of sustainable forest management strategies in the forestry sector. In a study using AHP, the analysis of the importance of environmental and economic factors in forest management in the evaluation of sustainable strategies shows how useful AHP is in such multi-criteria decision problems (Wolfslehner et al., 2005). AHP also helps to evaluate the long-term effects of each strategy by providing decision-makers with a range of options for balancing the criteria. In this context, AHP stands out as an effective method for making complex decisions in forest management in a more transparent and understandable way (Güngör & Şen, 2024).

Diaz-Balteiro and Romero (2008) also emphasized the advantages of AHP for the application of multi-criteria analysis in forest management decisions. In the study, the analysis using AHP revealed the importance of developing different multi-criteria analysis methods to better understand and extend the concept of forest sustainability. The authors concluded that AHP is a highly appropriate tool for addressing a wide range of issues in forest management, but forest sustainability needs to be considered in a broader context.

The Importance of AHP in Evaluating Social, Environmental and Economic Criteria

For AHP to be used successfully, it is important to construct a decision tree that combines social, environmental and economic factors (Saaty, 1977). This decision tree determines the relationship of each criterion to the other criteria and reveals the extent to which the decision maker should consider each factor. This method takes into account the ecological, economic and social values of forests when determining the relative importance of each criterion in forest management.

For example, Bousson (2001) describes the use of AHP in forest management as an approach that allows for the harmonized consideration of environmental, social and economic dimensions. AHP allows decision-makers to assess the importance of each factor at different levels and thus allows for more holistic and sustainable management strategies.

AHP is a highly effective method for forest certification and sustainable forest management. This methodology, in which environmental, social and economic aspects of forests are evaluated together, allows decision makers to make more informed and transparent decisions. This methodology helps to make more accurate, objective and systematic decisions in forest management and certification processes. The advantages offered by AHP are an important tool to increase the effectiveness of forest certification and ensure sustainable forest management (Şen & Güngör, 2018; Güngör & Şen, 2024).

Forest Certification and Applications in Turkey

Forest certification is the certification of a product, service, management style or personnel as a result of an independent third party's audit of compliance with established standards (Türkoğlu & Tolunay, 2013). Forest certification is applied to encourage better management of forests by building a bridge between environmentally conscious consumers and producers practicing sustainable forest management and to make forestry activities in line with the principles of sustainable development (Geray, 1999; Durusoy et al., 2002; Kuvan & Yıldırım, 2008; Şen & Genç, 2018; Aydın, et al., 2018; Şen & Güngör, 2019, Şen, 2021). Certification ensures that forest products are inspected at every stage from the first source to the final consumer (Salim et al., 1997; Akyol, 2010). This system aims to prevent the market supply of products obtained from forests that are illegal or poorly managed in ecological, economic and social terms.

Certification in forestry consists of two stages: Forest management certification (FM) and forest products certification (CoC - Chain of Custody). The first stage involves an audit of whether forests comply with the principles and indicators set for sustainable management. As a result of this audit, the forest is given a "Forest Management" certificate (Yadav, 2016). The second stage is the audit of the process of forest products from the point of harvest to retail sale. At this stage, the "Chain of Custody Certificate" (CoC) is issued by verifying that forest products are obtained from sustainable forests (Tolunay & Türkoğlu, 2014; Yıldırım et al., 2016). Certified products are kept under control throughout the entire process to support sustainable forest management (Akyol & Yıldız, 2018).

In the 1980s, the concept of forest certification emerged and many certification programs were developed. The most common certification bodies include the Programme for the Endorsement of Forest Certification (PEFC) and the Forest Stewardship Council (FSC) (Şen & Genç, 2017; Şen, 2021;). While

PEFC adopts the principle that forest certification should be local, FSC is an internationally recognized certification and has 1165 members in 89 countries (FSC, 2023).

In Turkey, forest certification practices were initiated for the first time by the General Directorate of Forestry (GDoF) in Aladağ Forest Management Directorate in 2010. In this process, FSC certification was preferred instead of PEFC. The reason for this is that there is no national certification system required for PEFC and the demand for FSC certified raw materials in Turkey and Europe is higher (Tolunay & Türkoğlu, 2014). As of 2023, Turkey has 8,348,624.05 hectares of forest area with FSC forest management certification (Aydın & Akyol, 2023) (Table 1) (Aydın and Akyol, 2023).

Table 1. Forest administrations with FSC certification in Turkey

Institution name	Area (ha)
Kastamonu OBM (Araç, Daday, Taşköprü, Tosya OBM)	314.938,90
Sinop OBM	59.009,54
Zonguldak OBM (Karabük, Yenice, Ovacık, Devrek, Ulus OBM)	278.947,25
Istanbul OBM	257.744,36
Amasya OBM	**1.560.419.89**
Bolu OBM (Bolu, Gerede, Aladağ, Dörtdivan and Seben OBM)	234.338,39
Adana OBM	750.842,00
Mersin OBM	833.260,88
Bursa OBM	149.323,30
Balıkesir OBM	676.210,34
Çanakkale OBM	570.558,00
Mugla OBM	**1.152.359,70**
Bolu OBM (Aladag OIS)	4.502,00
Konya OBM (Karaman and Ermenek OBM)	332.639,50
Antalya OBM	**1.173.530,00**
Total area	**8.348.624,05**

According to Table 1, the forest directorates with the highest number of FSC certificates in Turkey are Amasya, Antalya and Muğla, respectively. In this context, the research aims to conduct an analysis that evaluates FSC principles (criteria) and sustainability elements (social, environmental and economic).

Decision Tree

In this study, a decision tree model was created in accordance with the AHP method (Figure 1). This model is designed to analyze the commitment of forest regional directorates that receive forest certification to key principles (standards, employee relations, indigenous peoples, community relations, sustainable forest use, etc.). The model also seeks to measure how businesses value the three relevant aspects of sustainability (social, environmental and economic aspects) in order to make decisions about each principle. Accordingly, the model developed in this study is based on the ten principles (criteria) of FSC (Table 2).

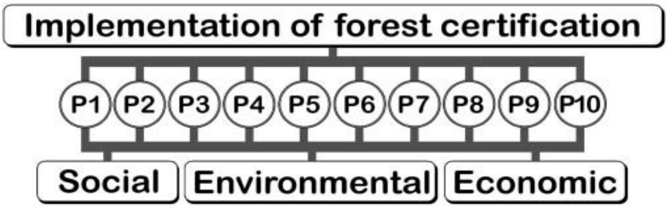

Figure 1. Decision tree for the implementation of forest certification: criteria (principles) and sustainability aspects.

Table 2. FSC criteria and principles considered in the research

Criteria	Principles
P1	Principle 1 (Compliance with the Law)
P2	Principle 2 (Workers' Rights and Conditions of Employment)
P3	Principle 3 (Rights of Indigenous Peoples)
P4	Principle 4 (Community Relations)
P5	Principle 5 (Forest Benefits)
P6	Principle 6 (Environmental Values and Impacts)
P7	Principle 7 (Management Planning)
P8	Principle 8 (Monitoring and Evaluation)
P9	Principle 9 (High Protection Values)
P10	Principle 10 (Evaluation of Management Activities)

In the study model, a questionnaire was developed based on the AHP method (Figure 1). In this questionnaire, the relationship between the ten FSC principles (criteria) for appropriateness in forest certification practice is shown, followed by the relationship between these principles and the three sustainability aspects (social, environmental and economic).

The questionnaire consists of four parts. The first part of the questionnaire asked for some general information such as the respondent's name (optional), gender, type of work and length of time worked on, length of time worked on environmental issues. In the second part, instructions on how to complete the questionnaire were provided in the document itself. At this stage, the experts compared the ten FSC criteria in Table 2 two by two according to the degree of difficulty of implementing forest certification using the AHP method. As a result of these comparisons, a pairwise comparison matrix and a priority vector of the FSC criterion were created in each regional forest directorate (RDM) (Amasya, Antalya and Muğla). In the third part of the questionnaire, the three sustainability aspects (social, environmental and economic) were compared two by two in relation to each FSC criterion, and then a priority vector was created for the studied CFMs (Amasya CFM, Antalya CFM and Muğla CFM). In the last part of the questionnaire, a thank you message was created to the surveyed experts for their cooperation.

In the research, for pairwise comparisons (in steps 2 and 3 of the questionnaire), the nine-unit scale defined by Saaty (2012), which includes values from 1 to 9 and their inverse values, was used. According to the AHP method, an inverse correspondence must follow from the same relationship. This means that if, for example, when comparing criterion P1 with P2, an expert assigns the value "3" on the scale (which means that criterion P1 is three times more difficult to implement in forest certification than criterion P2), then when comparing element P2 with P1, the inverse value should be assigned, which is "1/3". These values form the matrix of comparisons, which contains the values "1" diagonally. The priority vector is obtained by normalizing (averaging) the comparison values.

Moreover, according to Saaty (1997), it is important to know how reliable the consistency of the data is after making a decision, because it is not desirable to suffer from low data consistency leading to think that the decision may be random. Therefore, it is appropriate to calculate the consistency index (CR) of decisions proposed by Saaty (2012), which considers that an outcome is consistent when the CR≤ is 0.10. The AHP method proposes a proofreading when CR > 0.10, looking for possible errors or misunderstandings about the criteria and alternatives. In some cases, a recommendation may be to replace the respondent with another respondent who can provide more consistent values.

Research data

In the first step of the research, a trial was conducted with some experts and a few adjustments were made for the final implementation of the study instrument. For the final implementation, the questionnaires were conducted face-to-face with experts in three FMMs (Amasya, Antalya and Muğla). Experts They are experienced in FSC and PEFC Forest Certification Systems. In addition, some experts are well-known FSC researchers from universities. In this context, the survey was conducted with a total of 30 experts, 10 experts from each FDC.

FSC Principles Prioritization of Degree of Difficulty

Of the experts surveyed for prioritizing the degree of difficulty of FSC principles, 60% were male and 40% were female. 70% of the experts are experts of the relevant organization on certification and 30% are academics specialized in forest certification. More than half of the respondents (60%) have more than five years of experience in the same FMM, while 80% have at least ten years of experience in environmental sustainability . 86.6% of the respondents have a master's or doctoral degree and all of them are forest engineers.

Amasya Regional Directorate of Forestry Prioritization of FSC Principles

In Amasyalı OBM, experts compared ten FSC criteria pairwise according to the difficulty in implementation. The resulting comparison matrix data, mean and priority vector value are shown in Table 3.

Table 3. Priorities of difficulty in implementing FSC principles in Amasya OBM (normalization)

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	**SUM**	Rank
P1	0,23	0,23	0,29	0,22	0,13	0,08	0,13	0,18	0,21	0,14	1,82	1
P2	0,11	0,11	0,14	0,07	0,06	0,17	0,17	0,11	0,04	0,05	1,04	3
P3	0,11	0,11	0,14	0,36	0,32	0,21	0,21	0,18	0,04	0,05	1,74	2
P4	0,08	0,11	0,03	0,07	0,25	0,17	0,17	0,04	0,04	0,05	1,00	4
P5	0,11	0,11	0,03	0,02	0,06	0,21	0,17	0,14	0,04	0,05	0,94	5
P6	0,11	0,03	0,03	0,02	0,01	0,04	0,08	0,07	0,04	0,05	0,49	10
P7	0,08	0,03	0,03	0,02	0,02	0,02	0,04	0,22	0,21	0,09	0,74	7
P8	0,05	0,04	0,03	0,07	0,02	0,02	0,01	0,04	0,33	0,09	0,69	8
P9	0,05	0,11	0,14	0,07	0,06	0,04	0,01	0,00	0,04	0,41	0,94	6
P10	0,08	0,11	0,14	0,07	0,06	0,04	0,02	0,02	0,00	0,05	0,60	9
SUM	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	10,00	

The assessment of Amasya Regional Forestry Directorate (ARFD) reveals that there are significant challenges in forest certification practices, especially in complying with employee-related policies. In this context, in order to ensure full compliance with Forest Stewardship Certification (FSC) principles, the current management and organizational structure of Amasya FDF needs to be comprehensively reviewed and restructured in accordance with FSC principles. This process is not only limited to administrative level arrangements, but also requires a reshaping of the directorate's personnel management and training policies. Such a revision will allow for the minimization of problems both at the institutional level and in social relations.

It is clear that more emphasis should be placed on staff training in line with FSC principles. In particular, raising awareness and training of internal staff on FSC standards will increase the effectiveness of management processes, strengthen internal interactions and prevent potential conflicts in relations between the organization and local communities. At this point, it is emphasized that the organization of staff training programs should go beyond providing only theoretical knowledge on FSC principles and include practical training. Such training will allow staff to work more harmoniously with local communities and help them develop a deeper understanding of the certification process.

There is also a significant harmonization problem in the relations between the FSC organization of Amasya OBM and the local community. At this point, it is of great importance for the directorate to establish a more harmonized management structure with the local community. Shaping the management structure in a participatory manner that is sensitive to the needs and demands of local people will pave the way for a more robust cooperation and mutual understanding. This will lead to a solution-oriented approach not only in inter-institutional relations but also in interactions with the community. Collaboration with local communities will also be particularly useful in conflict management. Effective management of conflicts will minimize social unrest and contribute to overcoming the obstacles encountered in the implementation process of forest certification.

FSC practices also have the potential to create new job opportunities for local people. In this context, vocational training activities can make a significant contribution to rural development. For example, activities such as the production of non-wood forest products in forest areas can contribute to the economic development of local people, and in the process, the skills of local people to do business in line with FSC certification can be developed, contributing to the sustainable development of the region. In addition, FSC policies encourage respect for local people's traditions, cultural heritage and sacred sites. This is not only environmentally but also socially important. Healthy communication with local communities on these issues ensures the sustainability of forest management processes.

However, if this link between the authority and the community is not established, conflicts between local people and the relevant directorate will inevitably increase. Such conflicts can negatively affect the efficiency of the certification process and lead to a loss of support from the local community. This may jeopardize the success of the forest certification process and hinder the long-term sustainability of the certification. Therefore, a proactive approach should be adopted to resolve conflicts with local communities in Amasya FMM and a strong communication network with local communities should be established. Addressing such potential disconnects between the authority and the community will enable forest certification to move forward in a positive way.

Finally, the consistency ratio (CR) of the expert responses in Amasya OBM was calculated and this ratio is presented visually in Figure 2. It should be noted that the CR value indicates the consensus among experts and that these values vary for each directorate. These calculations are an important tool to assess the reliability and validity of the results.

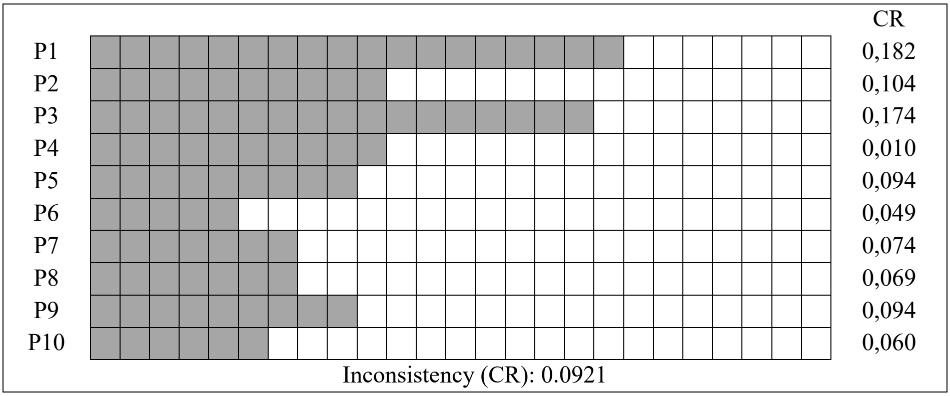

Figure 2. Inconsistency rate of expert results in Amasya OBM

As seen in Figure 2, the mean value of the consistency ratio (CR) of the decisions made by the experts of Amasya Regional Directorate of Forestry (RDFD) is 0.0921, which is generally below the limit value of 0.10, indicating that the decisions between the experts are consistent. However, the CR value is quite close to the 0.10 limit, suggesting that the results should be evaluated more carefully. This small inconsistency is only observed in the comparisons of four principles: P1 (0.182), P3 (0.174), P2 (0.104) and P4 (0.010). These four principles have higher priority values in the comparison shown in Table 3, indicating that there is not a full consensus among experts on the practical difficulties of applying these principles.

These inconsistencies regarding forest certification in Amasya FMM also indicate the existence of different interpretations and implementation challenges. Therefore, it is important to make the certification principles clearer and more understandable in order to create a common understanding among experts in the directorate. In this context, it is clear that forest certification standards need to be reviewed and a more consistent framework established to improve the applicability of these standards.

In particular, the difficulties encountered in the practical application of the principles related to FSC certification lead to some uncertainties among experts in Amasya OBM. These uncertainties suggest that the relevant certification principles need to be revised more carefully and that more training and information sharing is needed to minimize differences of opinion among experts in this process. Moreover, eliminating such inconsistencies will contribute to a more effective implementation of the FSC certification process and to identify and resolve potential problems in advance.

Amasya FMM experts evaluated the principles of forest certification in the context of sustainability elements, comparing them with social, environmental and economic factors. The results of these comparisons are more clearly illustrated by the mean values and priority vector calculations in Table 4. These calculations reveal how important each principle is for Amasya OBM, allowing the Directorate to identify where improvements need to be made in line with its sustainability goals. This data will enable experts at Amasya OBM to make decisions on the applicability of FSC principles on a more solid basis.

Table 4. of FSC principles according to sustainability elements in Amasya OBM

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	Priority Vector
Social	0,43	0,21	0,26	0,34	0,30	0,30	0,28	0,41	0,44	0,24	0,321
Environment	0,25	0,24	0,25	0,42	0,36	0,32	0,36	0,31	0,44	0,36	0,331
Economy	0,32	0,55	0,49	0,24	0,34	0,38	0,36	0,28	0,12	0,40	0,348

In Amasya CMM, when experts ranked FSC principles in terms of sustainability elements, the economic dimension (0.348) ranked first. This is followed by the environmental dimension (0.331) and the social dimension (0.321)

Priority of FSC Principles of Antalya Regional Directorate of Forestry

In the study conducted with experts in Antalya OBM, a pairwise comparison of the ten principles according to the difficulty in implementation was made and the resulting comparison matrix and priority vector are shown in Table 5.

Table 5. Priorities of difficulty in implementing FSC principles in Antalya OBM (normalization)

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	**SUM**	Rank
P1	0,29	0,75	0,35	0,21	0,19	0,19	0,19	0,18	0,16	0,04	2,54	1
P2	0,04	0,11	0,45	0,31	0,28	0,15	0,15	0,11	0,28	0,33	2,22	2
P3	0,04	0,01	0,05	0,31	0,28	0,19	0,19	0,18	0,03	0,04	1,33	3
P4	0,05	0,01	0,01	0,03	0,13	0,15	0,15	0,04	0,03	0,04	0,63	6
P5	0,05	0,01	0,01	0,01	0,03	0,19	0,15	0,15	0,03	0,04	0,66	4
P6	0,06	0,03	0,01	0,01	0,01	0,04	0,08	0,07	0,03	0,04	0,37	10
P7	0,06	0,03	0,01	0,01	0,01	0,02	0,04	0,22	0,16	0,07	0,62	7
P8	0,06	0,04	0,01	0,03	0,01	0,02	0,01	0,04	0,25	0,19	0,64	5
P9	0,06	0,01	0,05	0,03	0,03	0,04	0,01	0,00	0,03	0,19	0,45	9
P10	0,29	0,01	0,05	0,03	0,03	0,04	0,02	0,01	0,01	0,04	0,53	8
SUM	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	10,00	

According to Table 5, Antalya Regional Forestry Directorate (ARFD) experts gave the highest value among the FSC certification principles to P1 (Rights of Local Peoples) with 0.254. This is followed by P2 (Labor Rights and Employment Conditions) with 0.222 and P3 (Community Relations) with 0.133. This ranking shows that Antalya CMM gives high importance to social elements in the certification process. The fact that experts at Antalya FMM emphasize the importance of social dimensions such as the rights of local communities and workers' rights reveals that they take into account the social impacts of forest management and certification processes in this region. In addition, experts at Antalya OBM pay special attention to the relevance of principle P6 (Environmental Values and Impacts). The high value of this principle can be attributed to the fact that a large proportion of the certified areas in Antalya correspond to red pine plantations that have experienced major landscape transformation. Red pine plantations are considered to pose challenges in terms of fulfilling environmental values. This reflects the barriers faced in the realization of environmental sustainability objectives in the Antalya OBM.

Table 6 contains the mean values and priority vectors from the pairwise comparisons for each sustainability aspect (social, environmental and economic) on the difficulty of implementing forest certification, obtained from Antalya CFM experts. This data helps to identify the extent to which each principle is aligned with different sustainability aspects and provides a better understanding of the challenges faced in the certification process of Antalya CFM. It also reveals where improvements are needed to achieve sustainable forest management goals. These findings allow for the development of more effective strategies for practices in Antalya CFM.

Table 6. Prioritization of FSC principles according to sustainability elements in Antalya OBM

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	Priority Vector
Social	0,25	0,25	0,55	0,36	0,30	0,30	0,27	0,39	0,44	0,20	0,331
Environment	0,25	0,40	0,25	0,42	0,36	0,32	0,37	0,39	0,40	0,40	0,356
Economy	0,50	0,35	0,20	0,22	0,34	0,38	0,36	0,22	0,16	0,40	0,313

According to Antalya FMM experts, the environmental dimension (0.356) ranks first in terms of importance in the implementation of forest certification, followed by the social dimension (0.331) and the economic dimension (0.313). This result confirms that Principles 6 and 9 are seen as the most difficult principles to implement in practice by Antalya FMM experts (Table 6). Regarding the consistency ratio (CR) of Antalya OBM experts, the outputs are shown in Figure 3.

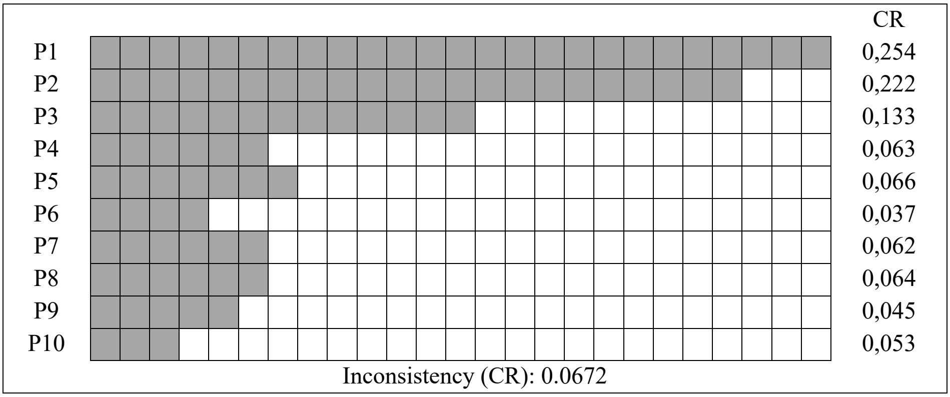

Figure 3. Inconsistency rate of expert results in Antalya OBM

In this case, the mean value of 0.0672 is lower than the maximum recommended value of 0.10 according to Saaty (2012). However, the discrepancy values for individual principles (P1, P2 and P3) were large for those principles identified as more difficult to implement in practice (Figure 3).

Priority of FSC Principles of Muğla Regional Directorate of Forestry

The comparison matrix and priority vector obtained from the pairwise comparison of the ten principles in Muğla CMM are shown in Table 7.

Table 7. Priorities of difficulty in implementing FSC principles in Mughal OBM (normalization)

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	**SUM**	Rank
P1	0,25	0,44	0,20	0,14	0,12	0,11	0,12	0,14	0,14	0,13	1,79	3
P2	0,13	0,22	0,59	0,28	0,24	0,19	0,16	0,11	0,26	0,18	2,34	1
P3	0,13	0,04	0,10	0,42	0,28	0,26	0,19	0,18	0,11	0,16	1,86	2
P4	0,08	0,04	0,01	0,05	0,24	0,15	0,12	0,11	0,03	0,05	0,87	5
P5	0,08	0,04	0,01	0,01	0,04	0,19	0,19	0,21	0,09	0,03	0,89	4
P6	0,08	0,04	0,01	0,01	0,01	0,04	0,16	0,07	0,09	0,08	0,59	7
P7	0,08	0,06	0,02	0,02	0,01	0,01	0,04	0,14	0,14	0,08	0,59	6
P8	0,06	0,07	0,02	0,02	0,01	0,02	0,01	0,04	0,11	0,13	0,49	8
P9	0,05	0,02	0,02	0,05	0,01	0,01	0,01	0,01	0,03	0,13	0,35	9
P10	0,05	0,03	0,02	0,02	0,04	0,01	0,01	0,01	0,01	0,03	0,23	10
SUM	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	10,00	

According to Table 7, the highest priority vectors in the implementation of forest certification for Muğla Regional Directorate of Forestry (MRFM) are given to the principles P1 (Benefits from Forestry), P2 (Labor Rights and Employment Conditions) and P3 (Community Relations), respectively. This finding shows that social and economic dimensions have an important place in the forest certification process in Muğla CFUG. In particular, it is understood that forest management in the Muğla region focuses on social and economic factors such as benefits from the forest and labor rights and community relations.

Experts at Muğla MCC conducted pairwise comparisons to determine the applicability and importance of each principle, taking into account the sustainability dimensions (social, environmental and economic). The mean values and priority vectors in Table 8 show the results from these comparisons. This data reveals how each sustainability dimension is associated with challenges in the implementation of forest certification and which dimensions have higher priority.

These findings indicate that social factors (local people's rights, labor rights, community relations) are more prominent in the forest certification process in Muğla CFUG and that these factors play a decisive role in the success of the practices in the certification process. In addition, environmental and economic factors are also considered, but with lower priority. These results emphasize that social and economic factors need to be improved and more effort should be made in these areas in order for Muğla CFM to achieve its sustainable forest management goals.

Table 8. Prioritization of FSC principles according to sustainability elements in Muğla OBM

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	Priority Vector
Social	0,43	0,35	0,54	0,34	0,31	0,3	0,28	0,28	0,41	0,24	0,348
Environment	0,25	0,3	0,31	0,32	0,35	0,32	0,33	0,31	0,44	0,32	0,325
Economy	0,32	0,35	0,15	0,34	0,34	0,38	0,36	0,41	0,12	0,44	0,321

According to Mugla FMM experts, the social dimension (0.348), followed by the environmental dimension (0.325) and the economic dimension (0.321) come first in terms of importance in the implementation of forest certification. Regarding the consistency ratio (CR) of Mugla FMM experts, the outputs are shown in Figure 4.

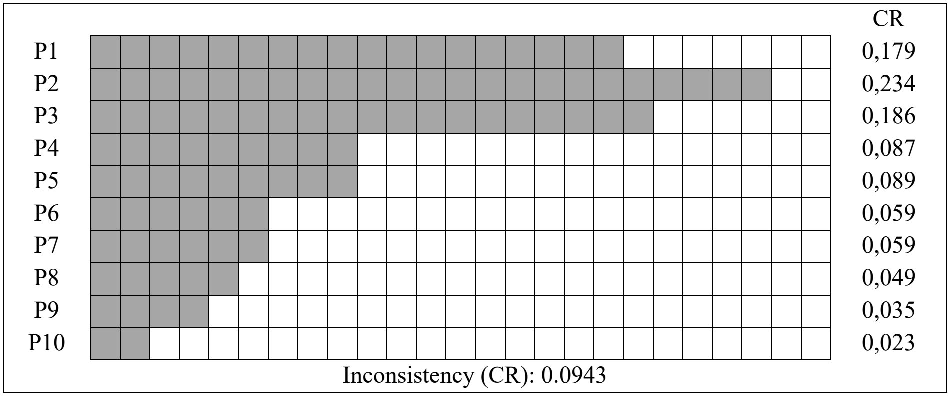

Figure 4. Inconsistency rate of expert results in Muğla OBM

According to Saaty (2012), the average inconsistency rate was found to be 0.0943, slightly below the maximum recommended inconsistency rate of 0.10, indicating that the experts of Muğla Regional Directorate of Forestry (MRD) have a certain consistency in their decisions. However, the high individual inconsistency values for some of the principles indicate a lack of consensus among the experts on the difficulty of applying these principles in practice. These high individual inconsistencies seen in Figure 4 indicate that there are different interpretations and understandings among the experts and that there may be difficulties in the implementation process for these principles.

However, it should also be taken into consideration that these inconsistencies may have arisen due to data limitations. The limited availability of data may cause the expert opinions in the Mugla FMM to be insufficient to provide a full representation on this issue. This was particularly evident in assessments of the implementation challenges of social dimensions such as local people's rights, labor rights and community relations. At this point, additional assessments with a wider range of experts could help to address these inconsistencies and reach a more accurate conclusion.

Comparison of FSC principles

With data from three forest regional directorates in Turkey, it is possible to sustain differences and similarities in expert perception of the level of difficulty of implementation in forest certification. In order to obtain the best comparison between the regional directorates, the principles that are considered the most difficult to implement in practice are shown in Figure 5.

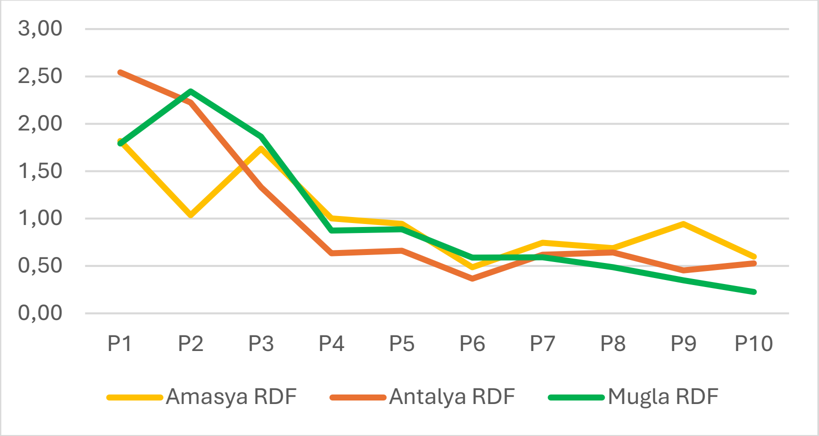

Figure 5. The challenge of implementing the FSC principle

When Figure 5 is analyzed, it is understood that the difficulty of implementing the first four FSC principles is higher than the others in all directorates. The country comparison values of the challenges related to the three aspects of certification (social, environmental and economic) are shown in Table 9 and Figure 6.

Table 9. of Amasya, Antalya and Mugla OBMs according to sustainability factors

OBM	Social	Environmental	Economic
Amasya	0.321	0.331	0.348
Antalya	0.331	0.346	0.313
Mugla	0.348	0.325	0.321
Average	0.334	0.338	0.328

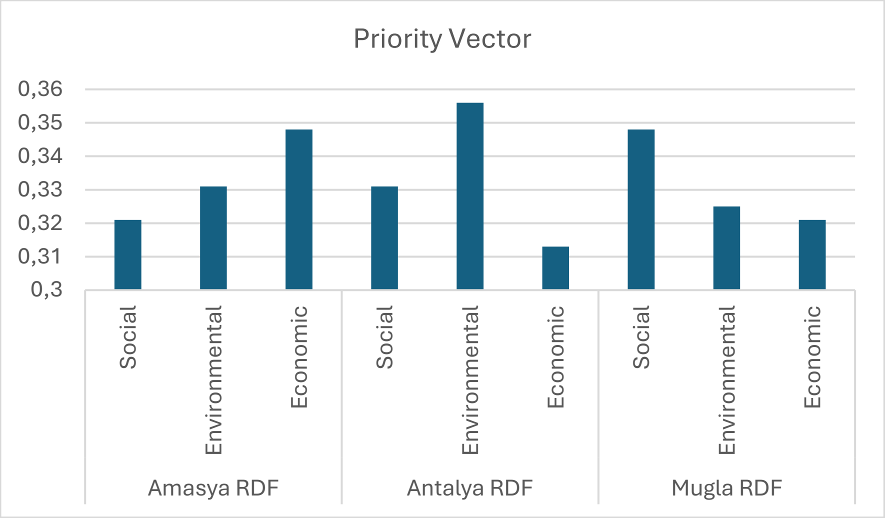

Figure 6. Comparison of sustainability elements of Amasya, Antalya and Muğla OBM

In this text, the challenges faced in implementing FSC certification for three different Regional Forest Directorates (RDMs) are analyzed in detail. The differences between Amasya, Antalya and Muğla CFUGs reflect the nature and priorities of the challenges faced by each directorate. For the Amasya FMM, challenges in implementing economic factors are prominent, while environmental factors are more prominent in the Antalya FMM and social factors are more prominent in the Muğla FMM. These differences reflect the effects of governance and environmental policies in each region.

It is noteworthy that environmental factors pose the biggest challenges, especially in Antalya FMM. Experts in Antalya focus on environmental factors, indicating that there are more challenges related to these elements. However, in Amasya CMM, economic factors are more prominent and the most difficult principle to overcome is defined as P9 (High Conservation Values). In the Mugla FMM, there are greater challenges related to social aspects, particularly principle P1 (Benefits from the Forest). This is due to the different ways in which social, economic and environmental factors interact in each region.

In Mugla MCC, social aspects present more challenges in terms of compliance with principles P2 (Workers' Rights and Employment Conditions), P3 (Indigenous Peoples' Rights) and P4 (Community Relations). This can be explained by the often confrontational relationships between in-house staff, local people and the community in Mugla FMM. Antalya and Mugla FMM experts were observed to focus more on principles related to management and organization, such as P8 (Monitoring and Evaluation) and P10 (Implementation of Management Activities). These findings are consistent with the conclusion of Pulido-Sierra (2013) when examining the feasibility of rubber FSC certification in Colombia that environmental and social dimensions lead to greater compliance challenges.

When we look at the consistency ratios in the analyzed data, it can be seen that Antalya FIM experts show a lower CR (consistency) value, while Amasya and Muğla FIM experts have CR values close to the 0.10 limit suggested by Saaty (2012) but higher. However, all results are consistent. This suggests that the Antalya OBM experts have more consensus than the experts of the other two directorates, and therefore Antalya's results have more validity.

The fact that there was less consensus among experts in Muğla CMM indicates that more expert opinions are needed to increase the validity of the results in Muğla. However, the consistency of the data from Muğla with the findings on the three aspects of the certification process increases the validity of these data. These results suggest that the differences between the three directorates are not only related to implementation challenges, but also reflect the specific circumstances in each directorate's own context.

Evaluations

The Analytic Hierarchy Process (AHP) is an effective Multi-Criteria Decision Making (MCDM) method to examine the practical challenges of forest certification. While AHP addresses inconsistencies and uncertainties in the decision-making process, it is still recognized as a powerful decision support tool. This method allows decision makers to compare preferences between alternatives in a systematic way, thus enabling decisions to be made by considering a large number of criteria. However, the AHP also has some limitations that need to be taken into account in decision-making processes, especially the inconsistency coefficients and differences of opinion among decision makers.

The application of the AHP to the cases of Amasya, Antalya and Muğla Regional Directorates of Forestry (RDFMs) yielded useful results in understanding the challenges associated with forest certification practices in each directorate. The similarities and differences between the opinions of experts in the three directorates reveal that challenges in the certification process vary regionally. In the case of Amasya FDC, it was found that there were difficulties in fulfilling economic aspects; in Antalya FDC, environmental aspects were considered as more complex principles; and in Muğla FDC, social aspects were identified as an important problem.

These findings show that AHP is an effective tool to ensure consistency of expert opinions in the decision-making process. However, there are several important factors that need to be considered for the validity of the results obtained. In particular, although the low inconsistency coefficients observed in Amasya and Muğla directorates (e.g. CV ratio close to 0.01) indicate a high degree of consistency in the experts' assessments, the results may still show a certain level of variability. Therefore, the results obtained need to be carefully evaluated depending on the sample of experts, the methods used and local conditions.

These assessments are important for identifying the most difficult principles to comply with in each directorate. These findings can help to develop strategies for continuous improvement of forest management standards. These strategies could include measures to prevent different interpretations of standards, as well as training of experts and local stakeholders on knowledge and interpretation. Periodic analyses can be used as an important tool for monitoring and improving the forest certification process.

Consequently, using AHP to identify challenges in forest certification practices can help decision makers and experts to manage processes more effectively. By proposing a systematic consideration and analysis of expert opinions at each stage of certification processes, this study aims to provide a stronger basis for promoting sustainable forest management. Furthermore, the results obtained with AHP offer the potential to improve the effectiveness of forest certification processes by contributing to the development of strategies to understand regional differences and challenges.

Study Limitations and Future Improvements

The AHP approach has some limitations and disadvantages. In this approach, the DM is asked to make a judgment based only on the criteria specified in the study. At this point, the DM is required to indicate the relative importance of one criterion over another or to favor one alternative over another. However, when the number of alternatives and criteria increases, the pairwise comparison process becomes cumbersome and the risk of inconsistency arises. Therefore, instead of using a single method such as AHP, there is a need for hybrid approaches where more than one method is evaluated together. Therefore, researchers or mine site managers should create an appropriate hybrid approach according to the nature of the problem they have. In this context, many methods such as COPRAS, PROMETHEE and MOORA are suitable to be used together with both SWARA and AHP.

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