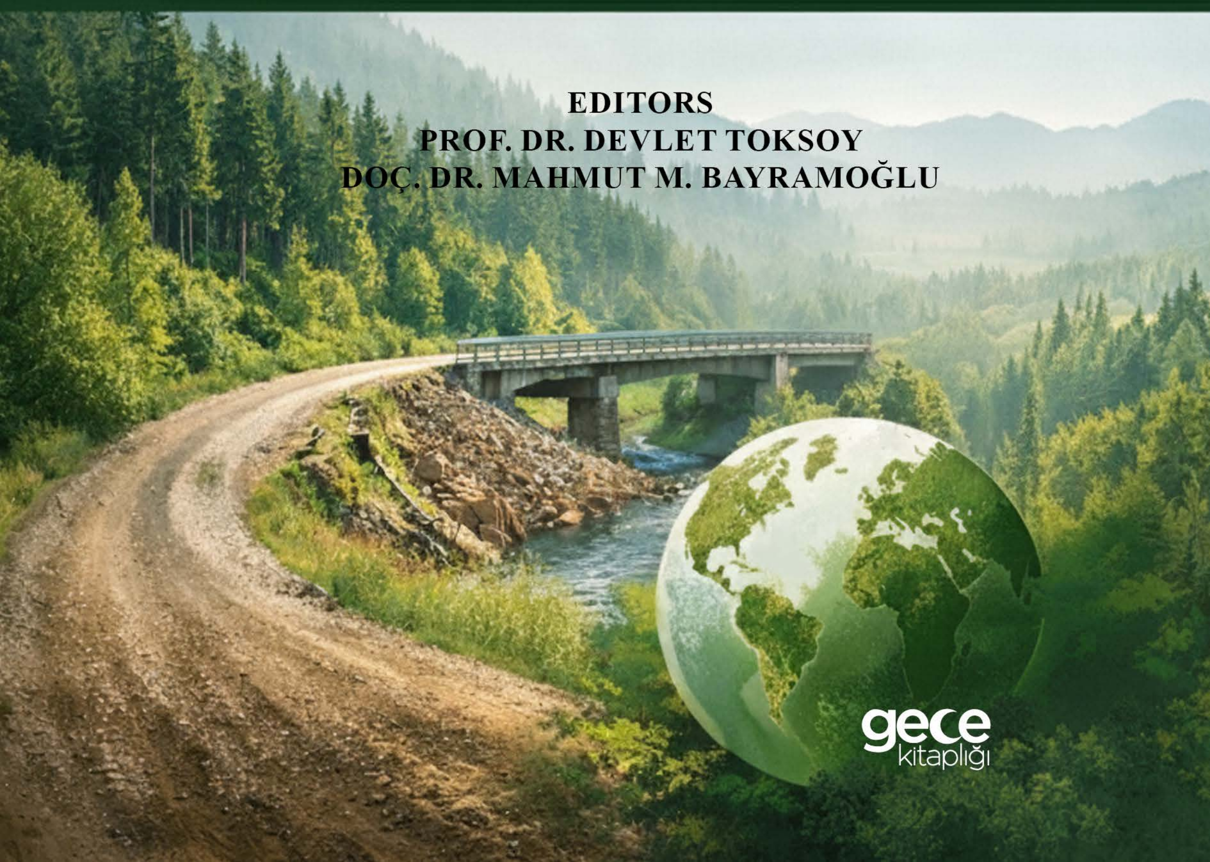
Forest Engineering

Methods, Theory and Applications



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(Theory, Methods and Applications)

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Chapter I - Economic Evaluation of Occupational Health and Safety (OHS) in Forestry

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1. Introduction

With the onset of industrialization worldwide, the issue of increasing work productivity in the workplace has gained great importance. For this purpose, the idea of improving all elements of the production process that affect work efficiency has emerged. The main elements of the production process in working life are primarily the labour force, production technique, technology, workplace conditions, and raw materials. Among these elements, the problems that most significantly affect work productivity and create a substantial economic burden on employers are those occurring in the workforce due to occupational accidents and diseases. Various organizations and institutions have proposed different definitions for occupational accidents and diseases. An occupational accident is defined by the International Labour Organization (ILO) (2015) as "*an unexpected and unplanned event that causes a specific harm or injury,*" while the World Health Organization (WHO) defines it as "*an unplanned event that often results in personal injuries, damage to machinery, tools, and equipment, and a temporary halt in production*"

(Akçay, 2021). The European Union Statistical Office (Eurostat) describes an occupational accident as "*a sudden event during the execution of work that causes physical or psychological harm*" (ESAW, 2012). In Turkey's current Occupational Health and Safety (OHS) Law (No. 6331), it is defined as "*an event occurring at the workplace or due to the conduct of work, resulting in death or causing physical or psychological impairment of bodily integrity*" (Occupational Health and Safety Law, 2012). Occupational accidents may result in loss of life, disability, short-term injury, psychological trauma, damage or breakdown of work machinery, and interruptions in the production process. In the accident pyramid developed by Heinrich, occupational accidents are classified as: major injury accidents (1 incident), minor injury accidents (29 incidents), and near-miss events (300 incidents). This model is based on the principle that serious occupational accidents often arise from the accumulation of less severe accidents and near-miss events (Heinrich, 1931). According to this theory, every 300 near-miss events predict 29 minor injury accidents, and every 29 minor injury accidents predict one major injury accident (Johnson, 2011). Another significant negative effect arising from the nature of work and manifesting overtime in the workforce is the occurrence of occupational diseases. The WHO defines occupational diseases as "*a group of diseases in which a cause-effect, stimulus-response relationship specific to the work performed can be demonstrated between a harmful agent and the human body exposed to it*" (Çalık et al., 2021). In Turkey's current OHS law (No. 6331), it is expressed as "*a disease arising as a result of exposure to occupational risks*." In the relevant legislation, occupational diseases are classified into five main groups based on the harmful agent and affected organ (Figure 1).

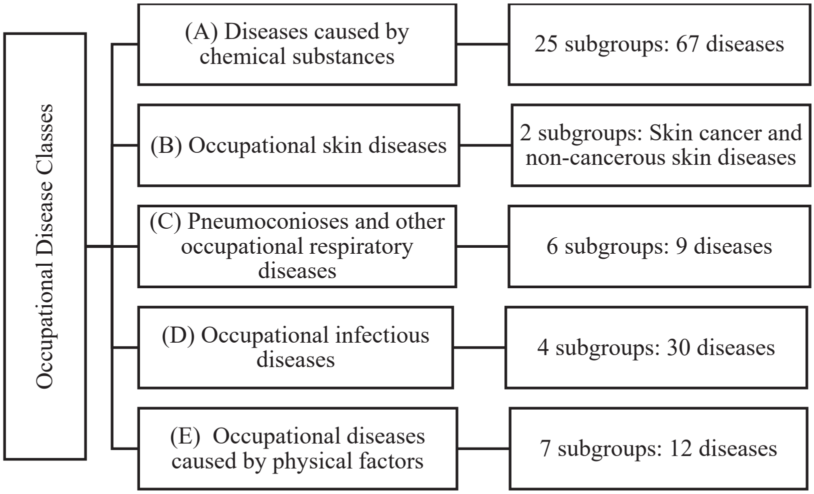

Figure 1. Main classes of occupational diseases

The concept of OHS emerged in the 19th century to prevent problems arising from work accidents and occupational diseases and to increase work efficiency in the workplace. The ILO defines OHS as "*the discipline dealing with the prevention of work-related injuries and diseases as well as the protection and promotion of the health of workers. It aims at the improvement of working conditions and environment*" (ILO, 1998). The main goal of OHS is to identify in advance situations in the workplace that may be harmful to health, take the necessary precautions, provide a safe, peaceful, and comfortable working environment and thus minimize work accidents and occupational diseases. To achieve these objectives, many legal regulations have been enacted internationally and nationally.

1.1. OHS legal framework

The most important international regulations regarding OHS are the European Union (EU) Directive 89/391/EEC and the ILO conventions (No. 155 and No. 161) (Council of the European Communities, 1989; ILO, 2001; Commission European, 2004). On a national scale, each country has developed legal regulations concerning OHS through its internal statutes.

In Turkey, some articles regarding OHS are included in the Constitution (No. 2709), the Labour Law (No. 4856), and the Social Insurance and General Health Insurance Law (No. 5510) (Constitution, 1982; Labour Law, 2003; SIH Law, 2006). In addition, the National Occupational Health and Safety Law (No. 6331) was enacted in 2012.

According to these legal regulations, employees' responsible for OHS practices:

- conducting or commissioning risk assessments,
- taking protective measures,
- providing training and information to employees,
- supplying the necessary equipment,
- providing personal protective equipment (PPE),
- monitoring and correcting compliance with OHS measures
- paid the costs of OHS measures by the employer

Furthermore, the relevant law clearly states that employers' responsibilities regarding OHS practices are not removed by outsourcing such services, and they remain liable for potential negative outcomes or deficiencies in the service.

Employees' responsible for OHS practices:

- using the provided PPE,
- avoid behaviors that endanger OHS,
- report hazards to the employer,
- cease work in risky situations.

In developing countries, employers often regard expenditures for the implementation of OHS measures as a waste of time and unnecessary expense. Especially in small-scale enterprises, the costs of OHS practices are frequently overlooked because they significantly increase labour expenses (Karadeniz, 2018). However, the costs incurred as a result of work accidents or occupational diseases due to the lack of OHS practices adversely affect not only the profit margin and competitiveness of works but also the country's gross domestic product (GDP) (Kılkış, 2014). Globally, approximately 2.93 million fatal and 395 million non-fatal work accidents occur annually (Perea et al., 2025; ILO, 2025). When evaluated on a global scale, the costs of these accidents are extremely high. In Turkey, the total health expenditures for the working labour force in 2023 amounted to 42,177,525,424 $ (1 USD = ~ 29.5 TL) (TSI, 2023). Moreover, considering undiagnosed occupational diseases, deficiencies in work accident records, and a workforce with more than 30% of unregistered workers, it can be anticipated that these expenses are much higher. Forestry activities are among the types of work with a high risk of accidents and occupational diseases. A variety of literature exists on OHS measures that can be taken to reduce work accidents in the forestry sector (Pellicer et al., 2014; Takala et al., 2014; Karamık and Şeker, 2015; EU OSHA, 2017; HSE, 2017; Ünver and Ergenç, 2021; Tompa et al., 2021). However, there are few comprehensive studies on the costs of OHS practices in forestry activities (Akgül et al., 2021; Ünver and Toksoy, 2025). In this chapter, the concept of OHS in forestry activities and the cost-generating factors related to OHS in forest enterprises are evaluated. Costs are primarily classified into two categories: the costs of OHS measures that enterprises are legally required to implement and the costs they may incur as a result of work accidents or occupational diseases.

2. Occupational Health and Safety in Forestry

Forestry encompasses a wide range of activities with unique dynamics, from forest management to timber harvesting and from forest road construction to firefighting (Güloğlu, Belkayalı & Bulut, 2017; Ünver and Kurdoğlu, 2024). These activities pose significant OHS risks due to factors such as open and challenging work environments (slope, rough terrain, climatic conditions), labour intensity, heavy work materials, external hazards (harmful plants, insects, wildlife), and the inherent nature of the work (Ünver-Okan and Acar, 2015). For these reasons, the forestry sector ranks among the highest-risk sectors in many developing countries (Kaakkurivaara et al., 2022). Due to these risks, the majority of occupational accidents that occur in forestry work can result in death, permanent disability or injury. Forestry jobs, which are considered 3D (dirty, dangerous, and demeaning) work by the ILO, are classified under four main headings and a total of 12 subheadings in the Statistical Classification of Economic Activities in the European Community (Nace Rev. 2) list (EU, 2023) (Table 1).

Table 1. NACE Rev.2 classes related to forestry work

Code	Description	Hazard Class
02	Forestry and Logging	
02.1	Silviculture and other forestry activities	
02.10	Silviculture and other forestry activities	
02.10.01	Growing of coppice woods (including pulpwood and firewood)	Hazard
02.10.02	Production of seedlings and seeds for growing forest	Slightly Hazard
02.10.03	Growing of forest trees (except coppice wood growing)	Slightly Hazard
02.2	Logging	
02.20	Logging	
02.20.01	Production of industrial and firewood (including production of charcoal in the forest using traditional methods)	Hazard
02.3	Gathering of wild-growing non-wood products	
02.30	Gathering of wild-growing non-wood products	
02.30.01	Gathering of wild-growing non-wood products (cork, root, cone, balsam, lacquer and resin, acorn, horse chestnut, moss and lichens, wildflowers, wild fruits, edible mushrooms, etc.)	Slightly Hazard
02.4	Support services for forestry	
02.40	Support services for forestry	
02.40.01	Supporting activities such as logging, pruning, peeling etc.	Hazard
02.40.02	Transportation, cutting and loading activities for cutting and cleaned trees in forests	Hazard
02.40.03	Silviculture and other forestry activities (thinning, pruning, transplanting etc.)	Hazard
02.40.04	Forest protection activities from pests (insects and diseases)	Very Hazard
02.40.05	Forest protection activities from fires and illegal logging	Hazard
02.40.06	Construction and maintenance activities of forest roads for protecting and maintaining the forest	Hazard
02.40.07	Other forestry activities (forestry inventories, forest management, forest management consulting services, research and development (maintenance, productivity, etc.) related to forest)	Slightly Hazard

The number of people employed in the agriculture and forestry sector worldwide accounts for approximately 0.4% of the total global workforce, amounting to approximately 13.7 million workers (ILO, 2017). In EU countries, this figure is approximately 500,000 people (Eurostat, 2020). In Turkey, the number of insured forestry workers corresponds to approximately 0.35% of insured workers. Almost all forests in Turkey are publicly owned and managed by the General Directorate of Forestry (GDF). In forest enterprises, in addition to permanent workers, a large number of seasonal/temporary workers are employed during certain times of the year for various tasks, such as fighting forest fires, pruning trees, transportation, forest road construction, afforestation, and nursery work. Over the past five years in Turkey, an average of 16 million m^3 of industrial wood and 6 million m^3 of firewood have been produced annually, totaling 22 million m^3 of wood raw material. In addition, an average of 7,756 km of forest roads has been built, approximately 267 million saplings have been produced, and 44,000 ha of forest area have been afforested. Approximately 64% of Turkey's forests are located that are vulnerable to fires. Between 2013 and 2022, there was an average of 2,783 forest fires per year, and an average of 22,919 ha of forested land damaged annually. Before the mega forest fires that occurred in 2021, an average of 7,000 - 8,000 temporary forest fire workers were employed each year to combat wildfires. After 2021, this figure increased to approximately 15,000 (GDF, 2022). Table 2 presents data on fatal and non-fatal occupational accidents and cases of incapacity in the forestry sector and across all sectors in Turkey over the past ten years.

Table 2. Data on occupational accidents and incapacity in forestry between 2014 and 2023

Years	Türkiye			Forestry sector			
	Non-fatal accidents	Fatal accidents	Temporary disability	Non-fatal accidents	Fatal accidents	Temporary disability	Permanent disability
2014	221366	1626	2.065.962	202	5	2699	30
2015	241547	1252	2.992.070	434	6	8413	121
2016	286068	1405	3.453.702	345	7	6343	393
2017	359866	1636	3.997.742	447	8	6804	825
2018	431276	1542	2.488.401	486	9	4905	1285
2019	422463	1147	3.627.934	477	9	5256	487
2020	384262	1231	3.492.824	509	12	5293	402
2021	511084	1382	4.650.312	1135	12	7683	382
2022	588823	1517	4.808.409	1469	10	11125	427
2023	681401	1966	4.817.279	1455	14	8161	366
Total	4128156	14704	36.394.635	6959	92	66682	4718

As shown in Table 2, work accidents in the forestry sector over the last ten years constitute approximately 0.17% of all work accidents in Turkey. Of the work accidents in the forestry sector, 1.31% resulted in death. This figure is higher than that in many other sectors classified as extremely dangerous, such as fishing, construction, and mining. The average rate of non-fatal work accidents in the forestry sector corresponds to approximately 0.17% of all non-fatal work accidents in Turkey. For temporary workers employed in forestry jobs other than forest firefighting, criteria such as education, work experience, or physical characteristics are not required during the hiring process. Seasonal/temporary workers hired for forest fire fighting are selected from among applicants who apply to the announcement and can complete a running course. According to legal grounds and current practices, forestry work is largely carried out by persons who have no work experience or training regarding the tasks or associated risks (Ünver and Ergenç, 2021). Due to the prevalence of unregistered labour in forestry in Turkey, most temporary workers do not have insurance for forestry work. Therefore, there are no complete or accurate records of work accidents and occupational diseases in forestry activities (Güloğlu et al., 2021). The Public Procurement Law (No. 4734), which came into force in Turkey in 2002, stipulated that all jobs carried out by tender would be governed accordingly. However, a year after the law came into effect, wood harvesting work was excluded from this law due to its unique conditions and conflicts with the provisions of the forestry law. Wood harvesting jobs are carried out under the requirements of the Forest Law (No. 6831) by forest villagers and cooperatives established to develop forest villages using a fixed-price system. This situation creates significant handicaps in terms of work efficiency and OHS. Hıntıkka (2011) determined that temporary workers have a higher risk of accidents than permanent workers owing to reasons such as lack of training and experience, job insecurity, constant workplace changes, and high turnover expectations.

3. Occupational Health and Safety Costs

Costs arising from OHS in businesses include (1) expenditures made for OHS precautions taken before occupational accidents and diseases occur and (2) expenses incurred after an occupational accident or disease has occurred. The costs arising from occupational accidents or diseases are divided into two categories: direct and indirect costs. The elements that generate OHS-related costs are illustrated in Figure 2.

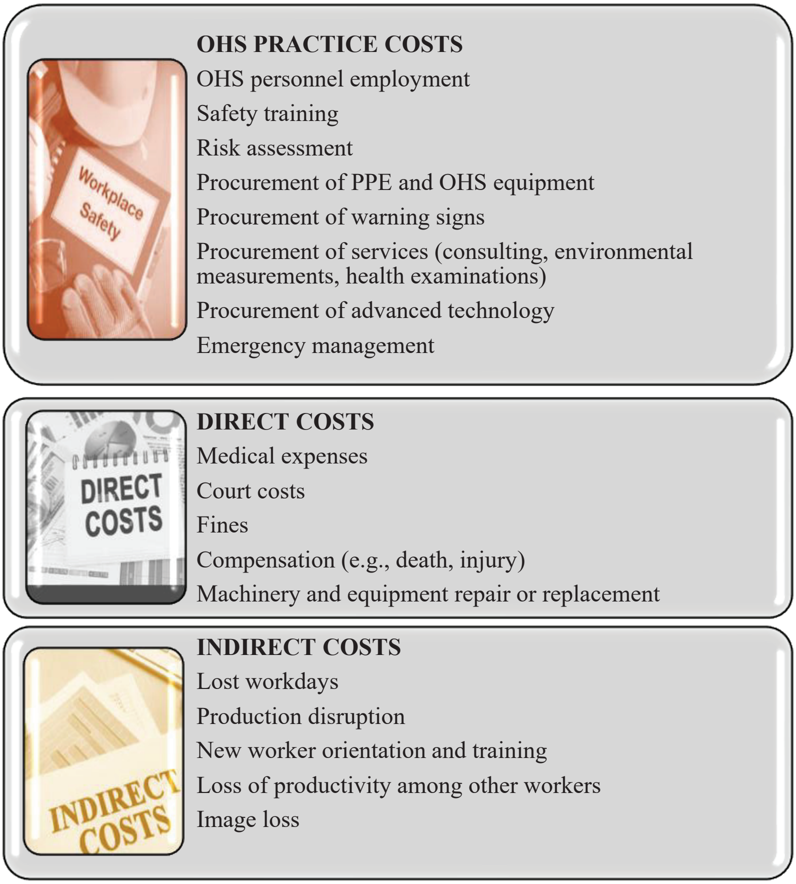

Figure 2. Occupational health and safety costs

Each of the cost components related to OHS that may arise, as shown in Figure 2, is summarized below.

3.1. Costs of preventive measures for occupational health and safety

Currently, due to increased public awareness and mandatory international and national legal regulations, it has become common for every enterprise to implement OHS measures according to the nature of their work and the characteristics of their workplace. Generally, the costs of workplace accidents caused by the absence or insufficiency of OHS measures are much higher than the expenses incurred in implementing such measures (Ikpe et al., 2011; Van den Broek et al., 2011; Wachter and Yorio, 2014; Bayram et al., 2017; Grimani et al., 2018; Öçal, 2023). In addition, it has been shown that the number and costs of occupational injuries can be significantly prevented or reduced through investments in OHS (López-Alonso et al., 2013; Frazier et al., 2013; Olcay et al., 2021). Metin and Kayalı (2018) stated that with good OHS practices, approximately 98% of workplace accidents and almost all occupational diseases can be prevented. The OHS measures that can be taken at workplaces include eliminating or controlling hazards at their source, using less hazardous techniques and methods, designing work systems that minimize risks, and ensuring the use of PPE. In many sectors, it may not be possible to eliminate or control risks at their sources. In such cases, it is preferable to take measures that reduce the extent and impact of existing risks. The primary measures taken by enterprises to ensure OHS include employing OHS personnel, risk assessment, environmental monitoring, health examinations, training, provision of PPE, installation of safety warning signs, the use of advanced technology, and emergency management plans. Employment of Occupational Health and Safety Personnel Employers are obliged to employ OHS personnel (such as OHS experts, workplace doctors, and other health workers) in numbers and qualifications that vary according to the hazard class of the work branch and the number of employees. Article 6 of the OHS Law, currently in force in Turkey, states, "*The employer assigns an occupational safety specialist, workplace doctor, and, in workplaces classified as Highly Hazardous with 10+ employees, other health personnel from among the employees. If there are no staff among the workforce who hold the required qualifications, all or part of this service may be procured from joint health and safety units*." The salaries and insurance expenses of OHS staff constitute significant costs for employers and are often overlooked. Risk Assessment One of the most important responsibilities legally mandated for employers regarding OHS is to conduct or have conducted risk assessments. Risk assessment includes identifying hazards that may arise in the workplace due to raw materials, machinery/equipment, workplace conditions, and production techniques, determining risk classes, and taking measures to minimize their harm. Risk analyses, initially carried out when the business is first established, are repeated in cases of changes in technology, production processes, or workplace conditions, and after any workplace accident or occupational disease. In forest enterprises, the employers are Forest Management Chiefs, who are responsible for ensuring that risk assessments are carried out for all forestry operations in all management subunits within the forest enterprise. In forest operations, risk assessments are often outsourced to specialist OHS firms. However, the relevant legislation clearly states that if risk analyses are outsourced, the employers' responsibility does not change, and they remain accountable for all deficiencies and errors in the outsourced work. Conducting risk assessments for each of the numerous types of forestry activities, each with unique site conditions and dynamics, incurs significant costs. Additionally, implementing measures developed to eliminate or minimize the identified hazards is a major cost item. Environmental Monitoring Among the most important OHS-related hazards in the workplace are dust, noise, vibration, gas, and smoke, depending on the nature of the work. The degree of harm posed by these hazards is determined by conducting environmental measurements for each hazard and comparing them with the limit values specified in the relevant regulations. Especially in high-risk jobs, personal (such as PPE) and collective (such as isolation or use of less hazardous techniques/technologies) protective measures that need to be taken according to the degree of risk associated with these parameters can be expensive. The use of devices required to measure each parameter, and the interpretation of the results require expertise. Therefore, environmental monitoring in workplaces is often contracted. This, in turn, incurs additional costs for employers.

Health Screening

It is envisaged that workers undergo periodic health screenings based on the hazard class of the workplace and the nature of their work (Low Hazard: every 5 years, Hazardous: every 3 years, and Very Hazardous: annually) (OHS Law, 2012). In addition to standard measurements conducted during health screenings, special examinations of relevant organs, such as the lungs, heart, respiratory system, ears, eyes, and skin, are also required according to the exposure risks arising from the specific nature of the work performed. All health screening costs are covered by the employer.

Training

According to Article 17 of the Occupational Health and Safety Law, employers are responsible for providing OHS training to employees before they start work, when there is a change in the workplace or job, when work equipment is changed, or when new technology is introduced. Article 6 of the Regulation on Procedures and Principles of Occupational Health and Safety Training for Employees specifies that employers are obliged to provide orientation training before employees start work, periodic training (Low Hazard: every 3 years, Hazardous: every 2 years, and Very Hazardous: annually) considering new and emerging risks, and refresher training before returning to work for those who have been away for more than six months (Official Gazette No. 28648, 2013). Employers or institutional staff may provide some training, but external training may also be arranged for employees when necessary. In addition to all expenses related to training, any time spent by employees on training is counted as working time and compensated as such, representing an additional cost.

Failure to document that employees have received the legally mandated training within the required timeframes in the event of a work accident or occupational disease can result in substantial penalties for employers.

Provision of personal protective equipment

It is the employer's responsibility to supply employees with the type and characteristics of PPE needed in the workplace and to ensure its use. Furthermore, PPE must be replaced by the employer in the event of breakage, malfunction, or loss of function. In forestry, the wide variety of activities involving different hazards necessitates the determination and supply of the most suitable PPE for each job. While in wood harvesting activities, resistance of PPE to cuts and impacts is a priority, in forest fire control, fire resistance becomes more important. Therefore, PPE such as helmets, masks, face shields, and work clothes used in one forestry job may not be suitable for use in other forestry jobs. It is stipulated by law that no deductions or payments can be made by employees for the provision of PPE.

Occupational safety warning sign equipment

Workplaces must be equipped with warning signs and boards that alert workers to the potential hazards they may be exposed to, depending on the raw materials used, technology, workplace conditions, and the nature of the work. All signs must be prepared according to their warning function and placed in appropriate locations where danger exists. It is the employer's responsibility to procure warning signs and boards that are designed for the specifics of each type of work, to ensure that they are properly placed in work areas, maintained, and replaced when necessary.

Use of advanced technology

When minimizing risks in workplaces, the first preference is to eliminate the risk at its source. Where this is not possible, hazardous elements are replaced by less dangerous ones. In this method, if the levels of physical hazards such as noise, sound, dust, or smoke produced by the machines/equipment used exceed the relevant limit values, it is recommended that they be replaced with less harmful alternatives. In forestry, the very high acquisition cost of the machines used constitutes a significant expense for employers when renewing technologies.

Emergency management plan

Costs incurred before an emergency include identifying risks and taking preventive measures, preparing procedures, procuring equipment to be used in the event of a disaster, and training employees.

3.2. Costs of occupational accidents and diseases

The costs incurred following occupational accidents and diseases are grouped into two categories: direct and indirect costs (Figure 2). Indirect costs related to occupational accidents are much higher than direct costs. Globally, the costs of occupational accidents and diseases correspond to 5.4% of the world's annual GDP and approximately 3.3% of that of EU countries (ILO, 2022). In the USA, the annual cost of workplace slips, trips, and falls alone is approximately $10 billion (Nenonen, 2013). The types of direct and indirect costs arising from occupational accidents and diseases are summarized below.

3.2.1. Direct costs

The main direct costs for OHS are the payments made for damages to the workforce, machinery/equipment, and the workplace as a result of occupational accidents or diseases. In addition, expenses caused by production time losses in the enterprise are included in this group. The elements classified as direct costs are summarized as follows:

Treatment expenses

If the employer delays fulfilling their obligation to cover the treatment expenses of workers who have suffered a workplace accident, resulting in an extension of the victim’s treatment period, permanent disability, or an increase in the degree of incapacity, the employer will be liable for all resulting damages.

Court costs

These costs include trial expenses and attorney fees arising from lawsuits filed by workers or their families exposed to workplace accidents or occupational diseases.

Penalties

These are expenses that employers are required to pay due to their failure to implement OHS measures mandated by current legal regulations. Article 4 of the OHS Law states that in the event of a workplace accident resulting in death or injury, an employer who is primarily responsible for not implementing OHS measures shall be penalized. In cases of workplace accidents occurring at legal entities, penalties are imposed on individuals acting on behalf of the legal entity and authorized in matters of occupational safety (OHS Law, 2012). Furthermore, in workplace accidents, if occupational safety specialists and workplace doctors are found at fault, they are subject to penalties.

Compensations

Compensation is the payment made to workers or their relatives as a result of work accidents and occupational diseases that occur due to the employer's shortcomings or inadequacies in OHS practices. Compensation is the money paid directly to the heirs of those who died as a result of the accident and to those who have become disabled or injured. Compensations to be paid are of two types: pecuniary compensation (permanent incapacity, temporary incapacity, care expenses, funeral expenses, and compensation for deprivation of support for relatives of the deceased) and non-pecuniary compensation. The amount to be paid as pecuniary compensation is calculated based on the victim's salary, age, gender, degree of disability, and degree of fault. Non-pecuniary compensation is paid to relieve the pain, sorrow, and psychological distress caused by accidents. There are no clear legal regulations regarding the calculation of non-pecuniary compensation. This compensation is determined by considering the financial status of the parties, degrees of fault, magnitude of non-pecuniary damage, and characteristics of the accident.

Machine/equipment repair and replacement expenses

In workplace accidents, not only is the workforce harmed, but various damages can also occur to the tools and machines used. Replacing tools and machines that have become completely unusable with identical or less hazardous alternatives incurs a significant expense. Another cost arises from the expenditures incurred for the repair or maintenance of damaged vehicles/machines.

3.2. Indirect Costs

Indirect costs are unbudgeted expenses related to workplace accidents that have long-term effects and negatively impact a business's profitability. Indirect costs, which represent approximately 70% of the total costs resulting from a lack of OHS implementation, are generally challenging to calculate because they often involve intangible factors. The elements that fall under the category of indirect costs can be summarized as follows.

Spatial analyses have also shown that landslide susceptibility varies with stand structure and site characteristics, indicating that such terrain-related risks can indirectly contribute to unsafe working environments and unplanned cost increases in forestry operations (Gümüş, Hatay & Ünver Okan, 2019).

Lost workdays

This covers all the time injured workers who are unable to work because of an accident. Employers are obliged to pay a full day's wage to employees who have had an accident and are unable to work for the remainder of the day. These costs include reduced work efficiency due to workforce shortages and payments made to injured employees, even when they are not working.

Disruptions in production

Production disruptions stem from both the loss of labour caused by the accident victim and other employees affected by the incident, as well as from machines damaged in the accident. Production delays due to workforce loss occur because injured workers cannot return to work until they have recovered, and other workers at the workplace lose time helping the injured, waiting for medical teams, or recovering from the shock of the accident. This is especially true if qualified employees, who are difficult to replace, are unable to work for a long period or leave the job, which may result in a temporary halt in operations. The costs related to machinery damage in an accident are twofold. The first comprises expenses incurred in repairing damaged tools or machines or purchasing new ones, depending on the severity of the damage. The second involves the partial or total suspension of work until new machines are provided or repairs are completed. Such situations may lead to businesses operating with lower performance, failing to fulfil orders on time, and incurring losses due to the workforce sitting idle. In forestry operations, production disruptions and unplanned work stoppages may also result from environmental degradation processes such as erosion and slope instability on forest roads (Hatay et al., 2024), which create unsafe working conditions and indirectly increase OHS-related costs (Mısırlıoğlu, Gümüş & Yoshimura, 2022; Mısırlıoğlu & Gümüş, 2024)

Adaptation and training of new workers

The adaptation and training of a new worker to replace an experienced employee who has had an accident represents a significant cost in terms of extra expenses and time. In particular, after the loss of a qualified worker, the performance of the new employee will be low until they get used to the job, and they will not be able to work efficiently.

Productivity loss among other workers

In workplaces where occupational accidents or occupational diseases occur, workers who are not directly affected may experience significant morale loss and trauma. The loss of motivation and unwillingness to work caused by this situation can slow down work or lead to a decrease in work quality.

Loss of image

Work accidents can damage the reputation of employers and businesses, negatively affecting their market preferences. In addition, a business where a workplace accident has occurred may suffer losses as qualified staff move to other companies. Muñiz et al. (2009) emphasized that a reduction in the costs of occupational accidents and diseases in businesses significantly contributes to improving the company's image and increasing work productivity.

4. Conclusion

Almost all forests in Turkey are state-owned and managed by the GDF, a public institution. In forestry activities, which are highly diverse and independent of each other, a small proportion of permanent workers and a large proportion of seasonal workers are employed in forestry activities. In particular, in very risky tasks carried out within forests, such as timber harvesting, extraction from the stand, afforestation, and fighting forest fires, most of the work is performed by seasonal workers. Most seasonal forestry workers do not have insurance related to their forestry work. This situation makes it difficult to obtain accurate and comprehensive data on workplace accidents or occupational diseases that occur during forestry activities. In addition, in legal regulations concerning OHS, employers are held responsible for activities such as conducting risk analyses, providing and ensuring the use of PPE, delivering training, and conducting regular health screenings. However, these activities are often neglected. Most accidents that occur during forestry activities, categorized as highly risky or risky, result in death or severe injury. If it is determined that the legal responsibilities regarding OHS have not been fulfilled or that necessary precautions have not been taken in the event of a workplace accident or occupational disease, managers may face high costs and penalties. Assessing the cost of OHS measures in forestry is necessary to use business resources more effectively, increase institutional efficiency, and improve general safety standards in the industry. The reduction in workplace accidents and occupational diseases due to OHS practices and measures will contribute to decreasing injuries and fatalities among workers. This will also minimize the compensation payments that businesses might have to make to injured parties or their relatives due to workplace accidents. This chapter explains the practices that need to be implemented for OHS in forestry activities and the costs that may arise due to the absence of such practices. The costs that may arise from insufficient OHS measures are discussed in detail under two categories: direct and indirect costs. In light of the information presented here, it is possible to raise awareness among forestry managers regarding the financial losses they may encounter depending on whether they implement OHS practices. Thus, by implementing the necessary OHS measures, it may be possible to reduce workplace accidents/occupational diseases in forestry activities and minimize the costs that could arise from such incidents.

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Chappter II - Economics of Forest Carbon Sinks: From the Case of Finland to a Perspective on Turkey

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1. Introduction

Global climate change, one of the most critical environmental and economic challenges of the twenty-first century, is reshaping the development policies of states. Rising greenhouse gas emissions constitute not only an environmental threat but also a key factor shaping economic sustainability in the energy, agriculture, and forestry sectors (Bayramoğlu & Demir, 2018; IPCC, 2023; Stern, 2007). Forest ecosystems, through their capacity to sequester carbon dioxide in biomass and soils, represent one of the most effective natural sinks against climate change (Bayramoğlu & Toksoy, 2010; Toksoy et al., 2020; FAO, 2022; Grassi et al., 2021; Bayramoğlu et al., 2025a)

The international climate regime has progressively transformed this natural function into an economic value. The process that began with the 1972 Stockholm Conference gained institutional character with the adoption of the United Nations Framework Convention on Climate Change (UNFCCC) in 1992 and the subsequent Kyoto Protocol in 1997 (UNFCCC, 1992; Altıner, 2011). The flexibility mechanisms introduced under the Kyoto Protocol—Emissions Trading, the Clean Development Mechanism, and Joint Implementation—turned carbon into a tradable economic asset (Sohngen & Mendelsohn, 2003; van Kooten & Johnston, 2016). Consequently, carbon sinks have come to be perceived not merely as environmental services but as market-based economic instruments. In this context, the concept of the “carbon sink economy” considers the carbon storage capacity of forests not only as a biophysical property but also as an economic and managerial value (Sedjo & Marland, 2003; Lahnalampi, 2024). In his study on Finland, Tuomas Lahnalampi (2024) demonstrated that carbon constitutes a strategic component of the national carbon budget rather than solely an environmental value. Finland’s market-oriented framework has turned carbon into a source of income for private forest owners (Grassi et al., 2021).

In Türkiye, discussions on forest carbon have accelerated since the 2010s. The country’s accession to the UNFCCC and the Paris Agreement has established the institutional foundations of national carbon policies (ÇŞİDB, 2024). Furthermore, carbon pricing frameworks developed under the European Green Deal directly influence Türkiye’s forestry sector (Aktaş, 2024). The “National Afforestation Carbon Standard Proposal” developed under the leadership of the General Directorate of Forestry (OGM) represents Türkiye’s first technical certification model (Pamukçu Albers et al., 2018). However, Kılıç Hernandez (2020) and Körpe Duru (2025) identified major obstacles to the development of the carbon economy, including legal ambiguities, lack of financial incentives, and insufficient monitoring and verification.

Although Finland and Türkiye possess similar ecological potential with respect to forest carbon policies, their governance models differ substantially. In Finland, approximately 60% of forests are privately owned, and carbon rights are recognized within the framework of ecosystem services (Lahnalampi, 2024; Grassi et al., 2021). In Türkiye, by contrast, 99% of forests are state-owned, and carbon is regarded as a public environmental asset (Kılıç Hernandez, 2019). While Finland’s strong institutional structure (Ministry of Agriculture and Forestry, Luke, Metsäkeskus) ensures transparency in carbon market operations, Türkiye’s multi-institutional structure leads to coordination challenges in practice (Körpe Duru, 2025). Additionally, Finland is integrated into the EU Emissions Trading System (EU ETS), whereas Türkiye remains active primarily in voluntary carbon markets (ÇŞİDB, 2024). Despite these differences, both countries place carbon sinks at the center of their national climate strategies and view them as instruments of sustainable development.

The economics of forest carbon sinks constitutes an emerging field that integrates nature-based solutions with market mechanisms. However, the effectiveness of such economic and institutional frameworks largely depends on human factors, including working conditions, operational efficiency, and the perceptions of forestry professionals involved in implementation processes (Ünver Okan & Acar, 2018; Ünver Okan, 2020; Ünver & Kurdoğlu, 2024). Building on the Finnish case, this study conducts a comparative examination of Türkiye's institutional and economic framework to analyze the economic, legal, and managerial dimensions of forest carbon. The research employs a qualitative comparative analysis, drawing on international literature, policy documents (FAO, UNEP, World Bank, ÇŞİDB, OGM), and economic indicators. Accordingly, the study aims to provide a conceptual and practical framework for developing a sustainable forest carbon economy model for Türkiye. The study is limited to a comparative analytical approach and does not incorporate quantitative modeling to measure the dynamic components of the carbon economy.

1.1. Economic Foundations of Forest Carbon Sinks

The acceleration of global climate change has necessitated a renewed assessment of the relationship between economic growth and natural capital. Since the second half of the twentieth century, the discipline of environmental economics has emphasized that environmental systems constitute capital assets that carry not only ecological but also economic value (Costanza et al., 1997; Pearce et al., 2006; Daly & Farley, 2011). This perspective is grounded in the natural capital approach, which regards the services provided by nature not as "non-market benefits," but as inputs to the economic production process (Daily, 1997). Moreover, forest ecosystems play a critical ecological and economic role in combating climate change due to their capacity to absorb atmospheric carbon dioxide through photosynthesis and store it in biomass (Grassi et al., 2021; FAO, 2022). Through carbon sequestration processes, forests offset a portion of the emissions generated by human activities; therefore, the concept of "carbon sinks" has gained increasing prominence in both environmental policy and financial analyses (Nabuurs et al., 2007; Pan et al., 2011; Sills et al., 2020).

1.1.1. Defining Carbon as an Economic Value

The economic value of carbon derives from two principal concepts: (i) the social cost of greenhouse gas emissions (the Social Cost of Carbon, SCC) and (ii) the opportunity cost of carbon sequestration. Stern (2007) and Nordhaus (2013) note that these two concepts are decisive in the economic analysis of carbon. The social cost of emitting one ton of carbon dioxide—such as health effects and increased disaster risks—is estimated to be between USD 85 and 190 (EPA, 2022; IPCC, 2023). In contrast, the sequestration of the same amount of carbon by forest ecosystems prevents this economic loss while strengthening the sustainability of ecosystem services (FAO, 2022; UNEP, 2023). In this regard, the carbon pricing approach has become a fundamental economic instrument of climate policy (World Bank, 2023). The carbon price represents the unit cost of emission reduction or carbon sequestration, making carbon a market-priced environmental service (Tietenberg, 2018).

The flexibility mechanisms initiated by the Kyoto Protocol (1997)—International Emissions Trading (IET), the Clean Development Mechanism (CDM), and Joint Implementation (JI)—enabled carbon to become a tradable economic asset (Altıner, 2011; van Kooten & Johnston, 2016). This process gave rise to the concept of the carbon market, transforming carbon into not only an environmental component but also a financial commodity (Hepburn et al., 2020). Defining carbon as an economic asset has made it possible to integrate forest ecosystems into the market economy. Forests are now evaluated not only as "green areas" but also as nature-based financial assets that generate economic benefits through carbon storage. This perspective supports market instruments such as carbon credits, carbon certificates, and payments for ecosystem services (Lahnalampi, 2024; Sills et al., 2020; FAO, 2022).

Approximately 75% of Finland's land area is covered by forests, making these regions a strategic component of the national carbon budget (Luke, 2023). In Finland, carbon sinks are defined as an economic resource under both the EU Emissions Trading System (EU ETS) and national forestry policies, and a system has been established in which carbon credits generate income for private forest owners (Lahnalampi, 2024). Thus, carbon has become not only a climate policy instrument but also a productive element of the national economy (Grassi et al., 2021).

The Finnish example represents one of the most successful applications of this transformation. In Türkiye, the economic value of carbon has only recently gained attention. Participation in voluntary carbon markets, commitments under the Paris Agreement, and the National Emission Reduction Plan have increased the development of carbon projects (ÇŞİDB, 2024). However, carbon pricing and valuation remain limited in Türkiye because structural factors—such as the legal ownership regime, lack of financial incentives, and deficiencies in MRV infrastructure—still hinder the recognition of carbon as an "economic resource" (Körpe Duru, 2025; Kılıç Hernandez, 2019; Kılıç Hernandez, 2020).

The economic value of carbon is not limited to its market price. When social cost, environmental benefits, and opportunity cost are evaluated together, forest carbon projects emerge as a strategic investment area for national development policies. Pearce et al. (2006) and Barbier (2019) emphasize that carbon sinks provide both direct economic benefits (income, employment, exports) and indirect societal gains (climate adaptation, rural development, biodiversity). In this respect, forest carbon represents a cornerstone not only of environmental economics but also of the broader sustainable development economy.

1.2. Economic Modeling of Forest Carbon

Forest carbon projects are evaluated in terms of their economic feasibility using classical financial analysis tools commonly applied in long-term capital investments, as such projects constitute not only environmental but also economic investment decisions. In this regard, the analysis typically consists of three fundamental indicators: Net Present Value (NPV), Internal Rate of Return (IRR), and Benefit–Cost Ratio (B/C) (Sohngen & Mendelsohn, 2003; Sedjo & Marland, 2003; Nordhaus, 2013; Stern, 2007).

Net Present Value (NPV) is calculated by discounting the revenues obtained from carbon sequestration projects (e.g., carbon credit sales, payments for ecosystem services) and the project costs (afforestation, monitoring, verification) to their present value using a discount rate (r) (Pearce et al., 2006). Here, the discount rate is of critical importance, as carbon projects are long-term investments (20–40 years). Lower discount rates (2%–4%) reflect a conservation-oriented approach that preserves environmental benefits, whereas higher rates devalue future ecological gains in favor of present decisions (Stern, 2007; Nordhaus, 2013; Heal, 2017; Pindyck, 2019). In the Finnish case, Lahnalampi (2024) calculated the net present value of carbon sequestration as €300–600 per hectare using a 3% discount rate. This value demonstrates that carbon can be regarded not only as an environmental component but also as an economic capital asset.

Complementing NPV analysis, another important indicator that measures the internal efficiency of a project is the Internal Rate of Return (IRR). IRR represents the project's internal rate of return—that is, the discount rate at which NPV becomes zero. If the IRR exceeds the social or financial discount rate, the project is considered economically feasible (Gittinger, 1982; Pearce, Atkinson & Mourato, 2006; Stern, 2007; Nordhaus, 2013; Boardman et al., 2018; Tietenberg, 2018). In Finland, average IRR values for forest carbon projects range between 5% and 7% (Luke, 2023). This is made possible by stable carbon prices (18–22 €/tCO_2). In Türkiye, however, relatively low voluntary market prices (7–9 €/tCO_2) often result in IRR values falling below zero, limiting the long-term financial attractiveness of carbon projects (ÇŞİDB, 2024).

In addition to returns, the economic efficiency of carbon projects must also be measured. At this point, the Benefit–Cost Ratio (B/C) method becomes relevant. B/C represents the ratio of total benefits (B) to total costs (C); if the ratio exceeds 1, the project is considered economically viable (Gittinger, 1982; Pearce & Turner, 1990; Hanley & Barbier, 2009; Daly & Farley, 2011; Boardman et al., 2018; Tietenberg, 2018). Carbon price, project duration, and monitoring costs are the primary determinants of this ratio. In Finland, the average B/C ratio for carbon projects is around 1.4 (Lahnalampi, 2024), demonstrating the contribution of carbon sequestration to forestry revenues. In Türkiye, this ratio is generally below 1 due to shorter project durations and lower market prices (Körpe Duru, 2025; Kılıç Hernandez, 2019).

Moreover, the economic performance of carbon sink projects must be assessed not only through financial indicators but also through the cost-effectiveness of emission reductions. For this reason, the concept of Marginal Abatement Cost (MAC) becomes important. MAC represents the unit cost of removing one ton of carbon from the atmosphere or preventing its emission (Sohngen & Mendelsohn, 2003). If the market price of carbon exceeds the MAC value, the project is economically meaningful; otherwise, it is not financially sustainable (Tietenberg, 2018). In addition, MAC is used to compare the cost-effectiveness of alternative policy instruments for emission reduction (Pindyck, 2019; Heal, 2017). Lahnalampi (2024) combined the NPV–IRR–MAC framework in the Finnish case to develop an optimal carbon management model. This model demonstrates that the economic value of forest carbon stocks depends not only on market prices but also on carbon permanence, leakage risk, and land-use costs. In Finland, this approach has created economic incentives for private forest owners while increasing the balancing capacity of the national carbon budget (Luke, 2023; FAO, 2022).

Preferring lower discount rates, incorporating social benefits into the model, and ensuring long-term financial stability are essential for the development of a carbon sink economy. Türkiye needs to integrate the economic value of carbon at both market and public policy levels and thereby adopt an approach that recognizes forest ecosystems as ecological capital (Kılıç Hernandez, 2019; Körpe Duru, 2025).

1.3. Economic and Ecological Balance in Carbon Sinks

The sustainability of the forest carbon economy depends not only on cost-effectiveness criteria but also on the long-term resilience of ecosystems. The integration of carbon sinks into the economy often raises the issue of balancing "economic efficiency" with "ecological sustainability." If carbon sequestration projects are planned solely on the basis of short-term financial returns, this may lead to long-term ecosystem degradation, loss of biodiversity, and a weakening of carbon storage capacity (Grassi et al., 2021). Therefore, FAO (2022) and UNEP (2023) emphasize that the carbon economy must be approached through a multidimensional management framework. This approach is built on the "triple bottom line" model, which evaluates environmental benefits, economic profitability, and social inclusiveness together. Within this model, not only the financial returns of carbon sequestration activities but also their impacts on local welfare, rural employment, and ecosystem integrity are assessed.

A successful example of this approach is Finland. The country has aligned economic incentives with ecological conservation goals under the principle of "multifunctional forest management" and has directed a portion of carbon revenues back into ecosystem restoration (Lahnalampi, 2024; Luke, 2023). Similarly, it is recommended that Türkiye integrate carbon finance mechanisms with the protection of forest ecosystems and allocate a certain percentage of carbon revenues to reforestation, monitoring, and local development activities (Kılıç Hernandez, 2019; Körpe Duru, 2025). In this way, the carbon economy can transcend being merely a market-based instrument and evolve into a holistic component of sustainable development.

2. Forest Carbon Management in Finland: Economic System, Policies, and Governance Structure

Finland is regarded as one of the most advanced examples of forest carbon management due to its high forest cover (over 75%), its well-developed carbon accounting infrastructure, and its carbon market structure integrated with European Union climate policies (Lahnalampi, 2024; Luke, 2023). The country treats its forest resources not only as ecological assets but also as economic and strategic resources, placing carbon sinks at the center of its sustainable development and energy policies. The Finnish model offers a multilayered governance structure that integrates market-based carbon management with ecological conservation principles.

Forest carbon management in Finland will be examined along three main axes: (i) the economic system and market mechanisms, (ii) national and regional policy frameworks, and (iii) the institutional and administrative structure. In this way, the model presented in Lahnalampi's (2024) economic analysis will be assessed through its implementation at the national level, and the financial, political, and institutional dimensions of forest carbon will be evaluated in a holistic manner.

2.1. Economic Framework and Market Mechanism of Forest Carbon Management in Finland

Finland possesses an economic structure fully aligned with the European Union's low-carbon development objectives, and the forestry sector lies at the center of this transition (Luke, 2023). The forestry sector accounts for approximately 4% of Finland's Gross Domestic Product and provides more than 20% of employment in rural areas (FAO, 2022). Therefore, forests are regarded not only as ecological assets but also as productive capital components of the national economy. Tuomas Lahnalampi's (2024) Economics of Carbon Sinks – Case of Finland proposes a unique model that integrates this economic system with carbon markets. According to Lahnalampi, carbon sinks in Finland are defined as "nature-based economic assets," and their economic value is calculated through three components: (i) carbon sequestration capacity, (ii) market price, and (iii) secondary benefits of ecosystem services (e.g., water regulation, soil fertility). The model demonstrates that forest carbon is not merely an environmental attribute but also an investment asset with economic rationality. The low discount rate applied in Finland (3%) and its long-term planning approach enhance the financial value of carbon and transform it into a strategic asset class within the national economy (Lahnalampi, 2024; Heal, 2017).

The forest carbon management system in Finland is supported by market-based mechanisms. Since 2005, the country has been fully integrated into the European Union Emissions Trading System (EU ETS), thereby linking carbon prices to an internationally standardized market structure (European Commission, 2023). In addition, for land-use and forestry activities outside the ETS (the LULUCF sector), a national carbon certification system has been developed. Under this system, private forest owners obtain certificates based on the amount of carbon sequestered and can sell these certificates on voluntary markets (Luke, 2023; FAO, 2022). Certificate prices vary depending on carbon density, permanence, and verification costs, generally ranging between 18–22 €/tCO_2 (Lahnalampi, 2024). This price stability makes forest carbon projects economically attractive, and the country's carbon sink capacity functions as a market instrument that stimulates private sector investment.

The economic structure of forest carbon management in Finland relies not only on market prices but also on the regulatory and incentivizing role of the state. The government provides private forest owners participating in carbon sequestration and monitoring activities with tax exemptions, long-term credit facilities, and reinvestment incentives linked to carbon revenues (FAO, 2022; Luke, 2023). The Finland National Climate and Energy Strategy, implemented in 2019, defined carbon sequestration as a sustainable component of forestry revenues and mandated the reinvestment of income generated from carbon credits into reforestation, monitoring infrastructure, and rural development projects (Ministry of the Environment Finland, 2020). This policy ensures that the carbon market operates not only as a profit-oriented mechanism but also as a tool for ecological reinvestment. The redistribution of carbon market revenues is one of the most distinctive features of the Finnish model. Approximately 30% of income from carbon credits is allocated to reforestation and carbon monitoring, while around 20% is directed toward low-carbon technologies and rural employment programs (Lahnalampi, 2024; FAO, 2022). This practice creates a circular financial structure that reinforces the environmental sustainability of the carbon economy. Lahnalampi (2024) defines this cycle as the "carbon reinvestment chain":

carbon sequestration → carbon credit → economic income → ecological investment → increased carbon sequestration capacity. Thus, Finland positions carbon not merely as a market commodity but as an element of sustainable capital flow.

The forest ownership structure in Finland is also a factor that enhances the economic efficiency of carbon management. Approximately 60% of forest areas in the country are privately owned—a figure significantly higher than the European average (Luke, 2023). Private forest owners, typically small-scale family enterprises, participate in carbon markets individually or through cooperatives (Hyytiäinen & Tahvonen, 2003). Institutions such as the Finnish Forest Centre and Luke (Natural Resources Institute Finland) provide technical support to these forest owners in carbon accounting, verification, and market access. As a result, the carbon economy has become not only an investment opportunity for large-scale actors but also a tool for income diversification for rural households. The multilayered structure of the economic framework is the key element that ensures the stability and inclusiveness of Finland's carbon market. Price fluctuations in the market are balanced through state regulatory interventions and the cyclical reinvestment of carbon credit revenues (European Commission, 2023). This model differs from the classical supply–demand cycle by simultaneously targeting economic stability and ecological integrity. The Finnish experience demonstrates that a carbon sink economy can be defined not only by financial returns but also by long-term social and environmental benefits.

2.2. Forest Policies and Legal Regulations in Finland

Finland regards forest management not only as an economic sector but also as a strategic policy domain in the fight against climate change. The country's policy architecture is shaped in full alignment with the European Union's 2050 Climate-Neutral Economy Strategy, with the protection and enhancement of carbon sinks constituting a fundamental component of national climate plans (European Commission, 2023; FAO, 2022). The Ministry of the Environment Finland (2020) defines national climate targets around the concept of a “carbon-neutral forest economy,” which encompasses both sustainable forest management and the economic and legal value of carbon sinks. Finland’s forest policy foundations were reinforced in the post-Kyoto Protocol era. The Forest Act (Metsälaki) and the Nature Conservation Act, enacted in the early 2000s, granted legal protection to the principles of sustainable forest management (Government of Finland, 2013). This legislation represents one of the first legal frameworks in Europe to explicitly safeguard the carbon sequestration function of forests. The updated Forest Strategy 2025, published in 2014, serves as an integrated policy document that manages multifunctional forest use, the bioeconomy, and carbon storage simultaneously (Luke, 2023). According to the strategy, forest management is not solely an economic activity based on timber production but also a public policy that integrates carbon storage, biodiversity conservation, and rural well-being.

The EU-level counterpart to Finland’s national forest policies is defined under the Land Use, Land Use Change and Forestry (LULUCF) Regulation (EU Regulation No. 2018/841). The LULUCF system requires member states to monitor and report the emissions and removals balance from forest-related activities (European Commission, 2023). Within this framework, Finland monitors and reports its annual carbon balance based on data from the National Forest Inventory (NFI). The Finnish Forest Centre and the Natural Resources Institute Finland (Luke) are responsible for managing this data system and conduct national carbon stock updates every five years (Luke, 2023). As a result, Finland is among the few EU member states that fully meet their LULUCF obligations.

At the legal level, Finland has also adopted specific legislation that defines carbon sequestration as a property right and regulates market-based transactions. The Carbon Sequestration and Ecosystem Services Act, enacted in 2019, defines the right to sequester carbon as an economic property right of forest owners (Ministry of the Environment Finland, 2020). This law provides legal guarantees for the transfer of carbon credits to third parties, their use as collateral, and other forms of securitization. Thus, carbon certificates have become not only environmental instruments but also legally recognized financial assets. This approach represents one of the most comprehensive integrations of carbon into private property law in Europe (Kettunen & Romppanen, 2021).

Finland's policy and legal architecture combines both top-down (state and EU policies) and bottom-up (local forest ownership and voluntary market participation) governance principles to ensure the long-term sustainability of carbon sinks. This dual model is referred to by environmental legal scholars as a multi-level governance structure (Nilsson & Krug, 2020). The structure distributes carbon storage responsibility not only to the state but also to individual forest owners and private sector actors, thereby enhancing both the effectiveness and inclusiveness of policy implementation. Consequently, forest carbon management in Finland is designed as an integrated system at both political and legal levels. There is a strong alignment between national law, EU legislation, and local practices. This system enables Finland to manage carbon sequestration capacity not only as a component of climate policy but also as a legally defined economic asset. In this regard, the Finnish model represents a replicable policy framework for forest-rich economies such as Türkiye.

2.3. Governance and Institutional Structure in Finland

Forest carbon management in Finland is built upon strong institutional coordination and a multi-actor governance structure. The main actors in the country include the Natural Resources Institute Finland (Luke), the Finnish Environment Institute (SYKE), the Finnish Forest Centre (Metsäkeskus), the Ministry of the Environment, the Ministry of

Agriculture and Forestry, and the Energy Authority. These institutions operate at different stages of forest carbon management—data generation, monitoring, verification, certification, and market transactions (Luke, 2023; FAO, 2022). This institutional architecture enables Finland's forest economy to be governed through a "science-based governance" approach. Luke is the technical authority responsible for the national carbon accounting and forest data system. The institution prepares the National Forest Inventory (NFI) reports published every five years and monitors changes in carbon stocks (Luke, 2023). These data are integrated with the ecological assessments conducted by SYKE. SYKE evaluates the ecosystem impacts on carbon stocks by monitoring land-use changes and biodiversity losses, particularly in the LULUCF sector (Soimakallio & Pihlainen, 2023).

The Finnish Forest Centre (Metsäkeskus) functions as an interface between forest owners and the private sector. The institution provides technical support for carbon sequestration projects, assists in carbon measurement and verification processes, and offers advisory services regarding access to voluntary carbon markets. A distinctive aspect of this structure is that it incorporates not only large-scale investors but also small forest owners and rural cooperatives into the carbon economy (Hyytiäinen & Tahvonen, 2003). Thus, Finland has developed an inclusive and participatory system for carbon management. The legal framework for institutional operations is clearly defined in the Carbon Sequestration and Ecosystem Services Act (2019) and the Forest Strategy 2025. These documents specify the mandates of public institutions, delineate authority boundaries, and establish data-sharing mechanisms (Ministry of the Environment Finland, 2020).

The governance system in Finland also includes an MRV (Measurement, Reporting and Verification) infrastructure based on international standards. The MRV system has been developed in accordance with IPCC (2006, 2019) guidelines and is supported by digital databases (FAO, 2022). Carbon sequestration levels are monitored through remote sensing and field measurements, and the data are integrated into the European Commission's EU Monitoring Mechanism Regulation (MMR) system (European Commission, 2023). With this structure, Finland is regarded as a model of data accuracy and international consistency in carbon accounting. Another noteworthy feature at the institutional level is the effectiveness of the public–private partnership (PPP) model. Private forestry companies, universities, and public research institutions work together to develop carbon measurement technologies, certification standards, and ecosystem service models (Luke, 2023; Nilsson & Krug, 2020). This approach ensures not only economic efficiency but also scientific robustness.

The success of Finland's governance model is closely associated with the continuity of institutional coordination and the transparency of data sharing. Inter-institutional information flow is carried out through the national platform known as the Open Forest Data Initiative. This platform consolidates carbon data submitted by forest owners into a centralized database and makes it accessible to all stakeholders (Luke, 2023). Consequently, decision-making processes become evidence-based, and a dynamic feedback loop is established between policy design and market implementation.

In conclusion, Finland's institutional structure exhibits a multilayered governance architecture in forest carbon management. Public institutions, research institutes, the private sector, and individual forest owners coordinate toward a shared ecological–economic objective. This structure provides a model that safeguards both market stability and ecosystem integrity, while also offering forest-rich countries such as Türkiye a practical roadmap for achieving institutional integration in carbon management.

2.4. From the Finnish Model to Türkiye: Adaptation Potential and Transfer Dynamics

Finland provides a multilayered model in the management of carbon sinks, integrating economic, political, and institutional dimensions. The country evaluates carbon not merely as a component of climate policy but as a strategic element of national economic capital, transforming market mechanisms into a financial framework that supports ecological sustainability (Lahnalampi, 2024; Luke, 2023; FAO, 2022). This approach is grounded in the concept of nature-based valuation and corresponds to the idea of a “sustainable carbon economy,” which integrates the biophysical capacity of carbon sequestration with its economic returns (Heal, 2017; Grassi et al., 2021). Finland’s success in this model has been achieved through the guiding role of the state (Ministry of the Environment Finland, 2020), the active participation of private forest owners (Hyytiäinen & Tahvonen, 2003), and science-based data governance (Luke, 2023; (Soimakallio & Pihlainen, 2023). The Finnish model has created a market discipline that enhances the economic value of carbon while simultaneously maintaining ecosystem integrity. This structure enables the national carbon balance to be monitored and reported in alignment with the EU’s LULUCF (Land Use, Land Use Change and Forestry) regulation (European Commission, 2023). Moreover, directing a portion of revenues from carbon credits (approximately 30%) into reforestation and rural development investments links economic circularity with ecological restoration (FAO, 2022; Lahnalampi, 2024). This “reinvestment chain” approach is also consistent with UNEP’s (2023) vision for nature-based solutions.

From Türkiye’s perspective, the Finnish experience represents not a directly replicable model but an adaptable governance system. Although the two countries differ in terms of forest ownership structure, climatic zones, carbon sequestration capacity, and institutional traditions (OGM, 2023; Kılıç Hernandez, 2019), Finland's multi-level governance structure is suitable for adaptation to Türkiye's forest management system. In particular, the reinvestment cycle of carbon revenues and financial stability mechanisms could be integrated into Türkiye's National Afforestation Carbon Standard Proposal (Pamukçu Albers et al., 2018) and the Climate Change Mitigation Strategy (2024–2030) (ÇŞİDB, 2024). Such an approach may reduce the financial vulnerabilities created by the currently low voluntary carbon market prices (7–9 €/tCO_2) (Körpe Duru, 2025). Another valuable aspect of the Finnish model for Türkiye is its conceptualization of the carbon economy not only as an environmental policy tool but also as a fundamental component of economic diversification, rural stability, and financial sustainability (Nordhaus, 2013; Stern, 2007). Türkiye faces structural limitations in integrating fully into carbon markets due to the fact that 99% of its forest resources are state-owned (OGM, 2023), which restricts direct market participation (Kılıç Hernandez, 2020). However, Finland's multi-actor model can be adapted to Türkiye's institutional structure through public–private–local cooperation. At this point, science-based decision-making, long-term financial planning, and transparent MRV (measurement–reporting–verification) systems are prerequisites for the sustainability of the carbon economy (IPCC, 2019; FAO, 2022; Körpe Duru, 2025).

In conclusion, the Finnish example demonstrates that carbon sinks can be viewed not only as instruments for emission reduction but also as the economic infrastructure of the green transition. When Türkiye's climate policies, forest management framework, and carbon markets are reconsidered from this perspective, strengthening the forest carbon economy both environmentally and financially becomes attainable. In the next section, Türkiye's current carbon policy, market structure, and institutional capacity will be analyzed comparatively in relation to the Finnish experience.

3. Forest Carbon Management and Economic Approaches in Türkiye

Türkiye's extensive forest resources offer significant potential for carbon sequestration, yet the integration of these ecosystems into the national carbon economy remains limited. The evolution of Türkiye's carbon management policies reflects an ongoing effort to align with international climate frameworks while developing institutional and market-based mechanisms suitable for national conditions.

3.1. Policy Evolution and International Alignment Process

Türkiye's carbon management has been shaped by the influence of international climate regimes since the 1990s. The United Nations Framework Convention on Climate Change (UNFCCC), signed in 1992, established the global framework for climate policies (UNFCCC, 1992; IPCC, 2001; Altıner, 2011). Türkiye became a party to this convention in 2004, marking the establishment of the first national basis for carbon policy (UNFCCC, 1992). Initially listed under both Annex I and Annex II countries, Türkiye was reclassified in 2001 as a "special circumstances" country solely under Annex I through the decisions of the Marrakech Conference (COP7) (Öztekin, 2019). This status granted Türkiye flexible obligations among developing countries (UNFCCC, 2001; Kılıç Hernandez, 2019). Such a special classification enabled Türkiye to adopt voluntariness in its carbon mitigation policies (Öztekin, 2019; Kılıç Hernandez, 2021). The Kyoto Protocol initiated the transformation of carbon into a market-based environmental policy tool. Although Türkiye was not subject to emission reduction obligations, it adopted voluntary market mechanisms analogous to the Kyoto flexibility instruments—International Emissions Trading (IET), the Clean Development Mechanism (CDM), and Joint Implementation (JI) (Altıner, 2011; Öztekin, 2019; van Kooten & Johnston, 2016). During this process, Türkiye gained experience in carbon certification through the development of the first voluntary projects based on carbon finance, particularly in renewable energy investments (FAO, 2022; Körpe Duru, 2025).

The institutionalization of national carbon management policies accelerated in the 2010s. The Climate Change Coordination Board (İDKK), established in 2010, coordinated sectoral greenhouse gas reduction targets; and with the Climate Change Adaptation Strategy and Action Plan (2011–2023), carbon management policies were integrated across forestry, agriculture, energy, and waste sectors (ÇŞİDB, 2012). The 2015 Paris Agreement marked a new turning point in Türkiye's carbon management. Under the Paris Agreement, all parties began submitting Nationally Determined Contributions (NDCs) and setting long-term carbon-neutrality targets (UNFCCC, 2016; IPCC, 2022). Türkiye ratified the Paris Agreement in 2021, announced its Net Zero Emissions target for 2053, and incorporated carbon management into its national development strategy (TBMM, 2021; ÇŞİDB, 2024). These developments were followed by the Climate Change Mitigation Strategy and Action Plan (2024–2030), which identified the enhancement of forest sink areas, the creation of carbon pricing mechanisms, and the development of sustainable finance instruments as priority policy areas (ÇŞİDB, 2024). Furthermore, the transformation initiated by the European Union's Green Deal reshaped Türkiye's carbon policies in the context of foreign trade. The Carbon Border Adjustment Mechanism (CBAM), which entered into force in 2021, integrated carbon pricing into the global trade system and increased the pressure on countries with strong trade relations with the EU—such as Türkiye—to establish carbon markets (European Commission, 2023; Aktaş, 2024). As a result, Türkiye launched the Carbon Pricing Mechanism Readiness Project in 2023 and initiated the design of a national emissions trading system (ETS) infrastructure (ÇŞİDB, 2023). The Climate Law Draft published in 2023 represents the first comprehensive legislative initiative aiming to establish legal certainty regarding carbon trading, certification, and ownership (ÇŞİDB, 2023).

Türkiye's carbon policies have evolved in parallel with developments in international climate governance, transitioning from voluntary obligations to market-based mechanisms, and from mitigation-focused policies to the emerging sink economy. However, the institutional consolidation of this transformation will require the clarification of legal definitions of carbon ownership, the digitalization of the MRV system, and the establishment of a legally secure national carbon market (Körpe Duru, 2025; Kılıç Hernandez, 2020; FAO, 2022).

3.2. Current Institutional, Legal, and Economic Structure

Türkiye's forest carbon framework is still in a formative stage, characterized by fragmented institutional responsibilities and limited economic incentives. While the Ministry of Environment, Urbanization and Climate Change (ÇŞİDB) leads national carbon policy efforts, coordination with forestry and energy institutions remains weak. Legally, carbon rights in state forests are undefined, and the market value of carbon credits is below global averages, reflecting structural and financial constraints.

3.2.1. Institutional and Regulatory Framework

Türkiye's institutional structure for carbon management has developed significantly over the past decade; however, with respect to forest carbon, it remains fragmented and limited on a sectoral basis. The coordination of carbon policies is primarily carried out by the Ministry of Environment, Urbanization and Climate Change (ÇŞİDB). In 2021, the Ministry established the Climate Change Directorate, initiating the development of the legal infrastructure for the national carbon market, the greenhouse gas inventory, and carbon pricing mechanisms (ÇŞİDB, 2024). The most important outputs of this structure have been the preparation of Türkiye's Climate Law Draft and the establishment of the National

Emissions Trading System (ETS) infrastructure (ÇŞİDB, 2023; World Bank, 2023).

In the forestry sector, the General Directorate of Forestry (OGM) is the main institution responsible for measuring, monitoring, and reporting carbon sinks. In the post-2020 period, OGM updated the national carbon stock maps. Within the scope of the National Forest Resources Monitoring System (UOKİS), it has conducted studies to determine biomass, soil, and dead organic matter carbon stocks (OGM, 2023). However, this system is not yet fully integrated with the national MRV portal (Pamukçu Albers et al., 2018; UNEP, 2023). Legally, forest carbon in Türkiye is still assessed within the framework of the "state forests" regime. The Forest Law No. 6831 does not explicitly regulate carbon sequestration. Nevertheless, amendments made in 2022 created a legal framework aimed at defining the economic value of ecosystem services (Kılıç Hernandez, 2020; Hernandez, 2019). Despite this, uncertainties remain regarding carbon ownership, revenue sharing, and certification authority. For instance, it is unclear whether carbon credits generated from a carbon project would be "owned by the state or by the project developer" (ÇŞİDB, 2024).

Another gap in Türkiye's carbon legislation is the legal status of carbon credits and the certification system. While carbon certification in Finland is regulated through national standards (Luke Standard, 2022), Türkiye has only developed the National Afforestation Carbon Standard Proposal (Pamukçu Albers et al., 2018). However, this standard has not yet been officially adopted. The institutionalization of certification at the national level is a prerequisite for integrating voluntary carbon projects into Türkiye's ETS system (ÇŞİDB, 2023; Körpe Duru, 2025).

In terms of institutional coordination, three major challenges stand out in Türkiye's carbon management:

1. **Multi-agency structure:** There are overlaps in duties and authority among the Ministry of Environment, Urbanization and

Climate Change (ÇŞİDB), the General Directorate of Forestry (OGM), the Ministry of Energy, and the Ministry of Treasury and Finance. This results in institutional delays in the collection and reinvestment of carbon revenues (Aktaş, 2024).

2. **Lack of data management integration:** Methodological discrepancies exist between the forest inventory data of the General Directorate of Forestry (OGM) and the national greenhouse gas inventory of the Ministry of Environment, Urbanization and Climate Change (ÇŞİDB). These inconsistencies hinder the economic monitoring of carbon stocks (OGM, 2023; UNEP, 2023).
3. **Insufficient financial instruments:** The use of carbon credits as collateral or financial assets has not yet been regulated in Türkiye. Unlike Finland, there are no "green bond" or "carbon fund" mechanisms in place (Lahnalampi, 2024; FAO, 2022).

3.2.2. Economic Valuation and Market Dynamics

In Türkiye, forest carbon was for a long time considered solely an ecological service, and the process of economic valuation began only in the late 2000s with the development of voluntary carbon markets. The first voluntary carbon projects implemented in Türkiye in 2005, under the Gold Standard and the Verified Carbon Standard (VCS), were applied primarily in the energy, industry, and waste management sectors. However, no internationally certified carbon project has yet been developed in the forestry sector (ÇŞİDB, 2024; Pamukçu Albers et al., 2018; OGM, 2023). This situation stems from both the lack of a legal framework and the structure of state-owned forests, which does not allow private sector participation (Kılıç Hernandez, 2020). As of 2023, Türkiye's forest carbon stocks amount to approximately 2.3 billion tons of CO_2 equivalent (OGM, 2023). This quantity has the capacity to offset nearly 30% of the country's total greenhouse gas emissions. However, despite this high ecological potential, the economic valuation of carbon remains limited. Voluntary carbon credits in Türkiye generally trade within the 6–9 €/tCO_2 price range, which is considerably lower than the global average (13–18 €/tCO_2), according to World Bank (2023) and ÇŞİDB (2024) reports. In Finland and other Northern European markets, carbon prices are in the range of 18–22 €/tCO_2 (FAO, 2022; Lahnalampi, 2024; Luke, 2023; Körpe Duru, 2025). This reflects weaknesses in Türkiye's carbon market, including a fragile price formation mechanism and limited transaction volume.

In the economic analysis of forest carbon projects, the three main indicators—Net Present Value (NPV), Internal Rate of Return (IRR), and Benefit–Cost Ratio (B/C)—are assessed only at a potential level in the context of Türkiye. In their study, Yılmaz and Mısır (2020) calculated the average Net Present Value (NPV) of forest carbon projects in Türkiye as 80–150 € per hectare. In Finland, Lahnalampi (2024) calculated NPV in the range of 300–600 € using a 3% discount rate. Although there are no direct Internal Rate of Return (IRR) calculations for forest carbon projects in Türkiye, IRR values for similar afforestation and forestry investments have ranged between 2–5% (Daşdemir, 1997). These low rates of return are associated with long investment payback periods, limited financing opportunities, and carbon prices remaining below the global average.

The weaknesses in Türkiye's carbon economy are based on four main factors:

1. **Lack of institutional incentives:** Financial mechanisms such as tax reductions, grants, or credit support for carbon sequestration projects have not yet been implemented (ÇŞİDB, 2024; FAO, 2022).
2. **Uncertainty regarding carbon ownership:** Due to the ownership structure of state forests (99% under state control), there is no legal clarity regarding the sharing of carbon revenues and the participation of the private sector (Kılıç Hernandez, 2019).

3. **Insufficient MRV infrastructure:** Although a legally based MRV system for greenhouse gas emissions was established in Türkiye in 2014, an integrated MRV infrastructure for forest carbon and the LULUCF sectors has not yet been developed (ÇŞİDB, 2014; OGM, 2023; UNEP, 2023).
4. **Limited market scale:** As of 2024, the total crediting volume of Türkiye's voluntary carbon market is approximately 12 million tons of CO_2—only about 10% of Finland's annual sink capacity (Luke, 2023; Lahnalampi, 2024).

Türkiye is taking significant steps toward institutionalizing its carbon economy. The Carbon Pricing Mechanism Readiness Project launched in 2023 and the establishment of the National Emissions Trading System (ETS) infrastructure have laid the institutional foundation for market-based climate policies (ÇŞİDB, 2023). For the ETS to be implemented effectively, carbon credits must be integrated into a national certification system—such as the National Afforestation Carbon Standard Proposal (Pamukçu Albers et al., 2018). Moreover, linking carbon revenues to a reinvestment cycle will create a new source of funding for rural development and forest rehabilitation (Körpe Duru, 2025).

From an economic assessment perspective, Türkiye's forest carbon economy has high potential but low returns. Therefore, carbon investments should adopt low discount rates (2–3%) and long project durations (30–40 years) (Stern, 2007; Nordhaus, 2013). In addition, Marginal Abatement Cost (MAC) analyses indicate that the cost of carbon sequestration in Türkiye is in the range of 8–11 €/tCO_2 (ÇŞİDB, 2024; World Bank, 2023). When the market price of carbon falls below this value, projects are not financially sustainable.

Türkiye is in the process of defining the economic value of forest carbon. According to FAO (2022), if the legal framework is clarified, market incentives are strengthened, and the MRV system is institutionalized, the contribution of forest-based climate solutions to the global economy could exceed USD 200 billion annually by 2030. In this context, Türkiye's forest carbon economy carries significant growth potential. The success of this process depends on integrating the principles of science-based planning, multi-actor governance, and financial sustainability—similar to the Finnish model.

3.3. Future Outlook and Policy Directions

Although Türkiye has made significant progress in carbon management over the past decade, structural transformation—particularly in the area of forest carbon—has not yet been fully completed. The Climate Change Mitigation Strategy and Action Plan (2024–2030), developed at the national level, identifies the establishment of carbon markets, the integration of carbon pricing into the economy, and the enhancement of the financial value of carbon sinks as priority objectives (ÇŞİDB, 2024). Within this framework, supporting forest ecosystem services through mechanisms and strengthening the link between rural development and the carbon economy are envisioned (Yıldızbaş et al., 2023).

Türkiye's carbon management can be further developed along three strategic axes for the future:

1. **Legal Integration:** Clear legal regulations must be established regarding carbon credits, property rights, and revenue sharing. Incorporating the concepts of carbon sequestration and carbon trading into the Forest Law No. 6831 would encourage private sector participation and project-based carbon investments (Kılıç Hernandez, 2019; Kılıç Hernandez, 2020). In addition, the National Afforestation Carbon Standard (Ülgen & Güneş, 2016; Pamukçu Albers et al., 2018) should be granted legal status to create a certification mechanism aligned with international markets.

2. **Institutional Coordination:** Data sharing and management coherence must be ensured among MRV, ETS, and carbon certification processes. For this purpose, a central body similar to a National Carbon Management Authority could be established. This institution could provide coordination among the ÇŞİDB, OGM, and the Ministry of Treasury and Finance, thereby creating consistency in data standardization, monitoring, and verification processes (OGM, 2023; UNEP, 2023). In addition, science-based decision-making processes should be institutionalized through collaboration among academia, public institutions, and the private sector.
3. **Financial Innovation:** Recognizing carbon credits as financial assets in Türkiye is critical for deepening the carbon market. A National Carbon Fund, green bonds, sustainable investment certificates, and carbon-credit-backed financial instruments should be developed (FAO, 2022; World Bank, 2023; Lahnalampi, 2024; Körpe Duru, 2025). Moreover, allocating a portion of carbon revenues to rural development and forest rehabilitation projects would generate both social and ecological benefits (Bayramoğlu et al., 2025b; Ülgen & Güneş, 2016; Pamukçu Albers et al., 2018). The implementation of these strategic orientations would transform Türkiye's carbon economy into not only an environmental policy domain but also an economic pillar of its development strategy. As demonstrated in the Finnish model, integrating carbon markets with sustainable finance can support both rural stability and economic diversification (Lahnalampi, 2024; Luke, 2023).

Türkiye has recognized the economic potential of its carbon sinks; however, to fully activate this potential, it requires an integrated governance model built upon legal clarity, institutional coordination, and financial sustainability. This transformation will serve as a strategic lever not only for climate policy but also for green growth, energy security, and rural development objectives (FAO, 2022; Lahnalampi, 2024; ÇŞİDB, 2024; Körpe Duru, 2025).

4. Comparative Analysis: Economic, Institutional, and Policy Implications for Carbon Management in Finland and Türkiye

Although Finland and Türkiye have different historical and institutional structures in forest carbon management, both countries pursue similar objectives in integrating carbon sinks into their economic policies as part of their efforts to combat climate change. Finland has developed a systematic economic model that treats carbon as a component of national capital (Lahnalampi, 2024; Luke, 2023), whereas Türkiye is still in the process of establishing the institutional and legal foundations of this system (ÇŞİDB, 2024; Körpe Duru, 2025). The experiences of both countries demonstrate that the carbon economy is not only a financial domain but also an area of governance-related and social transformation (FAO, 2022; UNEP, 2023).

4.1. Economic Comparison: Market Value of Carbon and Financial Mechanisms

Finland evaluates carbon sinks as a market-oriented ecosystem service and transforms carbon credits into a sustainable source of income within the forest economy (Lahnalampi, 2024). As of 2023, carbon prices range between 18–22 €/tCO_2, and high liquidity is maintained between voluntary and compliance markets (Luke, 2023; FAO, 2022). Finland has also institutionalized mechanisms such as “green bonds” and “carbon funds” to support carbon investments. These instruments have increased the participation of private forest owners in carbon projects and integrated the forest sink economy into the national financial system (World Bank, 2023).

In Türkiye, by contrast, carbon prices are in the range of 6–9 €/tCO_2, and voluntary markets have low transaction volumes (Öztekin, 2019; Ateş & Mısır, 2020; Yıldızbaş et al., 2023; ÇŞİDB, 2024; Körpe Duru, 2025). Carbon funds, green bonds, or publicly supported carbon investment schemes have not yet been established in a systematic manner. Furthermore, the use of carbon credits as financial instruments carries legal uncertainty (Kılıç Hernandez, 2020; Körpe Duru, 2025). While the Finnish model utilizes low discount rates (2–3%) to integrate long-term environmental returns into economic planning (Lahnalampi, 2024), Türkiye still relies on short-term cost-based discounting approaches (Nordhaus, 2013; Stern, 2007). This highlights Türkiye's lack of long-term sustainable financing mechanisms for carbon investments (Bayramoğlu & Küçükbekir, 2022).

4.2. Institutional Comparison: Governance and Implementation Capacity

Finland implements carbon management through a multi-level and participatory governance model. The regulatory role of the state is supported by the active participation of private forest owners and science-based data production (Lahnalampi, 2024; Luke, 2023; FAO, 2022). Institutions such as the Forest Carbon Council have institutionalized public–private cooperation, and farmers, academia, and civil society actors are included in decision-making processes (Lahnalampi, 2024).

In Türkiye, however, the institutional structure is more fragmented. The coordination of carbon policies is carried out by the Ministry of Environment, Urbanization and Climate Change (ÇŞİDB), while the General Directorate of Forestry (OGM) is responsible for monitoring and reporting carbon stocks (ÇŞİDB, 2024; OGM, 2023). Yet, there is no integrated data system connecting MRV, ETS, and carbon certification processes (ÇŞİDB, 2014; UNEP, 2023). This leads to delays in decision-making and overlapping mandates. Moreover, private sector participation in Türkiye is more limited compared to Finland, as 99% of forest ownership remains under state control (Kılıç Hernandez, 2020).

The institutional success of Finland rests on transparent data management, horizontal coordination, and market stability. Türkiye's progress in this area depends on expanding the MRV system to fully cover the LULUCF sector and granting legal recognition to national carbon standards (Pamukçu Albers et al., 2018; Kılıç Hernandez, 2020; ÇŞİDB, 2024; Körpe Duru, 2025).

4.3. Policy and Legal Comparison: Regulatory Structure and Ownership Dimension

In Finland, the carbon economy has gained legal status since 2016 under the concept of "natural capital," and carbon ownership has been explicitly defined for private forest owners (FAO, 2022; Luke, 2023; Lahnalampi, 2024). This regulatory framework has enabled the rapid institutionalization of the carbon market and has integrated forest management with financial instruments.

In Türkiye, however, the ownership of carbon credits remains uncertain; the Forest Law No. 6831 does not regulate the transfer of carbon as an economic asset (Kılıç Hernandez, 2019; Kılıç Hernandez, 2020). Türkiye is currently in the process of legalizing carbon pricing and an emissions trading system as part of the 2024 Climate Change Mitigation Strategy and Action Plan (ÇŞİDB, 2024). This regulatory move carries significant transformative potential in recognizing carbon not only as an environmental asset but also as an economic and fiscal component. However, Türkiye's success will depend on linking carbon revenues to a reinvestment cycle, as demonstrated in the Finnish example (Körpe Duru, 2025).

4.4. MRV Systems and Data Management

Finland's MRV system has attained an integrated structure since the 2010s; under the coordination of the Luke Institute and the Finnish

Environment Institute (SYKE), land use, carbon stock changes, and emission data have been integrated at the national level (Luke, 2023).

Although Türkiye's MRV system was established in 2014, forest carbon and the LULUCF sectors have not yet been incorporated (ÇŞİDB, 2014; OGM, 2023). Methodological discrepancies persist between the databases of OGM and ÇŞİDB, which limits the verifiability of carbon stocks and constrains market reliability (UNEP, 2023; Pamukçu Albers et al., 2018).

Finland's MRV infrastructure enables carbon credits to be traded reliably in international markets (Luke, 2023; Lahnalampi, 2024).

Türkiye's current structure has a verification capacity confined to voluntary markets. This disparity directly affects Türkiye's integration into international carbon trade (World Bank, 2023; FAO, 2022).

5. Conclusion and Recommendations

Global climate change has transformed natural resource management from being merely an environmental issue into a field of economic and political transformation. In this process, forests play a critical role not only in maintaining ecosystem balance but also in shaping carbon markets through their carbon sequestration capacity (Grassi et al., 2021; Seyhan & Bayramoğlu, 2021; FAO, 2022; Seyhan & Bayramoğlu, 2023). Forest carbon is not solely a biophysical process; it is simultaneously a financial asset, an economic policy instrument, and a strategic component of sustainable development (Sohngen & Mendelsohn, 2003; UNEP, 2023).

Through the examples of Finland and Türkiye, this study has examined the multidimensional structure of the forest carbon economy and assessed the interaction between economic rationality, institutional capacity, and legal infrastructure. Finland has developed a governance model that views carbon as a component of national capital, balancing economic efficiency with ecological sustainability (Lahnalampi, 2024;

Luke, 2023). The country has established institutional trust and long-term financial stability in the carbon market through low discount rates (2–3%), green bonds, carbon funds, and a robust MRV system (FAO, 2022; World Bank, 2023). Finland's carbon management has become not only a driver of climate objectives but also a catalyst for rural development and economic diversification.

Türkiye has made notable progress in carbon management over the past decade and has laid the foundation for a national carbon market and emissions trading system (ETS) through the 2024–2030 Climate Change Mitigation Strategy and Action Plan (ÇŞİDB, 2024). However, in the context of forest carbon, legal ambiguities regarding carbon ownership, shortcomings in institutional coordination, and the lack of integration between the MRV system and forest data limit the functional effectiveness of the carbon economy (Kılıç Hernandez, 2020; OGM, 2023; Körpe Duru, 2025). These constraints hinder Türkiye's ability to translate its high forest sink potential into economic value.

The Finnish experience does not represent a model that Türkiye can replicate directly, but rather one that can be adapted. Considering Türkiye's ecological, ownership, and socio-economic conditions, an adaptive carbon management model should be built upon flexible institutional structures, participatory planning processes, and principles of science-based decision-making. To strengthen its carbon economy, Türkiye must establish a balanced system among economic integration, institutional coordination, legal clarity, and financial sustainability.

The development of carbon markets is contingent upon integrating carbon into the national financial system. Long-term financing mechanisms should be established through green bonds, carbon funds, and sustainable investment certificates, and carbon credits should be recognized as investment instruments within the banking sector. The application of low discount rates (2–3%) in long-term projects will enable the inclusion of environmental benefits in economic planning (Nordhaus, 2013; Stern, 2007). A portion of carbon revenues should be directed into rural development funds, thereby enhancing social inclusiveness and supporting income diversification among forest-dependent communities.

At the institutional level, coordination must be ensured among the MRV, ETS, and carbon certification systems, and a multi-stakeholder National Carbon Management Authority should be established to govern these processes. This institution should create an integrated structure for monitoring, reporting, certification, and data management, while strengthening data sharing and coordination between OGM and ÇŞİDB. Additionally, decision-making mechanisms should be made more transparent through cooperation among academia, public institutions, and the private sector, institutionalizing science-based governance.

From a legal standpoint, the explicit definition of carbon ownership and revenue sharing is essential for the participation of the private sector in carbon markets. Accordingly, the Forest Law No. 6831 should be updated to encompass carbon sequestration, crediting, and revenue-sharing processes. The national afforestation carbon standard should be granted legal status to ensure the recognition of carbon as an economic asset. This legal clarity will enhance investor confidence and facilitate integration into international markets.

The science-based governance model successfully implemented in Finland serves as an important example for Türkiye. Similar to the roles of LUKE and SYKE, an open-access National Carbon Information Platform should be established to collect, verify, and share carbon data. Such a system would strengthen the standardization of MRV processes and facilitate Türkiye's access to international carbon markets.

The Finnish model embodies a comprehensive approach that integrates economic rationality with ecological sustainability. If Türkiye succeeds in adapting this model to its own socio-economic and institutional context, its carbon economy will contribute to both environmental and development objectives.

A carbon management model will support Türkiye not only in achieving climate neutrality but also in generating transformation in rural development, green finance, and ecosystem services. This strategic approach will enable Türkiye to shift from being a passive actor in the carbon economy to becoming one of the regional leaders of the green transition.

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Chappter III - Forest Road Hydrogeology: Design and Dimensioning Principles of Hydraulic Structures

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1. Introduction

Global warming and climate change are generating profound impacts on both natural ecosystems and engineering infrastructures worldwide. Increasing greenhouse gas emissions have disrupted the atmospheric energy balance, leading to a significant rise in global temperatures and a marked increase in the frequency and intensity of extreme climatic events (IPCC, 2021). Irregularities in precipitation regimes have resulted in more intense rainfall over shorter durations, which in turn has increased surface runoff (Bayramoğlu and Demir, 2018). This phenomenon places considerable strain on the design capacities of small-scale hydraulic structures, especially those located in rural areas—and substantially heightens the risk of flooding.

Rural infrastructure systems are generally composed of structures that were designed based on historical climate data and built under limited economic resources. In addition, recent macroeconomic analyses indicate that the forestry sector in Türkiye is increasingly shaped by international economic integration and structural transformations, which indirectly influence investment capacity and infrastructure planning in rural forest areas (Bayramoglu et al., 2025a). These structures play a critical role in directing, storing, and distributing water efficiently. Therefore, the factors to be considered in the design of hydraulic structures are crucial not only from an engineering standpoint but also in terms of environmental sustainability. In addition to technical and environmental considerations, the effectiveness of hydraulic structure design on forest roads is closely related to human-related factors such as working conditions, operational efficiency, and professional decision-making processes (Ünver Okan & Acar, 2017; Ünver Okan, 2020; Ünver & Kurdoğlu, 2024). However, recent precipitation trends have exceeded the hydraulic resistance thresholds of many of these structures, resulting in significant damage. Extreme rainfall events have led to increased surface runoff, causing culvert blockages, scouring bridge piers, and overloading of flood control structures (Milly et al., 2008). Such events not only cause physical destruction but also disrupt rural transportation networks, hinder forest operations, damage agricultural lands, and temporarily paralyze local economies.

The post-flood repair and reconstruction costs impose a substantial burden on the limited budgets of rural communities. Most existing hydraulic structures were dimensioned according to specific return periods—such as 25 or 50-year flood discharges—but recent flash flood events have greatly exceeded these design thresholds (Türkeş, 2012). Consequently, it has become imperative to reassess rural hydraulic structures considering updated climate data and modern hydrological modeling techniques. Unless resilient, sustainable, and cost-effective designs are developed, the evolving hydraulic regime driven by climate change will continue to pose a serious threat to the continuity of rural infrastructure systems.

At the same time, the global shift toward renewable energy—particularly biomass—has underscored the importance of sustainably managing forest and water resources, as increasing bioenergy demand can influence ecosystem integrity and rural land-use dynamics (Toksoy et al., 2020). Protected area management has increasingly emphasized the environmental and economic importance of ecosystem services, particularly those linked to water resources, placing sustainable hydrological planning at the center of rural development strategies (Bayramoglu et al., 2025b; İnanç Özkan & Aksu, 2025a). Therefore, the design of hydraulic structures in rural landscapes must be evaluated in conjunction with ecosystem conservation principles and the sustainable use of natural water systems.

The dimensioning of hydraulic structures is based on specific engineering principles and local environmental conditions. Topographic characteristics such as slope, aspect, and elevation play a decisive role in hydrological processes, influencing water movement, soil saturation, and runoff dynamics (Kazama et al., 2021). For this reason, these parameters must be accurately assessed when planning rural hydraulic structures, forest roads, or landslide-prone areas (Gümüş, Hatay & Ünver Okan, 2019; Hatay et al., 2024). During this process, factors such as flow management, discharge capacity, local climatic parameters, and soil characteristics must be considered. Particularly, the impacts of these structures on surrounding settlements and their integration with the natural ecosystem are of critical importance for ensuring long-term sustainability.

1.1. Importance of Water Resources in Rural Areas

Rural areas represent the geographical settings where the impacts of natural resource conservation and sustainable use on social welfare are most distinctly observed. In these regions, agricultural production, drinking water supply, and livestock activities are largely dependent on the effective management of local water resources. The sustainable management of water resources is of strategic importance not only for economic development but also for maintaining social stability and environmental balance within rural communities (FAO, 2020).

In countries such as Türkiye, which lies within a semi-arid climate zone, the seasonal distribution of water and flood risks in rural areas play a decisive role in infrastructure planning. Therefore, the controlled management of water and the proper planning of hydraulic structures for flood control are of vital importance.

The significance of water resources in rural areas is a critical factor for both the sustainability of natural ecosystems and the quality of life of local populations. Water plays a vital role in meeting fundamental needs such as agriculture, drinking water, energy production, and ecosystem conservation. Hence, water management in rural regions must ensure the efficient and sustainable utilization of these resources.

Numerous studies highlight the contribution of water harvesting practices to sustainability in rural areas. Hacısalihoglu (2022) emphasized the importance of rainwater harvesting in meeting the potential water demand of rural settlements. Particularly in regions with limited water availability, water harvesting serves as an effective method for improving agricultural productivity and ensuring water security. This approach significantly facilitates local communities' access to water and enhances the water supply required for agricultural activities.

The management of water resources directly influences the social and economic structures of rural economies. The role of women in rural development is also shaped by their access to water resources. The study by Yuceer and Demiryurek (2020) identified the constraints faced by rural women entrepreneurs and demonstrated how water availability affects the development of these initiatives. Access to water is essential for women to support household economies and to participate more effectively in local markets.

Moreover, the conservation of water resources in rural areas is vital for maintaining ecosystem integrity and biological diversity. Karataş (2023) noted that the depletion of water resources disproportionately affects communities living in rural regions. While rural communities sustain their livelihoods through agricultural activities, they also play an active role in preserving environmental balance.

In conclusion, water resources in rural areas encompass numerous social, economic, and ecological dimensions that directly influence quality of life. Proper planning and management of water use are crucial for improving agricultural productivity, supporting local economies, and ensuring environmental sustainability. Furthermore, water is also one of the primary factors contributing to damage on rural roads (Kalantari and Folkeson, 2013; Öztürk, 2020).

1.2. Definition and Classification of Hydraulic Structures

Ensuring the continuity and functionality of forest and rural road networks is directly related to protecting these roads from the adverse effects of surface and subsurface water. Rainfall, snowmelt, and groundwater infiltration into the road body can gradually reduce the bearing capacity of the road, cause surface deformations, and even lead to structural failures. To prevent such effects, both surface and subsurface drainage systems are designed along the road alignment and retaining or revetment walls are constructed to improve slope stability.

However, rural and forest roads often intersect natural watercourses such as rivers, streams, or drainage channels. At these points, it is essential to ensure the uninterrupted flow of water without altering its natural course — a critical engineering requirement for both road safety and ecosystem stability. Therefore, structures built to convey water—such as bridges, culverts, humps, drainage ditches, channels, and pipes—as well as their protective components, including riprap and aprons, are collectively referred to as hydraulic engineering structures, or more simply, hydraulic structures (Ozcelik, 1982; Bayoglu, 1997).

Hydraulic structures not only provide safe water conveyance but also form integral components of the structural system that preserves the integrity and service life of road infrastructure. The design of these structures must consider local geotechnical and hydrological conditions; in other words, they should be dimensioned in accordance with topography, material properties, and drainage capacity to ensure long-lasting and cost-effective performance. Improperly selected or incorrectly placed structures, regardless of the quality of materials and workmanship, fail to withstand external forces and eventually lose their functionality (Schwab, 1994). For this reason, drainage systems are considered among the most critical technical components in forest road construction (Rezvani, 2012; Ozturk, 2020).

The main types of hydraulic structures commonly planned and applied in forest roads are illustrated in Figure 1.

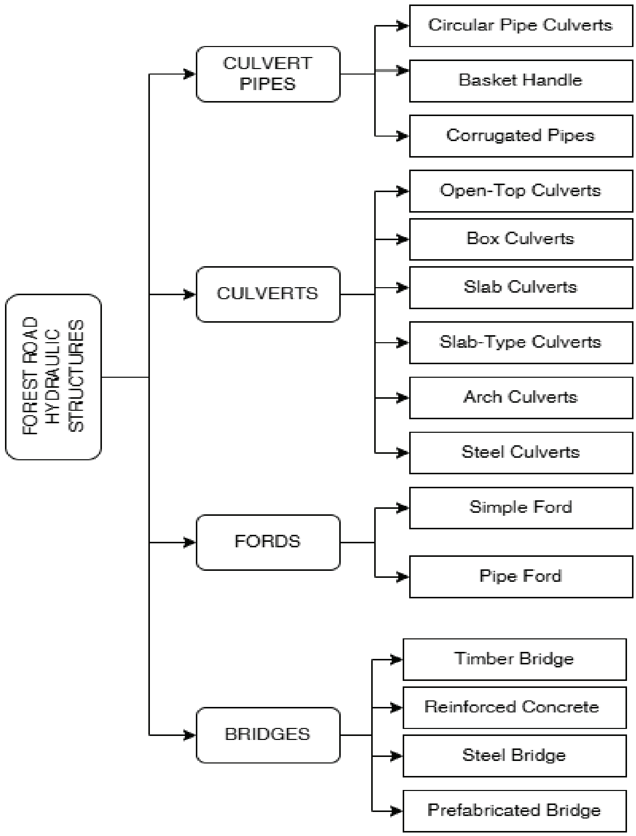

Figure 1. *Classification of hydraulic structures used in forest roads (Ozturk ve Hasdemir, 2021)*

Hydraulic structures are designed to regulate water flow and ensure that both environmental and structural components can function safely and effectively. Among these, culvert pipes, culverts, and fords stand out as the most employed fundamental elements. These structures control the natural flow of water, thereby protecting road infrastructure while also contributing to the continuity of the surrounding hydrological balance (Erdas, 1997; Ozturk, 2010; Demir, 2019).

a) Culvert Pipes

Among the small-scale hydraulic structures frequently used in forest road construction, culvert pipes are enclosed conduits designed to safely convey surface water and flood flows beneath the road platform without causing damage (Figure 2). These elements are typically made of concrete or plastic materials, most often in the form of circular cross-section underground pipes. Depending on local topography, drainage gradient, and soil conditions, culvert pipes can be constructed as precast circular modules or as cast-in-place basket-handle types. Such structures are particularly preferred for conveying the flow of small streams or tributaries under the road body in a controlled manner (Bayoglu, 1997; Erdas, 1997; Karaman, 2001).

The functionality of culvert pipes largely depends on proper sizing and the application of appropriate construction techniques. Inadequate estimation of hydraulic capacity or improper site selection relative to topographic conditions can result in excessive flow loading during rainy periods. Under such circumstances, culvert pipes are prone to structural failures such as collapse, cracking, displacement, or clogging. Pipes with insufficient diameters or inadequate embedment depths tend to accumulate sediment and organic material carried by the flow, obstructing water passage and significantly reducing hydraulic performance (Erdas, 1997; Karaman, 2001).

Moreover, improper drainage gradients or the absence of riprap protection at the inlet and outlet can cause rapid water backflow, leading to scouring and deformation at the pipe base. These conditions not only reduce the bearing capacity of the road body but also substantially increase maintenance costs. Therefore, in designing culvert pipes, it is essential to ensure accurate hydrological data analysis, appropriate material selection, and engineering optimization according to site-specific soil and hydraulic conditions (Bayoglu, 1997).

Figure 2. *Example of structural failure in a culvert pipe caused by inadequate dimensioning*

b) Culverts

In rural road networks, particularly in regions with high flow volumes where the hydraulic capacity of culvert pipes becomes insufficient, structures designed to safely convey surface and flood flows without damaging the road body are referred to as culverts (Figure 3). It is well established that culverts are the most used drainage structures in forest roads (Anonymus, 2010).

Figure 3. *Example of a properly designed culvert in a forest road (Ozturk & Inan, 2010)*

The use of surface drainage systems in forest roads began in the 1930s and has since become an integral component of road engineering. In this context, culvert pipes and culverts play a fundamental role in safely draining rainfall and seepage water from cut slopes without causing damage to the road platform. Rainwater is generally collected by roadside ditches and then directed along drainage channels to the opposite side of the road through a culvert pipe or culvert structure (Ozturk & Inan, 2010).

At the outlet sections of culverts, various structural or natural energy dissipation measures are employed when flow velocity is high. To prevent direct erosion of the ground surface, vegetative covers, riprap stones, or concrete energy dissipators are commonly used (Kramer, 2001). In addition, both the inlet and outlet sections of culverts and culvert pipes are equipped with headwalls, which act as supporting elements. These components protect the structure against scouring caused by flowing water, enhance overall stability, and ensure long-term performance.

Culverts are generally closed hydraulic structures installed beneath the road surface to transfer surface flow safely from one side to the other. Depending on their size and function, they are typically categorized into small and large culverts (OGM, 2008). In rural road infrastructure, structures with an opening width of up to 6 meters are classified as culverts, whereas those with larger openings are considered bridges. Culverts can be constructed either perpendicular to the road axis or at a skewed angle, depending on the planned road alignment. In rural areas, it is generally recommended that culverts with openings around 3 meters be preferred instead of bridge-type culverts with 6-meter spans, for reasons of cost efficiency and structural suitability (Bayoglu, 1997; Ozcelik, 1982).

Small culverts are typically positioned close to the road surface in steep rural sections to collect surface runoff. These structures may be open-topped stone or timber constructions or closed-section reinforced concrete types. In regions with significant transport of sediment and debris (e.g., mud, stones, branches), the culvert cross-section must be dimensioned to accommodate these materials, or additional protective measures such as grates, sedimentation basins, or filter structures should be incorporated (Erdas, 1997).

Accurate dimensioning of culverts is crucial for ensuring both flood safety and the long-term stability of road infrastructure. Otherwise, inadequate cross-sectional sizing or improper slope alignment can result in blockages, backflow, slope scouring, and loss of road stability. Therefore, culvert design projects should be based on careful hydrological analyses supported by on-site observations of local flow conditions.

c) Fords

Among the hydraulic structures frequently preferred in rural road construction due to their low cost and ease of implementation, fords represent another widely used solution (Figures 4 and 5). Fords are typically constructed on wide, dry streambeds that remain inactive for most of the year but are exposed to flood flows during rainy periods. The primary purpose of these structures is to allow water to pass safely and in a controlled manner over the road surface during flood events, thereby preventing damage to the road body (Bayoglu, 1997; Demir, 2019).

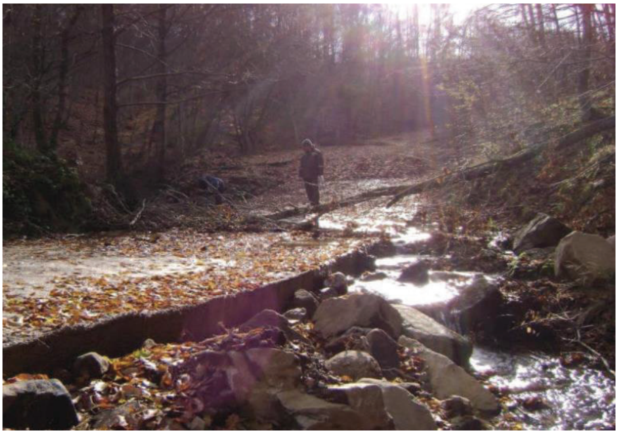

Figure 4. *Example of a ford constructed on a riverbed (Gormez, 2012)*

In sloping terrains where the sediment load is high, but water discharge remains low, simple fords without culvert pipes are generally preferred. Conversely, in some stream crossings where the water flow continues throughout the year or reaches high discharge levels during flood periods, pipe ford systems are employed. These types of structures provide a safe and economical solution for conveying water during both low-flow and flood conditions, particularly in locations where bridge construction is neither economically nor technically feasible (Karaman, 2001).

Figure 5. *Example of a ford constructed in London (URL-1)*

When constructed under appropriate slope and soil conditions, fords offer both cost advantages and environmental compatibility, making them a sustainable solution in rural infrastructure planning. However, in cases of design errors or insufficient structural reinforcement, problems such as surface erosion and material deposition may occur during flood periods. Therefore, the site selection and dimensioning of fords should be carried out with careful consideration of local hydrological data and stream morphology.

d) Bridges

In rural and mountainous regions, stream and river crossing points represent the most critical sections in the planning of road networks from an engineering perspective. The proper positioning of these crossings and the selection of an appropriate structural type are of great importance for ensuring both hydraulic safety and economic sustainability. Although bridges used in stream crossings generally entail high construction costs, when properly designed they offer durable and safe long-term solutions. However, in rural or forest roads with low traffic volumes, bridge construction is often not the most cost-effective option (Erdas, 1997).

For small-scale stream or dry channel crossings, precast concrete culvert pipes, cast-in-place basket-handle culverts, or small slab or stone-deck culverts are often sufficient. In contrast, where the streamed widens and flood discharges increase, the use of multiple culvert pipes or large culvert structures become technically complex and economically inefficient (Bayoglu, 1997). In such cases, constructing a bridge structure capable of conveying the water flow continuously and safely becomes inevitable (Figure 6).

Figure 6. *Example of a concrete bridge used in a rural forest road drainage system (URL-2)*

In rural hydraulic engineering, structures with a span length exceeding six meters are classified as bridges. This classification serves as a fundamental distinction in determining design criteria and in conducting structural and hydraulic calculations (Bayoglu, 1997). Bridge designs must consider factors such as span length, river hydrograph characteristics, soil bearing capacity, and traffic loads, with particular attention given to providing adequate freeboard during flood events.

Consequently, hydraulic structures occupy a critical intersection between road engineering and water management disciplines. Their proper planning plays a vital role in reducing flood risks and ensuring the continuity of rural transportation networks.

1.3. Technical and Environmental Challenges in Rural Infrastructure Planning

One of the main technical challenges in rural infrastructure planning is the inadequacy of existing systems. In many rural regions, the current infrastructure has become obsolete over time and is no longer capable of meeting modern demands. This inadequacy causes problems in the provision of essential services such as transportation, water distribution, and energy supply (Bottero et al., 2019). Furthermore, climate change has intensified pressures on rural infrastructure, emphasizing the need for additional engineering solutions to enhance resilience against natural disasters (Yi, 2024).

Deficiencies in policy and governance also contribute to the technical challenges in rural areas. Rural infrastructure planning is often constrained by centralized strategies that fail to adequately consider local needs. As a result, planning processes carried out without the participation of local communities tend to be inefficient and unsustainable (Ruan et al., 2022; İnanç Özkan & Aksu; 2025b). To ensure the construction of resilient infrastructure, it is essential to integrate local knowledge and community experience into the planning process (Azhimov & Manukhina, 2023).

Environmental Challenges

Another significant challenge in rural infrastructure planning is the neglect of environmental impacts. Rural areas are of critical importance for natural resource conservation and biodiversity protection. However, improper planning may trigger negative environmental consequences such as habitat loss, water pollution, and soil erosion (Krūkle et al., 2019). For example, the expansion of agricultural activities often leads to the contamination of natural water resources and the reduction of arable land (Damodaram et al., 2010).

The integration of green infrastructure into rural planning can help mitigate these environmental problems. Green infrastructure contributes to water management, ecosystem service preservation, and climate adaptation (Luca et al., 2021). Nevertheless, financial and technical constraints encountered during project implementation continue to pose barriers to developing sustainable strategies (Brunetti et al., 2016).

In conclusion, the technical and environmental challenges faced in rural infrastructure planning represent critical factors that must be addressed to develop effective and sustainable solutions. The major technical and environmental challenges identified in rural infrastructure planning are summarized in Table 1. Overcoming these challenges requires active participation of local communities, efficient resource management, and the integration of environmental sustainability into all stages of planning and implementation.

Table 1. *Main Technical and Environmental Challenges in Rural Infrastructure Planning*

Category	Main Challenge	Impact	Suggested Approach
Technical	Outdated and inadequate infrastructure	Reduced service quality and increased maintenance costs	Modernization and preventive maintenance programs
Technical	Climate change and extreme weather events	Damage to hydraulic structures and reduced resilience	Climate-adaptive and resilient design standards
Governance	Centralized planning neglecting local needs	Inefficient resource use and low sustainability	Participatory, community-based planning
Environmental	Habitat loss, soil erosion, and water pollution	Decline in biodiversity and ecosystem services	Environmental impact assessment and eco-based management
Sustainability	Limited use of green infrastructure	Missed opportunities for natural flood control and adaptation	Integration of nature-based solutions in planning

1.4. Methods Used in the Dimensioning of Hydraulic Structures

The impacts of global climate change have made it essential to develop new approaches for the planning and management of rural infrastructure systems. Increasing irregularities in precipitation, flash floods, and higher surface runoff have pushed the design limits of existing hydraulic structures, reducing their resilience and operational lifespan. This situation particularly affects structures such as culvert pipes, culverts, fords, and bridges, which are vital for ensuring safe water conveyance in forest and rural road networks. As discussed in the previous sections, the sustainability of rural infrastructure depends not only on constructing new facilities but also on accurately assessing the hydraulic performance of existing ones. Therefore, the proper dimensioning of hydraulic structures is a crucial engineering step for minimizing flood risks and maintaining the long-term functionality of road networks.

In this context, some of the methods applied for the dimensioning of hydraulic structures are as follows:

a) Talbot Method

Seckin (1967) stated that in the selection of a hydraulic structure, the primary consideration should be to determine the most economical dimensions that can convey the maximum flood discharge without causing damage to the road or surrounding areas. For this purpose, he identified the Talbot formula as the fundamental equation used for the initial dimensioning of hydraulic structures.

Even today, according to the OGM Communiqué No. 292 (OGM, 2008), the Talbot method remains the most widely used approach in the design of hydraulic structures for forest roads. The discharge value obtained from the Talbot formula serves as an initial reference value, which is then refined through the planner’s engineering judgment by considering factors such as cross-sectional width, structure dimensions, and peak rainfall events with 50- and 100-year return periods (Gumus, 2021).

$$S = 5{,}791 * C^4 * \sqrt[4]{A^3}$$

S : cross-sectional area of the hydraulic structure (m²)

A : drainage basin area (km²)

C : coefficient depending on the topographic characteristics of the watershed.

The coefficient C is determined based on the morphological and topographic characteristics of the watershed. Reference values for the C coefficient are provided Table 2.

Table 2. *Talbot coefficient (c) values according to watershed morphology (OGM, 2008)*

Terrain Type and Slope Characteristics	**C (Talbot Coefficient)**
Flat, permeable terrain fully covered with vegetation (average slope 10–20%)	0.2
Flat, permeable terrain covered with deciduous forest (average slope 10–30%)	0.3
Flat, permeable terrain covered with coniferous forest (average slope 10–30%)	0.4
Undulating, moderately permeable terrain with mixed (deciduous and coniferous) vegetation, canopy density class 3 (average slope 30–50%)	0.5
Undulating, moderately permeable terrain with mixed vegetation, canopy density classes 0–2 (average slope 30–50%)	0.6
Rugged, impermeable terrain with sparse vegetation (canopy density class 0–1, slope 40–60%)	0.7
Steep, forested, permeable terrain (average slope >60%)	0.8
Very steep, bare and impermeable terrain (average slope >60%)	0.9

The selection of the C coefficient in the Talbot formula is left to the planner’s professional judgment and experience. However, the OGM Communiqué No. 292 does not provide any specific guidance on how this experience should be evaluated or incorporated into the decision-making process. This situation increases the subjective nature of the method and may lead to variations in results among different planners. Selecting different C coefficients for similar watershed conditions can cause significant discrepancies in the dimensioning of hydraulic structures. Therefore, to enhance objectivity in planning, it is important to develop regional standards, reference datasets, or decision-support systems that can assist in the selection of appropriate C coefficient values.

b) HEC-RAS Software

Acil et al., (2023) and Demir (2019) emphasized in their studies the use of the HEC-RAS software for the dimensioning of hydraulic structures on forest roads. Accurate determination of the water surface profile in HEC-RAS requires precise estimation of the surface roughness conditions, represented by the Manning's roughness coefficient (n) (Table 3).

Since the Manning's n value is a highly variable parameter, it depends on numerous factors, including surface roughness, vegetation characteristics, channel irregularities, bed slope, meandering, scouring and deposition, obstructions, channel shape and dimensions, discharge rate, seasonal changes, temperature, and suspended or bed materials (Ardiclioglu, 2017).

The Manning's *n* coefficient can be obtained through various methods. In Türkiye, the modified Cowan method, as adopted by the General Directorate of State Hydraulic Works (DSI), is the most commonly applied approach, and its parameterization is presented in Table 3 (DSI, 2016).

$$n = m * (n_b + n_1 + n_2 + n_3 + n_4)$$

n = represents the *Manning's roughness coefficient*,

m = denotes the *meandering coefficient* of the channel,

n_b = corresponds to the *base value reflecting the material type,*

n_1 = represents the *slope condition*,

n_2 = accounts for the *variation in cross-section*,

n_3 = represents the *influence of structures and obstructions*,

n_4 = denotes the *vegetation characteristics*.

The final Manning's n value is determined by combining these parameters based on the planner's professional experience, using the reference data provided in Table 3.

__Table 3.__ Manning's Roughness Coefficient Calculation Table

Riverbed Material	Concrete	Median Particle Diameter (mm)	-	n_b	0.012-0.018
	Rock		-		-
	Hard Soil		-		0.025-0.032
	Coarse Sand		1-2		0.026-0.035
	Fine Gravel		-		-
	Gravel		2-64		0.028-0.035
	Coarse Gravel		-		-
	Large Stones		64-256		0.030-0.050
	Boulder		>256		0.040-0.070
Channel Slope Condition	Smooth			n_1	0.000
		Concrete Wall			0.003
	Minor Roughness	Stone Wall			0.005
		Riprap (Stacked Stones)			0.008
	Moderate Roughness	Bare Rock or Soil Slope (without vegetation)			0.010
		Unstacked stone riprap			0.015
	Severe Roughness	Vegetated slope (with trees)			0.020
Channel Cross-Section Variation	Gradual variation			n_2	0.000
	Occasional variation				0.005
	Frequent variation				0.010-0.015
Channel Obstructions	Negligible	(Obstruction Area / Cross-Sectional Area) × 100	<%5	n_3	0.000
	Minor		%5-15		0.010-0.015
	Noticeable/Moderate		%15-50		0.020-0.030
	Severe		>%50		0.040-0.060
Channel Vegetation Density	Low			n_4	0.002-0.010
	Moderate				0.010-0.025
	High				0.025-0.050
	Very High				0.050-0.10
Channel Meandering	Negligible	Dere uzunluğu/kuş uçuşu uzunluk	1-1.2	m	1.000
	Noticeable/Moderate		1.2-1.5		1.150
	Severe		>1.5		1.300

c) SCS-CN Method and Selected Empirical Formulas

To determine the appropriate dimensions of a hydraulic structure to be constructed at a stream crossing, it is essential to estimate the design discharge. Since it is not feasible to install gauging stations within the basin area of each cross-drainage structure along forest roads, the peak discharges must be calculated using empirical or semi-empirical hydrological methods.

Among these, the SCS-CN (Soil Conservation Service – Curve Number) method and several empirical formulas are widely used in current hydrological design practices (Naghdi et al., 2022).

Within the empirical approaches, the Rational Formula (KGM, 2005) is commonly applied. When determining the runoff coefficient (C) in this formula, the coefficient values are selected based on the soil type, land use, and surface characteristics, typically relying on the planner's professional judgment (Table 4).

$$Q = \frac{\mathrm{C} * \dot{\mathrm{I}} * \mathrm{A}}{3.6}$$

In the formula;

Q = Maximum discharge (m^3/sn)

C = Runoff coefficient, representing the ratio of surface runoff to total rainfall (expressed as a percentage)

$\dot{\mathrm{I}}$ = Rainfall intensity corresponding to the time of concentration (mm/saat)

A = Basin area (km^2)

Table 4. Runoff Coefficients (Singh, 1992)

Surface Type and Characteristics	**Runoff Coefficient (C)**
Impervious surfaces	0.90–0.95
Steep and bare surfaces	0.80–0.90
Undulating and bare surfaces	0.60–0.80
Flat and bare surfaces	0.50–0.70
Undulating grasslands	0.40–0.65
Deciduous forests	0.35–0.60
Coniferous forests	0.25–0.50
Orchards	0.15–0.40
Agricultural fields in valley bottoms	0.10–0.30

Another empirical method used by the General Directorate of Highways (KGM, 2005) is the Synthetic Unit Hydrograph Method. In this approach, the curve number (CN_i) parameter, which represents runoff potential for different catchment areas, is manually selected by the planner based on land use and hydrological characteristics.

Similarly, in the Kursteiner Formula, the α parameter (adaptation coefficient) is determined by choosing between two return period discharges — HQ_{50} and HQ_{100} — corresponding to 50-year and 100-year flood events, respectively (Table 5).

$$HQ = \text{a} * \frac{AB^2}{3}$$

HQ = Peak discharge (m^3/s)

AB = Basin area (km^2)

A = Adaptation (adjustment) coefficient (Table 5)

Table 5. Adaptation (adjustment) coefficient

Land Cover Characteristics	HQ_{100}	HQ_{50}
Flat or hilly terrain with dense vegetation and fertile soil	9	5
Steep terrain with sparse vegetation and impervious surface	12	8

In the SCS-CN (Soil Conservation Service – Curve Number) method, the following parameters must be known:

- Land use and cover type
- Hydrological Soil Group (HSG)
- Daily rainfall data (mm)
- Antecedent moisture condition (AMC)

In this method, the direct runoff is calculated using equations that depend on the curve number (CN) value of the watershed. The SCS-CN method estimates the amount of runoff based on land cover, soil properties, and rainfall characteristics (Das and Paul, 2006).

As in other empirical approaches, several parameters in this method are also selected and adjusted according to the planner's professional experience (Table 6).

Table 6. Curve Number (CN) Values Used in the SCS Model (Chow et al., 1988)

Land Use/Land Cover	Hydrological Soil Groups			
	A	B	C	D
Forest formation	30	55	70	77
Agricultural areas	72	81	88	91
Maquis (shrubland) formation	45	66	77	83
Grassland formation	39	61	74	80
Open areas / settlements	54	70	80	85
Olive groves	36	60	73	79

The Nethydro model is a Netcad module designed to define catchment boundaries and drainage networks. It performs rainfall analyses for all distribution types, calculates peak discharges based on unit hydrographs, and identifies flood-prone areas along stream channels according to discharge values for different return periods. Using a digital elevation model (DEM), Nethydro enables basin modeling, flood discharge estimation, and the generation of hydraulic cross-sections for engineering design purposes (URL-3). In this software, rainfall data from meteorological stations, as well as land cover and soil type information, are entered manually by the user (Misirlioglu & Gumus, 2022).

In small-scale catchments, the Rational Method is frequently applied to determine the maximum discharge using rainfall duration and runoff coefficient (C). The C factor, representing the ratio between surface runoff and rainfall, is selected according to slope, land use, and surface characteristics (Schwab et al., 1993; Aruga et al., 2005).

Among the widely used techniques for the dimensioning of drainage structures, hydrological discharge calculations remain fundamental. These analyses must consider the natural water cycle, ensuring that the design reflects actual flow conditions. Celik et al. (2025) emphasize that training on forest construction and drainage engineering should include such hydrological design computations, as determining flow direction and velocity allows for accurate sizing of drainage conduits and culverts.

Moreover, the application of hydrological modeling tools plays an increasingly significant role in designing drainage structures. Such models integrate parameters including rainfall characteristics, soil types, and catchment morphology to simulate runoff processes more precisely, thereby minimizing the risk of design errors (Kale, 2021).

In addition, Geographic Information Systems (GIS) have become an integral part of drainage structure design. By combining spatial data such as land use, topography, and slope, GIS supports the identification of the most suitable locations and dimensions for hydraulic structures. Acar (2015) highlights the importance of designing drainage systems in harmony with natural terrain and environmental sensitivity, which contributes to both engineering efficiency and ecological sustainability.

Finally, the analysis of rainfall data within a watershed represents another critical component in drainage structure planning. Evaluating streamflow records for sub-basins over different time periods allows for the design of more balanced and effective drainage networks (Degerli & Turhan, 2022). Implementing such approaches can help mitigate erosion, flooding, and waterlogging risks along forest roads.

2. Conclusions

In Turkish forestry, the Talbot formula remains the most applied method for designing hydraulic structures along forest roads. However, this approach considers only the catchment area (A) and the runoff coefficient (C), while neglecting critical hydrological factors such as the spatial variability of rainfall, terrain morphology, soil permeability, and vegetation cover. As a result, the current applications often fail to reflect local hydrological conditions accurately, leading to potential underestimation or overdesign of cross-drainage structures.

Although other empirical approaches such as the Rational Method and the SCS-CN Model provide a more detailed consideration of rainfall and surface characteristics, these methods are still highly dependent on the planner’s experience. This dependence can cause inconsistencies when applied across regions with different geomorphological and climatic conditions. Particularly in small, forested catchments, where hydrological and topographical variability is high, such methods alone may not yield reliable design results.

To overcome these limitations, the integration of Geographic Information Systems (GIS) and Digital Elevation Models (DEMs) is essential. GIS-based hydrological analyses allow for the precise modeling of watershed morphology, slope, flow direction, and flow accumulation, thus enabling more realistic and sustainable sizing of hydraulic structures. By incorporating spatial data and modern hydrological modeling, it becomes possible to reduce flood and erosion risks while significantly increasing the service life of these engineering structures.

In conclusion, enhancing the traditional design methods used in Turkish forestry through the application of modern GIS-supported hydrological techniques is a strategic necessity. Such integration will contribute to the construction of more resilient, efficient, and climate-adaptive infrastructure systems within forest road networks.

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Chapter IV - Post-Operation Vegetation Restoration in Open Pit Mines: Bentonite Mine Sample Site

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Introduction

While mining activities, whether open-pit or underground, are crucial for a country's development, they can have potentially irreversible impacts on the natural environment. A fundamental component of mining operations is the reduction or elimination of these harmful impacts and the restoration of the operating area to its natural state. Bentonite mine, an example of open-pit mining, significantly disrupts the soil, fauna, flora, and landscape integrity of the area where it operates. After the cessation of mining operations, such areas should be rehabilitated through geological, geotechnical, and ecological rehabilitation processes.

Rehabilitation at mining sites is essential not only for restoring ecological balance but also for regional sustainability and social acceptance. The success of post-mining rehabilitation practices depends not only on ecological design principles but also on implementation efficiency, working conditions, and the professional decisions taken during field applications (Ünver Okan & Acar, 2017; Ünver Okan, 2020; Ünver & Kurdoğlu, 2024). These rehabilitation efforts can be implemented using various approaches in different regions and countries. Ecologically based rehabilitation, one of these approaches, aims to restore the functioning of an ecosystem that has been disrupted. This model aims to achieve both physical rehabilitation and the restoration of ecological balance by harnessing the self-healing power of nature (Hobbs & Harris, 2001). The ICMM (2019) reports also state that this approach can yield benefits in the long term.

Description of the Example Project Site

This study was developed using an example for planning rehabilitation practices following the operation of a bentonite mine. The site covered an area of approximately 128,000 m² and is characterized by excavation areas formed during the operation, steep slopes, and clay layers that pose a landslide risk. The site's surroundings are a natural forest ecosystem, with a temperate climate, abundant rainfall, and proximity to the coast, covered with beech, oak, chestnut, acacia, and alder species.

Open-pit mining operations cause permanent changes in the natural landscape, such as deep pits, steep slopes, and drainage problems. These structural changes increase the risk of landslides in the region and lead to waterlogging and erosion. Rehabilitation of such areas can only be achieved through a series of technical analyses and procedures. These are:

1. Drainage System and Slope Stabilization

The first task to be undertaken is to ensure the safety of the steep slopes that emerge after the operation. To this end, a 1:1.5 slope should be created, taking into account the slope angle, material properties, and drainage structure. Natural drainage lines should be planned to prevent rockfall at the tops of the slopes, and controlled water flow should be ensured. The drainage system should be designed to ensure that rainwater and other surface waters flowing into the area are discharged in accordance with the natural topography. This will prevent both soil loss and waterlogging in the area.

2. Erosion and Landslide Prevention

Erosion control is crucial for stabilizing surface movement. Especially in mining sites with bentonite and clay layers, as in this case study, surface water runoff should be directed to areas that will not pose a hazard through drainage systems. Additionally, on steep slopes, a grass mixture containing 40% *Festuca arundinacea* TURBO RZ, 30% *Festuca arundinacea* FIRACES, 20% *Lolium perenne*, and 10% *Poa pratensis* can be used as an additional measure to counteract erosion. This practice will increase surface stability and help conserve soil moisture.

3. Soil Remediation and Organic Matter Enrichment

In mining sites like this, where fertile soil has been completely removed, soil reclamation is a fundamental step in restoring the area to its former state, thus creating a productive structure. First, in the bentonite quarry area, coarse stones and rubble should be laid on the bottom to create a natural drainage structure, followed immediately by a layer of finer material. A 30-cm-thick layer of organic-rich topsoil should be laid on top of this permeable base layer. This practice is crucial for increasing both water permeability and microbial activity.

4. Plant Species Selection and Determination of Planting Methods

In rehabilitation projects, the cultivation of the mine site with vegetation constitutes the ecological component of the project. In such areas, it is important to prioritize species native to the region's natural flora whenever possible. Adaptation problems in planted or transplanted plants are another undesirable problem. While various planting techniques and methods exist, a triangular (hexagonal) planting method was used in this demonstration project. This method improves soil retention capacity by balancing root and crown development. Examples of species that could be used in the demonstration project area include common alder (*Alnus glutinosa*), acacia (*Robinia pseudoacacia*), white willow (*Salix alba*), oak (*Quercus* sp.), almond (*Prunus amygdalus*), and stone pine (*Pinus pinea*). Additionally, vine species such as honeysuckle (*Lonicera* sp.) and Chinese wisteria (*Wisteria sinensis*) could be added to the list to enhance the visual quality of the lower slopes.

5. Creation of Ecological and Landscape Restoration Design

The goal of ecological restoration is not simply to restore vegetation to the area after mining operations. It also aims to restore ecosystem functions. Therefore, to enhance biodiversity, vegetation should be arranged in layers (tree, shrub, and herbaceous cover), thereby increasing habitat diversity. Establishing plant biodiversity will also support wildlife development and create a holistic landscape quality.

6. Monitoring, Maintenance, and Sustainability

As with any project, success in rehabilitation can be achieved through long-term monitoring and maintenance programs. Therefore, several five-year monitoring and maintenance periods should be conducted to assess plant growth, control erosion and landslides, and ensure drainage system functionality. The intensity of interventions should be gradually reduced to support the restoration of the environment to its natural state (Cooke and Johnson, 2020).

Restoration of Post-Mining Excavation Areas to Nature

This model assumes that open-pit mining is used in natural stone (limestone) quarries. Open-pit mining can create unique and partially permanent landforms, including benches, pits, slopes, and hillocks. Therefore, it is not possible to restore the land, which will be destroyed and its natural balance disrupted by the operation of a natural stone (limestone) quarry, to its original state through various recreation and recultivation methods after the operation. Restoration efforts will aim to restore the degraded land to its former state as closely as possible, ensuring its full compatibility with its surroundings.

If any pits or depressions arise as a result of material removal, coarse materials such as stone and rubble will be placed at the bottom, with finer materials at the top. The purpose of this stacking is to increase the porosity and permeability of the reclaimed area. Placing the coarse materials at the bottom will also facilitate natural drainage.

Before rehabilitation can begin, the clay deposit responsible for the landslide must be removed. However, factors such as the absence of a suitable storage area within the project site and the region's intense rainfall pose challenges for safely storing the excavated clay. This situation could increase the susceptibility of the remaining material to further landslides.

Determining Safe Slope Angles in the Sample Site, Ensuring Sensitivity of Slopes and Steps

The first step in organizing the post-production operations at the site is to secure steep slopes, ridges, and steps. The topsoil layer in the sample site is assumed to be very shallow (0-5 cm). In this case, it is not possible to separate the soil layer from the material; therefore, it will be evaluated using natural stone material. Consequently, it is assumed that there will be no soil storage area at the site.

Because it is not possible to separate the limestone raw material extracted from the operational areas from the waste material, the waste material will be handled as natural stone. Consequently, no separate waste disposal area is anticipated within the operation site.

As part of the rehabilitation of the quarry areas following the completion of operational activities, particular attention should be given to securing steep slopes and ensuring their long-term stability. The slopes should be designed to minimize the risks of rockfall and slope failure. As a result of the production activities conducted within the operational areas, stepped landforms will develop on the sites. The geological and geotechnical investigations of these stepped slopes — including scientific analysis and evaluation of parameters such as critical angle, bench height and width, and overall slope angle — will be addressed in the Geological and Geotechnical section and are therefore beyond the scope of this section.

Rehabilitation and Organization of Overburden, Waste, and Storage Areas

The topsoil layer within the operational areas is very shallow, ranging between 0 and 5 cm, and cannot be separated from the underlying material. Therefore, it will be handled together with the natural stone material, and no separate soil storage area will be established at the project site. Similarly, since it is not possible to separate the limestone raw material extracted from the operating areas from the waste material, the latter will also be managed together with the natural stone material. Consequently, no waste disposal area will be required within the project site.

Adoption of Preventive Measures Against Possible Erosion

Clay from the quarry will be recovered for use in production. This will allow the limestone quarry and the overlying clay layer, which poses a landslide risk, to be reused in production activities. However, this also means that the planned rehabilitation activities will need to be carried out gradually over time. Furthermore, water that may accumulate in the upper basin of the quarry must be managed and discharged through an appropriate drainage system to prevent continuous movement of the clay mass in the upper layer.

The new morphology resulting from the mining operations will not create depressions where water may accumulate. Since the production activities will be carried out progressively at higher elevations and will consist of sloped surfaces, as mentioned in previous sections, water will naturally be directed away from the area through the drainage system.

With the construction of the fill and drainage network, no water accumulation is expected. The constructed drainage system will convey runoff to the existing natural drainage channels. Since technical details should be addressed in the Geology and Geotechnical section of the rehabilitation projects, they will not be included in this section. Upon closure of the area to operations and once geological and geotechnical stability against potential landslides is ensured, vegetative rehabilitation will be initiated to restore ecological balance and adapt the site to the regional vegetation structure.

Topsoil Replacement and Rehabilitation Works

The soil structure, vegetation, and planting techniques are crucial for the successful rehabilitation of the regraded landform that will be created following the removal of the clay mass and limestone bedrock, as described in previous sections of the quarry area. The rehabilitation operations in the area will be implemented according to the layout illustrated in Figure 1.

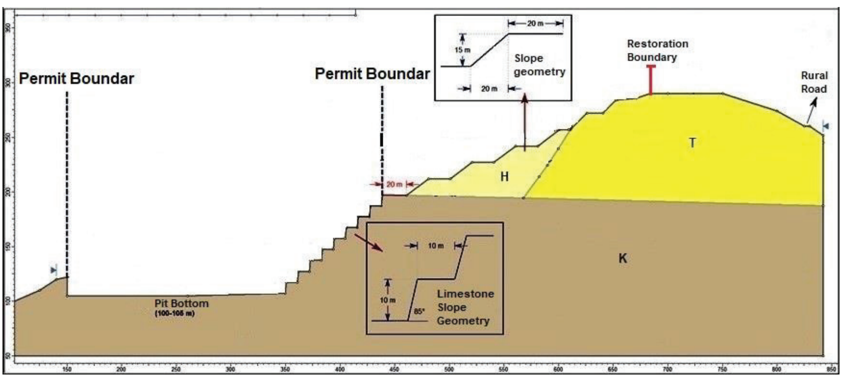

Figure 1. Post-operational, pre-rehabilitation condition of the quarry area.

Rehabilitation works in the study area will be conducted over an area approximately 400 m wide and 320 m long, covering a total of about 128,000 m² (Figure 2). The upper zone adjacent to this area is covered with vegetation, including beech, oak, chestnut, acacia, alder, and hornbeam. The soil characteristics in this zone are similar to those of the area previously affected by landslides. In this section, surface water should be directed to a designated area and discharged through a controlled drainage system.

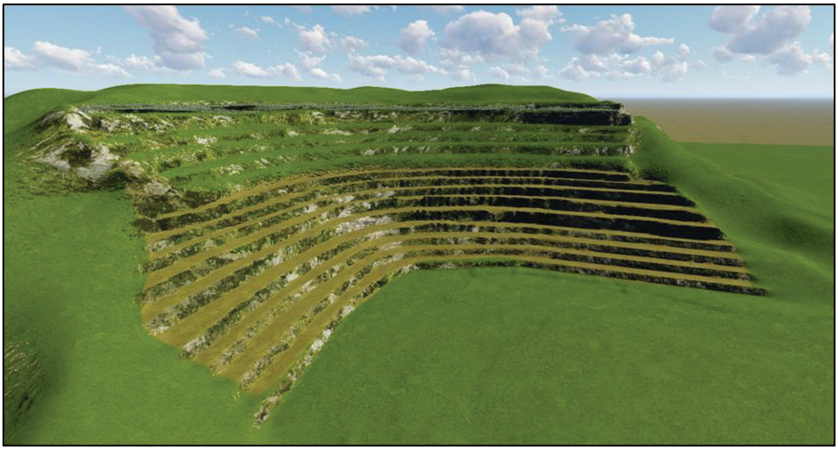

Figure 2. Three-dimensional terrain model of the quarry area after operation and before rehabilitation.

In the sketch prepared following the completion of quarry operations, grading or benching was considered in two separate sections. The first section is the steep zone where the limestone parent material is exposed, with a face angle of 85 degrees. After grading in this section, the soil will be tilled using a double ripper to delineate the limestone bedrock before planting on the terraces. This process will eliminate permeability and aeration problems in the hard, compact layer that restricts root penetration. Subsequently, a 30 cm thick layer of organically rich forest soil will be spread over the area (Figure 3).

After soil spreading, planting will be carried out with tree saplings that have strong root development, high soil retention capacity, and the ability to enrich the soil with organic matter while adapting well to local ecological conditions. Common alder (*Alnus glutinosa*), acacia (*Robinia pseudoacacia*), white willow (*Salix alba*), oak (*Quercus* sp.), almond (*Prunus amygdalus*), wild pear (*Pyrus elaeagnifolia*), and stone pine (*Pinus pinea*) species may be used as alternative planting options.

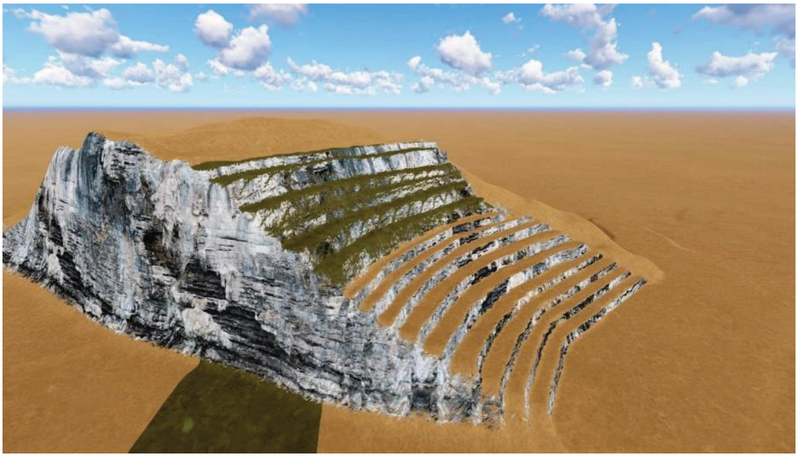

Figure 3. 3D sectional view of the land preparation before planting.

The hexagonal planting method (3 × 3 m) should be applied as indicated in Figure 4. Bare-root saplings aged 1+0 years can be used. Whenever possible, at least two different species from the aforementioned list should be used to enhance biodiversity, support wildlife development, and create a more natural composition. As shown in Figure 1, the terrace width is 10 m (except for the top terrace, which is 20 m), and saplings can be planted in three rows using the triangular planting method. During planting, a spacing of 1.1 m should be maintained from the front and back edges of each terrace. On a 20-meter-wide terrace located at the upper limestone bedrock level, planting can be arranged in seven rows with a 90 cm spacing from the terrace borders. The total area designated for soil tillage and soil spreading with a double ripper is 40,000 m².

Planting System

Triangular Planting (Hexagonal Pattern):

In this system, trees are planted at the corners of equilateral triangles (Figure 4). This arrangement provides equal spacing in all directions, allowing the roots and crowns to utilize the available space efficiently. The row spacing is calculated as 0.866 times the tree spacing within the row. The number of trees established using this system is approximately 15% higher than that of square planting.

The required number of saplings per decare can be calculated using the formula:

Number of saplings = (1000 m² / a²) × 1.15,

where a represents the length of one side of the triangle (m).

Although the number of saplings is higher compared to square or rectangular planting systems, the corridors that typically form between rows in these patterns are not created in the hexagonal arrangement. This results in reduced rainwater runoff and increased soil water-holding capacity. As the saplings mature, the continuous canopy that forms will further decrease the velocity and amount of rainwater reaching the soil surface. In addition, root development will enhance soil retention and provide greater surface protection against erosion.

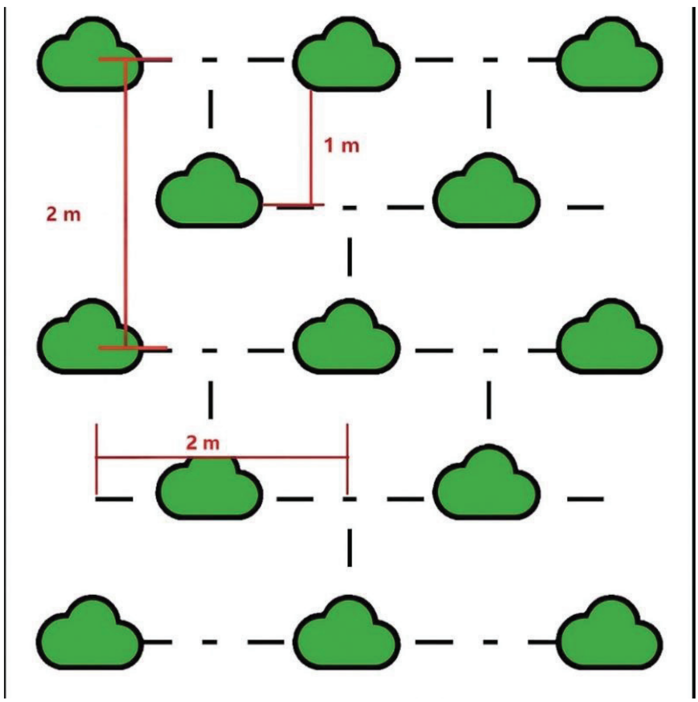

Figure 4. Sapling planting layout on the constructed terraces.

The upper slope of the terrace consists of limestone with an inclination of about 85 degrees, making soil application unsuitable. The establishment of woody plant species in this area will be difficult, and any subsequent planting attempts may lead to undesirable outcomes. To improve the visual quality of these areas, it would be appropriate to plant perennial climbing species at 1.5–2 m intervals on the lower slopes of the terraces, allowing them to spread downward to cover the slope. Species that can be considered for their visual value and regional adaptability include honeysuckle (*Lonicera* sp.), Chinese wisteria (*Wisteria sinensis*), caper (*Capparis* sp.), ivy (*Hedera helix*, *H. colchica*), clematis (*Clematis* sp.), passionflower (*Passiflora caerulea*), and trumpet vine (*Campsis radicans*, *C. grandiflora*).

In the upper part of the excavation site, where the remaining sandy clay (H) and clay–sand–tuff (T) materials are graded, activities should be implemented to maintain the slope stabilization established for the area's rehabilitation. In this region, characterized by a gentler, graded slope, wire mesh should be applied to the slopes, followed by the sowing of a mixed grass seed composition. Once the wire mesh has been laid and secured, a grass mixture consisting of 40% *Festuca arundinacea* TURBO RZ + 30% *Festuca arundinacea* FIRACES + 20% *Lolium perenne* SUN + 10% *Poa pratensis* PRAFIN, considered suitable for the regional conditions (moist and water-seepage-prone areas), should be used. The total area requiring wire mesh application and grass planting is estimated at approximately 61,000 m^2. The amount of grass seed required can be calculated based on a seeding rate of 15–20 g per m^2.

In the terrace area formed by sandy clay (H) and clay–sand–tuff (T) masses, no soil preparation is required, and planting can begin directly. Since the soil in this area is loose, planting shrubs rather than trees is more appropriate. Tall tree species should not be used here, as they may impose excessive load on the loose soil and potentially trigger landslides in the future.

Proposed shrub species include rosehip (*Rosa canina*), firethorn (*Pyracantha coccinea*), lilac (*Syringa vulgaris*), Spanish broom (*Spartium junceum*), tamarisk (*Tamarix* sp.), hawthorn (*Crataegus* sp.), red barberry (*Berberis vulgaris*), spindle wood (*Euonymus europaeus*), Japanese spindle (*Euonymus japonicus*), privet (*Ligustrum vulgare*), cherry laurel (*Prunus laurocerasus*), oleaster (*Elaeagnus angustifolia*), and sea buckthorn (*Elaeagnus rhamnoides*). One-year-old bare-root saplings of these species can be used for planting.

Planting is recommended at 1 × 2 m spacing, following the planting template shown in Figure 5. The total area designated for shrub planting is approximately 42,000 m². The number of saplings required for this area can be estimated based on a planting density of 500 saplings per 1,000 m². It is recommended to use at least two different species from the aforementioned list to promote biodiversity, support wildlife development, and create a more natural composition. Illustrative views of the quarry site following planting are presented in Figures 6 and 7.

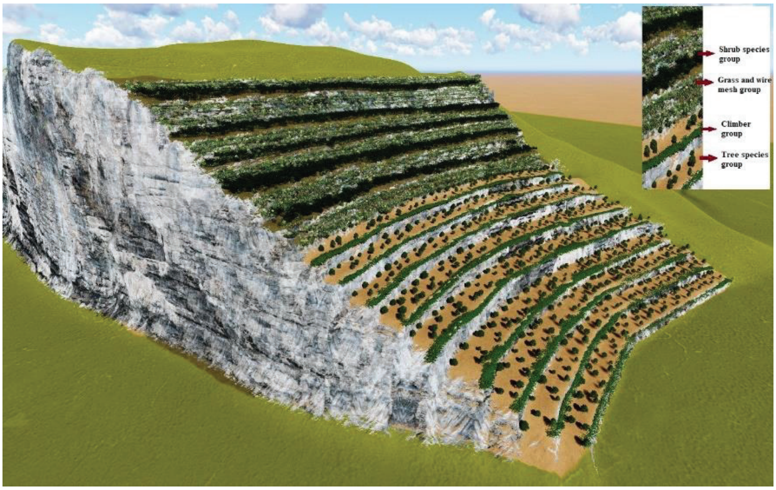

Figure 6. Estimated 3D cross-sectional view of vegetation in the early years.

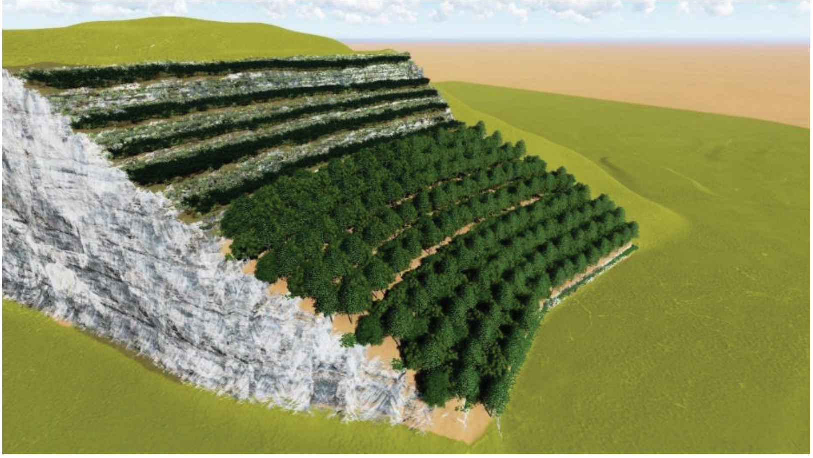

Figure 7. Estimated view of the vegetated area after 10–15 years (3D cross-sectional image).

This study only focused on the ecological assessment and sampling of the planting process. However, rehabilitation work in bentonite pit open-pit mines requires the participation of multidisciplinary teams. A holistic approach should be taken to address the geological, geotechnical, and ecological processes involved, including soil and flora. This exemplary project only addresses the potential stages and methods of planting rehabilitation, which aim to restore the site to a near-natural state.

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Chapter V - From Barriers to Opportunities: The Digital Transformation of Forestry

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1. Introduction

Digitalization has emerged as a defining force of the twenty-first century, profoundly reshaping nearly every human endeavor, from manufacturing and healthcare to agriculture and energy (Palander et al., 2024). Forestry, a long-standing and traditional resource-based industry, navigates a unique interface between natural ecosystems and technological advancements (Bespalova et al., 2021). This sector operates within complex ecological, spatial, and social systems that inherently resist straightforward automation. Nevertheless, increasing environmental and climatic pressures—stemming from deforestation, biodiversity loss, and the escalating effects of climate change—are compelling the forestry industry toward an inevitable digital transformation (Causevic et al., 2024).

The concepts of Industry 4.0, Smart Forests, and Precision Forestry have expanded the traditional boundaries of forest management. These approaches view forests not as static ecosystems to be measured and harvested, but as dynamic, data-driven systems that can be monitored, modeled, and improved continuously (Picchio et al., 2019). Technologies such as remote sensing, artificial intelligence (AI), and the Internet of Things (IoT) are creating new opportunities to plan, monitor, and manage forest operations more efficiently. They also support broader sustainability goals. The merging of ecological science and digital technology is therefore redefining how forestry is understood and practiced (Urzedo et al., 2022).

Historically, forestry has evolved in parallel with technological change. The shift from paper-based inventories to GIS-enabled forest data systems marked a major turning point in the late twentieth century (Chen & Zhu, 2013). More recently, the advent of cloud computing, remote sensing, and real-time spatial analytics has transformed how forest information is collected, processed, shared, and governed (Döllner et al., 2023). Each technological stage improved accuracy, efficiency, and spatial awareness; yet today's digital transformation reflects a deeper shift—forest data are no longer static records, but live, continuously updated systems that underpin adaptive management and cross-sector collaboration.

This global shift aligns with a broader trend of digital transformation observed across all natural resource sectors (Sasaki & Abe, 2025). For instance, precision farming technologies in agriculture enable the near real-time optimization of crop yields and resource utilization (Hatanaka et al., 2021). Similarly, within the energy and mining industries, digital twins and predictive analytics have become integral for enhancing safety, strategic planning, and overall sustainability (Zhou, 2024). Forestry, however, is confronted with the unique challenge of integrating these digital innovations while simultaneously upholding ecological integrity and its multifaceted values (Tagarakis et al., 2024). This tension between technological opportunity and environmental responsibility lies at the heart of modern forest governance.

At the global scale, the significance of digitalization within the forestry sector has garnered substantial scholarly and policy interest. Prominent international frameworks, such as the Food and Agriculture Organization's digital-forest initiatives (FAO 2022) and the EU Forest

Strategy 2030 (European Commission, 2021) underscore the transformative capacity of digital technologies in fostering climate-neutral and biodiversity-positive results. Similarly, the United Nations's Sustainable Development Goals — particularly Goals 13 (Climate Action) and 15 (Life on Land) — underline digital innovation as a key driver for sustainable natural-resource management (UN 2023). These global frameworks show that digitalization is not only a technical process but also a transformation in governance, offering the potential for greater transparency, participation, and accountability in forest policy.

Nevertheless, the digitalization of forestry is neither simple nor universal. Forests are often remote, data-scarce, and ecologically sensitive. The infrastructure required for real-time monitoring is frequently missing, and many forestry institutions still face cultural resistance and limited digital capacity. As a result, the sector most dependent on natural systems remains one of the slowest to digitize. Understanding the technical, institutional, and social roots of this paradox is essential to determine whether—and under what conditions—forestry can truly become digital.

However, this growing reliance on digital tools also introduces critical questions concerning ethics, data ownership, and knowledge. For instance, who controls digital forest data? How do algorithms influence our perception and management of ecosystems? While promising efficiency and precision, digital platforms risk oversimplifying complex forest systems into mere datasets (Nitoslawski et al., 2021). Such concerns highlight the potential for technological determinism and data colonialism, themes crucial for shaping the future design and governance of digital ecosystems in forestry. Therefore, any discussion of digitalization must balance technological optimism with ecological awareness and social responsibility (Gabrys et al., 2022).

This chapter explores the possibility, necessity, and limits of digitalization in forestry from a global perspective. It aims to synthesize conceptual and technological advances, identify barriers to transformation, and highlight emerging pathways toward a digital and sustainable forestry paradigm. By combining insights from technology, environmental governance, and socio-ecological systems thinking, this chapter offers a comprehensive view of how digitalization may reshape forest management and policy in the years to come.

The following sections build this argument step by step. Section 2 provides the conceptual background and key terminology that frame digitalization within natural resource sectors. Section 3 reviews the current state of digital technologies in forestry, outlining how data, analytics, and infrastructure are reshaping forest management. Sections 4 and 5 then examine the barriers and opportunities that define this transition—introducing the 4C (Connectivity, Capacity, Culture, Cost) constraints and the 4O (Optimization, Observation, Openness, Orchestration) pathways that together chart the evolution of digital forestry. Finally, Section 6 outlines future research directions and governance priorities, highlighting how ethical, institutional, and ecological integration will determine the success of this transformation.

Ultimately, this chapter seeks to answer one central question: Can forestry truly become digital—and if so, how can it move from 4C barriers—Connectivity, Capacity, Culture, and Cost— to the 4O opportunities—Optimization, Observation, Openness, and Orchestration under sustainable and ethical conditions?

2. Conceptual Background: Digitalization in Natural Resource Sectors

2.1. Terminological Distinctions: Digitization, Digitalization, and Digital Transformation

The discussion on digital transformation in natural resource sectors is often complicated by overlapping terms. Digitization, digitalization, and digital transformation are frequently used interchangeably, but they describe different levels of technological and organizational change (Marks & Al-Ali, 2020). Understanding these distinctions is essential for explaining how forestry, with its complex ecological, spatial, and socio-economic systems, can navigate its own digital journey.

Digitization refers to the transformation of analog data into a digital format (Marks & Al-Ali, 2020). This fundamental step lays the groundwork for subsequent advancements in digital integration. Within the forestry sector, initial applications encompassed the conversion of physical maps into digital versions, the establishment of digital forest inventory systems, and the utilization of Geographic Information Systems for spatial data management (Chen & Zhu, 2013). Such initiatives significantly enhanced data precision, availability, and retention capabilities, thereby facilitating advanced spatial analyses previously unattainable through analog approaches.

Digitalization, in contrast, goes beyond simple data conversion. It refers to using digital tools to improve, automate, or redesign management processes (Zerafat et al., 2023). In forestry, this includes data-driven decision systems, cloud-based monitoring platforms, and automated workflows for harvesting, logistics, or road maintenance (Unver & Kurdoglu, 2024). Digitalization also requires institutional change—it reshapes how organizations collect, interpret, and act on information

(Urzedo et al., 2022). For instance, when a forest management unit integrates real-time sensor data to monitor fire risk or optimize maintenance schedules, it is engaging in digitalization rather than basic digitization (Sommer et al., 2024).

Digital transformation is the most comprehensive stage. It changes not only the tools but also the structure, culture, and mindset of an organization. In forestry, it means embedding digital systems across all levels—from field operations and planning to policy and stakeholder engagement (Sommer et al., 2024). Smart Forestry and Forest 4.0 represent this stage: interconnected technologies enabling adaptive, transparent, and sustainable management decisions (Feng & Audy, 2020; Hoppen et al., 2024).

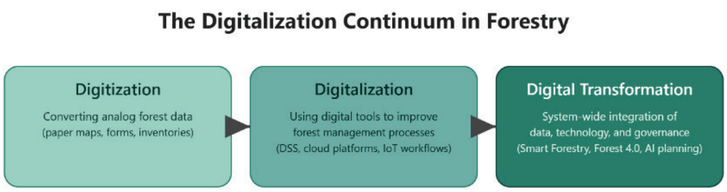

Figure 1. The digitalization continuum in forestry. The process evolves from digitization (conversion of analog data) to digitalization (use of digital tools in management processes), culminating in digital transformation—a systemic shift in culture, governance, and technological integration.

These three stages—digitization, digitalization, and digital transformation—are interconnected but not strictly sequential. Progress depends on context, capacity, and governance structures. While some forestry organizations already employ advanced tools such as AI-based analytics, open data platforms, and satellite monitoring, others remain at early stages due to limited funding, infrastructure, or institutional inertia. Digital transformation in forestry should therefore be understood as a gradual, context-specific evolution rather than a uniform or inevitable process (Figure 1).

The meaning of digitalization in natural resource management also extends beyond technology. It raises questions about how knowledge is produced, who controls data, and how decisions about nature are made through digital systems. Forest data are never neutral—they reflect ecological values, policy priorities, and social perspectives (Gabrys et al., 2022). Therefore, the digital transformation of forestry should not only aim for efficiency but also ensure inclusivity, transparency, and ethical governance (Rantala et al., 2020).

In summary, digitization refers to technical data conversion, digitalization to the organizational use of digital tools, and digital transformation to a systemic change in logic and culture. Recognizing these stages provides the conceptual foundation for analyzing how digital technologies are reshaping forestry. The next section compares how agriculture, mining, and forestry have experienced digitalization, revealing shared opportunities and unique challenges.

2.2. Comparative View Across Natural Resource Sectors (Agriculture–Mining–Forestry)

The pace of digitalization has varied significantly across natural resource sectors. Agriculture and mining have adopted digital technologies rapidly (Krachunova et al., 2025), while forestry faces greater ecological and institutional complexity (Devi et al., 2025). Comparing these sectors helps clarify why forestry's digital transition has been slower and more fragmented.

In agriculture, digital tools have revolutionized how farmers manage land and resources. The rise of precision agriculture in the 1990s introduced GPS-guided machinery, variable-rate application, and satellite monitoring. Today, digital platforms, IoT sensors, and drones provide real-time data for soil, crop, and weather analysis. Data analytics has become vital for optimizing production, managing supply chains, and promoting climate-smart agriculture. Because farming systems are usually privately owned and have fast feedback cycles, digital adoption has been relatively straightforward and profitable (Singh et al., 2024).

In mining, digital transformation—often described as Mining 4.0—has been driven by automation, safety, and cost efficiency. Technologies such as autonomous vehicles, digital twins, and real-time monitoring systems are now standard in many operations. Centralized control centers use live data from sensors to improve productivity and safety. The mining sector's large-scale investments, corporate structure, and stable working environments have enabled a faster and deeper digital transition than in other sectors (Nagaralawala, 2025).

Forestry, on the other hand, operates within living ecosystems that are vast, dynamic, and interdependent. Forests are not simple production units; they encompass biodiversity, water systems, carbon cycles, and human communities. Ecological processes unfold over decades, making it difficult to apply short-term digital models. Forestry operations often take place in remote areas with limited connectivity, and governance tends to be fragmented—shared among public agencies, private owners, and local communities with differing objectives and data systems. These conditions make digitalization in forestry more complex, slower, and highly dependent on context (Himes et al., 2023; Jäntti & Aho, 2022; Kankaanhuhta et al., 2021; Nitoslawski et al., 2021; Palander et al., 2024; Rantala et al., 2020; Sommer et al., 2024; Misirlioğlu & Gümüş, 2024).

Table 1. Comparative overview of digitalization in natural resource sectors.

Sector	Key Technologies	Main Drivers	Challenges	Digital Maturity
Agriculture	Precision farming, IoT sensors, drones, satellite imagery, data analytics	Yield optimization, input efficiency, climate-smart practices	Data fragmentation, adoption cost for smallholders	High
Mining	Digital twins, autonomous vehicles, real-time monitoring, predictive maintenance	Safety, cost reduction, operational efficiency	High energy use, system complexity, cybersecurity	High
Forestry	Remote sensing (LiDAR, UAVs), GIS, AI-based decision support, cloud data systems	Sustainability, resource efficiency, transparency	Ecological complexity, fragmented governance, limited capacity	Medium

As summarized in Table 1, agriculture and mining have progressed rapidly toward digital integration, whereas forestry remains comparatively less mature. The differences among these sectors highlight how ecological complexity, governance structures, and data interoperability shape the pace of digital transformation.

The spatio-temporal complexity of forestry data also makes digitalization challenging. Forest inventories must integrate diverse information—species composition, biomass, canopy structure, soil, and terrain—collected across wide areas and long time periods. Monitoring forest health or carbon dynamics requires combining multiple data sources: satellite imagery, LiDAR scans, and ground sensors (Borghi et al., 2025; Brandt et al., 2024). Since ecological processes evolve over long periods, digital systems must handle both high-frequency operational data and slow ecological trends. Managing such heterogeneous data requires robust computational systems capable of handling big spatial data without losing ecological detail (Porter et al., 2005).

Despite these challenges, forestry is gradually entering a digital era through several complementary frameworks.

- Smart Forestry applies Industry 4.0 principles by linking sensors, AI, and connected networks to support intelligent forest management. Examples include early-warning systems for forest fires using deep learning and IoT technologies.
- e-Forestry focuses on digital workflows and institutional transparency. It builds online platforms for permits, reporting, and data sharing, enhancing efficiency and stakeholder participation.
- Data-Driven Forest Management emphasizes the use of analytics, simulation models, and decision support tools to plan and evaluate forest operations based on measurable evidence. It seeks to balance ecological, economic, and social goals through integrated, evidence-based approaches (Bayramoğlu et al., 2025).

Together, these frameworks show that digitalization in forestry goes beyond technology—it represents a transformation in knowledge systems, decision-making, and governance. Although forestry's progress has been slower than other sectors, it demonstrates increasing innovation and adaptation. The convergence of remote sensing, geospatial analytics, and artificial intelligence now offers unprecedented opportunities to understand and manage forests as complex adaptive systems rather than static resources (Borz et al., 2022; Urzedo et al., 2022; Wang et al., 2025).

Realizing this potential, however, requires more than technological readiness. It also depends on addressing issues of governance, culture, and ethics—topics that will be explored in the following sections of this chapter.

3. Current State of Digital Technologies in Forestry

Digital transformation in forestry unfolds across multiple technological domains that interact through a layered digital ecosystem. These layers—data collection, analytics, cloud infrastructure, and governance—represent a continuum that connects field-level sensing to strategic decision-making. Understanding how these components interrelate is essential for identifying innovation bottlenecks and designing integrated digital systems, as illustrated in Figure 2.

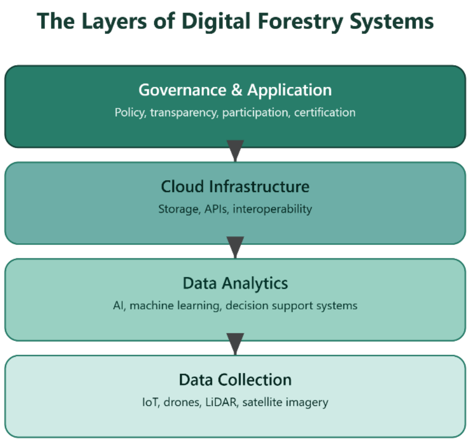

Figure 2. Conceptual layers of digital forestry systems. The framework illustrates the vertical integration of data collection, analytics, cloud infrastructure, and governance functions—showing how digital technologies evolve from environmental sensing to decision-making and policy application.

This layered structure provides the foundation for analysing the current state of digital technologies in forestry. The following subsections explore these components in greater detail—starting with remote sensing and geospatial systems, which serve as the primary data sources for digital forest management.

3.1 Remote Sensing and Geospatial Technologies

Remote sensing and geospatial technologies are at the core of digital transformation in forestry. They provide the spatial and temporal data needed to monitor forest ecosystems, evaluate management decisions, and model environmental change (Latterini et al., 2025; Palander et al., 2024). Since the 1970s, satellite imagery has offered a way to observe large forest areas with consistent temporal coverage. In the past two decades, technological advances—especially in LiDAR, drones, and high-resolution multispectral sensors—have dramatically increased both the precision and accessibility of spatial data (Maeda et al., 2025; Marcello et al., 2024).

Modern remote sensing enables forest professionals to map tree species, estimate biomass, and monitor forest health with unprecedented detail (Ullah et al., 2025). Satellite constellations such as Landsat, Sentinel, and PlanetScope deliver imagery at resolutions that allow the detection of canopy gaps, logging activities, and pest outbreaks (Francini et al., 2020; Güloğlu et al., 2021; Espíndola & Ebecken, 2023; Massey et al., 2023; Grabska-Szwagrzyk et al., 2024). LiDAR technology, by capturing three-dimensional structural information, provides detailed measurements of canopy height, stand volume, and terrain morphology—data that are critical for inventory accuracy and habitat modeling.

Unmanned aerial vehicles (UAV) have further revolutionized forest monitoring by offering flexible, cost-effective, and high-resolution data acquisition at local scales (Marcello et al., 2024). UAVs can acquire imagery in challenging atmospheric conditions and across difficult topographies, effectively bridging the observational gap between satellite and ground-based systems. When combined with photogrammetry and machine-learning classification, UAVs enable the real-time detection of disease, storm damage, or illegal logging (Iheaturu et al., 2024; Spiers et al., 2025). Such technologies enable near-continuous surveillance of forest conditions, turning once-static inventories into living digital maps. Such technologies enable near-continuous surveillance of forest conditions, turning once-static inventories into living digital maps (Figure 3).

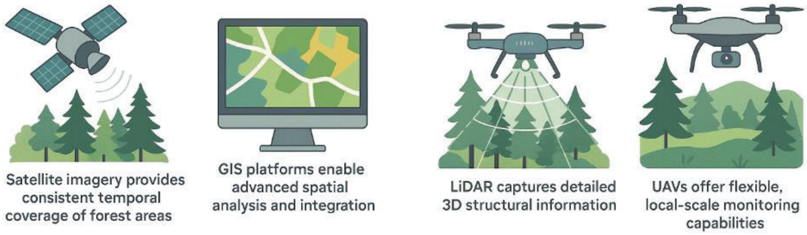

Figure 3. Remote sensing and geospatial technologies in forestry. The diagram illustrates the integration of satellite imagery (e.g., Landsat, Sentinel), LiDAR scanning, and UAV-based data with GIS layers for forest monitoring, analysis, and decision support.

Integration with Geographic Information Systems (GIS) is what transforms these data into decision-ready information. GIS platforms allow managers to overlay forest inventory data, road networks (Gümüş et al. 2008), soil maps, and ownership boundaries within a single analytical environment (Całka & Szostak, 2025). This integration supports multi-criteria planning—such as optimizing harvesting routes, analyzing erosion risk, or identifying areas of high ecological value. Spatial analysis tools, coupled with Python or R-based geoprocessing scripts, have also improved automation and reproducibility in forest planning (Eberhard et al., 2025; Paradis, 2025).

The emergence of open-source geospatial tools has made these technologies more accessible to public institutions and researchers. Platforms such as QGIS, Google Earth Engine, and Open Foris allow users to analyze remote-sensing data without extensive local computing resources (Leinonen et al., 2018). Cloud-based workflows now facilitate large-scale deforestation monitoring, forest-cover change detection, and carbon-stock estimation. These systems are increasingly integrated with national forest information systems and global reporting frameworks, such as REDD+ (Sy et al., 2013) and FAO's Forest Resources Assessment.

Despite rapid progress, several limitations remain. High-resolution data often require significant storage and processing capacity, and differences in spatial resolution or temporal frequency can complicate data integration. In many regions, especially in developing countries, the lack of stable internet connections and trained personnel limits the effective use of advanced geospatial analytics. Furthermore, while remote sensing can provide quantitative indicators, it cannot always capture qualitative aspects such as forest structure diversity or social use patterns (Nitoslawski et al., 2021; Xu et al., 2024).

Even with these challenges, remote sensing and GIS technologies have fundamentally changed the way forests are mapped, monitored, and managed. They have shifted forestry from periodic field measurements to continuous spatial observation, forming the backbone of digital forest management. The next section extends this discussion to data analytics and artificial intelligence, which build on these spatial datasets to support predictive modeling and decision automation. These geospatial systems form the foundation upon which advanced data analytics and AI applications can build predictive and integrative forest insights.

3.2 Data Analytics and Artificial Intelligence Applications

The growing availability of forest data from remote sensing, sensors, and field surveys has opened the door to advanced data analytics and artificial intelligence in forestry. These technologies are transforming how forest resources are monitored, modeled, and managed. Instead of relying solely on static inventories or manual assessments, modern forestry now increasingly uses predictive and data-driven approaches to improve planning and decision-making (Palander et al., 2024).

Data analytics plays a central role in processing and interpreting the vast datasets generated by digital technologies. Forest managers use statistical and computational models to extract meaningful patterns from satellite imagery, LiDAR point clouds, and IoT sensor networks (Massey et al., 2023; Ullah et al., 2025). For example, machine-learning algorithms are applied to classify tree species (Grabska-Szwagrzyk et al., 2024), predict timber yield, and estimate aboveground biomass (Ullah et al., 2025). Time-series analysis of remote-sensing data allows the detection of forest disturbances such as fires, pest outbreaks, or illegal logging (Güloğlu, Belkayalı & Bulut, 2017; Espíndola & Ebecken, 2023; Francini et al., 2020). Advanced analytics also supports long-term monitoring of carbon fluxes and ecosystem services, contributing to climate-change mitigation efforts (Sy et al., 2013).

Artificial intelligence has expanded these capabilities further. AI systems, especially those based on machine learning and deep learning, can automatically recognize complex patterns that traditional models might overlook. Convolutional neural networks are used to detect canopy gaps, map forest types, or assess deforestation risk from high-resolution imagery (Francini et al., 2020; Grabska-Szwagrzyk et al., 2024). Recurrent neural networks can model temporal dynamics, predicting fire spread or disease progression based on environmental variables. These methods allow faster and more objective analyses, reducing human error and increasing the reproducibility of forest assessments.

Decision-support systems powered by AI are also gaining importance in operational forestry. By integrating spatial, economic, and ecological data, these systems can simulate management scenarios and suggest optimized strategies. For instance, multi-criteria decision models can evaluate trade-offs between timber production, biodiversity conservation, and road network efficiency (Eberhard et al., 2025). Such tools enable planners to make informed choices that balance economic returns with sustainability goals. When integrated with GIS platforms, DSS applications provide visual interfaces that help managers explore alternative options interactively (Całka & Szostak, 2025).

Another promising development is the rise of digital twins—virtual replicas of forest ecosystems that continuously update with real-time data. These digital models combine remote-sensing inputs, field measurements, and AI simulations to represent the current state of forest stands. They can be used to test management interventions, forecast growth, or assess climate impacts without disturbing actual ecosystems. Digital twins thus offer a powerful framework for adaptive and transparent forest management.

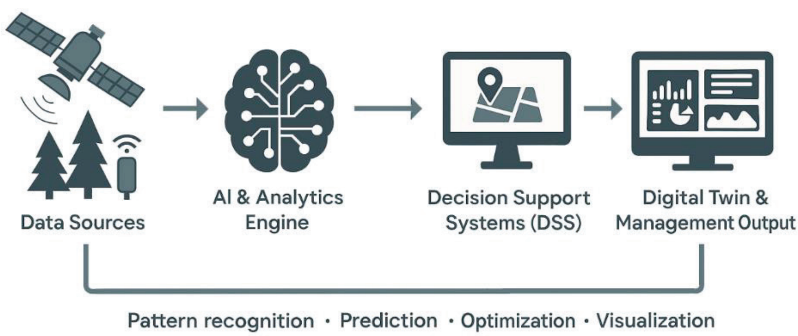

Figure 4. AI and data analytics ecosystem in digital forestry. The diagram illustrates the data flow from remote sensing and field inputs through AI and analytical models to decision-support systems and digital twins that guide forest management.

Despite these advances, several challenges persist. The quality of AI predictions depends heavily on data availability and representativeness (Bansal et al., 2025; Prieur et al., 2021). In many forest regions, datasets are incomplete, inconsistent, or biased toward easily accessible areas, which can lead to machine-learning models trained on limited samples not generalizing well to different forest types or climatic zones (Jarray et al., 2023). Moreover, the integration of multi-source data—ranging from sensor readings to socioeconomic indicators—requires common data formats, metadata standards, and strong data governance (Balestra et al., 2024; Liang & Gamarra, 2020; Mushtaq et al., 2024). This complexity is exacerbated by differences in spatial resolution or temporal frequency (Palander et al., 2024). The lack of skilled personnel in data science and programming also remains a significant barrier, particularly within public forestry agencies (Konovalova et al., 2023; Liang & Gamarra, 2020).

Ethical and transparency concerns are also emerging. As decision-making becomes more automated, questions arise about accountability and fairness (Galaz et al., 2021). Algorithms can unintentionally reinforce existing biases in data collection or prioritization, potentially influencing resource allocation or policy focus (Galaz et al., 2021; Urzedo et al., 2024). Therefore, a critical aspect of AI-based forestry is not only technical performance but also the explainability and interpretability of models (Gevaert, 2022). Ensuring that digital decisions remain transparent and socially responsible is crucial for maintaining trust among stakeholders.

In summary, data analytics and AI are moving forestry toward a predictive and adaptive management paradigm. They enable the transition from descriptive reporting to proactive planning and optimization. However, the benefits of these technologies can only be fully realized if supported by high-quality data, strong institutional capacity, and ethical governance frameworks. The following section examines the cloud platforms and data infrastructures that make such integration and scalability possible in the era of digital forestry.

3.3 Cloud Platforms and Data Infrastructure

The rapid expansion of digital data in forestry has made cloud platforms and integrated data infrastructures essential components of modern forest management (Palander et al., 2024). As remote sensing, IoT, and AI systems generate vast amounts of spatial and temporal data, cloud computing provides the storage, computing power, and connectivity needed to process and share this information efficiently (Massey et al., 2023; Ullah et al., 2025). These platforms have become the backbone of digital forestry, supporting collaboration, scalability, and real-time access across organizations and regions.

Cloud-based systems enable forest data to be stored and analyzed without the need for local high-performance hardware (Palander et al., 2024; Ullah et al., 2025). This democratizes access to advanced analytical tools, especially for public agencies and research institutions with limited resources, by lowering the barrier of expensive local infrastructure (Gouw et al., 2020) and promoting data transparency and sharing (Liang & Gamarra, 2020; Rantala et al., 2020). Through web-based interfaces, forest managers can now visualize, analyze, and share complex datasets from anywhere, leveraging the collaborative and real-time access capabilities of cloud platforms (Rantala et al., 2020; Ullah et al., 2025). Platforms such as Google Earth Engine, Amazon Web Services, and Microsoft Azure provide infrastructure for remote-sensing analysis, predictive modeling, and AI-driven monitoring (Ullah et al., 2025). Open-access tools like FAO's Open Foris, Collect Earth Online, and Global Forest Watch allow users to evaluate forest-cover change, carbon stocks, and land-use dynamics using standardized workflows and supporting remote sensing applications (Espíndola & Ebecken, 2023; Mushtaq et al., 2024; Sy et al., 2013).

Beyond global platforms, many countries are developing national forest data infrastructures to integrate administrative, ecological, and spatial information. These systems act as central repositories for forest inventories, ownership data, and geospatial layers such as roads, soil types, and protected areas (Küçükbekir & Bayramoğlu, 2022). They facilitate interdepartmental coordination, reduce duplication of data collection, and improve policy transparency (Rantala et al., 2020). For instance, Nordic and Central European countries have established digital forest information systems that combine remote sensing with ground measurements (Massey et al., 2023; Palander et al., 2024), providing near-real-time updates on forest conditions (Francini et al., 2020). Such infrastructures support evidence-based decision-making, enabling adaptive management at both local and national levels.

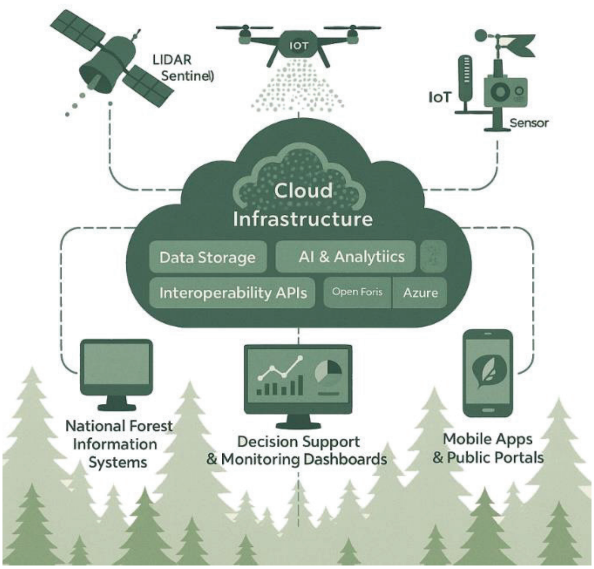

Figure 5. Cloud platforms and data infrastructures in digital forestry. The diagram illustrates how remote-sensing, LiDAR, UAV, and IoT data flow into cloud-based systems for storage, AI and analytics, and interoperability. These infrastructures in turn support national forest information systems, decision-support dashboards, and mobile applications for managers and the public.

An important advantage of cloud platforms is interoperability—the ability of different systems to exchange and use information seamlessly. Standardized metadata, open APIs, and harmonized classification systems make it possible for forestry datasets to interact with agricultural, hydrological, or climate databases. This integration is crucial for cross-sector planning, such as modeling watershed dynamics or assessing ecosystem services. However, achieving full interoperability remains a challenge. Differences in data standards, file formats, and spatial reference systems still hinder smooth integration across institutions and countries (Balestra et al., 2024; Mushtaq et al., 2024).

Another critical aspect is data governance and security. As forest data move into cloud environments, ensuring privacy, ownership rights, and compliance with national regulations becomes increasingly complex. Questions arise over who controls shared data, how long it can be stored, and for what purposes it can be used. Many public forest agencies still lack comprehensive data-sharing policies or cybersecurity frameworks. In addition, the use of commercial cloud services raises concerns about dependency on private vendors and the long-term sustainability of subscription-based models. Developing open, transparent, and secure data governance systems will therefore be key to maintaining trust in digital forestry initiatives (Rantala et al., 2020).

From a technical standpoint, cloud computing also supports the integration of real-time data streams from IoT devices and sensor networks. For example, weather stations, soil moisture sensors, and camera traps can transmit continuous data to central platforms, where it can be processed by automated scripts or AI algorithms. This capability transforms forest management from a reactive to a proactive system, allowing early detection of risks such as fire, disease, or illegal activity (Espíndola & Ebecken, 2023; Francini et al., 2020; Grabska-Szwagrzyk et al., 2024). Combined with visualization dashboards and mobile apps, these systems provide managers and policymakers with actionable insights at multiple scales (Figure5).

Despite these advantages, challenges persist. Many forest institutions in developing regions face limited internet connectivity, high cloud-service costs, and a shortage of technical expertise. Dependence on external platforms may also lead to data sovereignty issues, where national data are stored and processed outside domestic legal frameworks. Addressing these constraints requires capacity-building programs, open-source alternatives, and international cooperation to promote equitable digital access.

In conclusion, cloud platforms and data infrastructures are fundamental to realizing the full potential of digital forestry. They enable the storage, integration, and analysis of diverse datasets while fostering collaboration and transparency across scales. However, their success depends on robust governance frameworks, technical interoperability, and sustainable access. Together, these systems form the digital backbone that connects remote sensing, artificial intelligence, and field operations—laying the foundation for truly data-driven forest management.

4. Barriers and Constraints: The 4C Model

Despite the rapid progress of digital technology, the transition toward fully digital forestry remains uneven. Many countries and institutions face obstacles that limit their capacity to adopt, scale, or sustain digital innovations. These challenges can be grouped under a 4C framework—Connectivity, Capacity, Culture, and Cost—which together capture the technical, institutional, social, and economic dimensions of digital constraints in forestry.

4.1 Connectivity

Limited digital infrastructure is perhaps the most fundamental barrier. Forest operations often occur in remote, mountainous, or densely vegetated areas with poor or intermittent internet access. Without reliable connectivity, real-time data transmission from sensors, drones, or IoT devices becomes impossible (Francini et al., 2020; Grabska-Szwagrzyk et al., 2024). Satellite-based communication systems can help bridge this gap but remain expensive and energy-intensive.

In many regions, national forest services rely on outdated internal networks or stand-alone databases that do not support real-time synchronization (Rantala et al., 2020). This lack of connectivity restricts data sharing between local offices, regional centers, and national headquarters, reducing the effectiveness of digital decision systems. Strengthening communication infrastructure, promoting 5G coverage in rural areas, and investing in edge-computing solutions can help reduce this gap—but these require strong policy support and public–private cooperation.

4.2 Capacity

Digital transformation depends not only on infrastructure but also on human capacity. Many forestry institutions lack personnel trained in data analytics, GIS, programming, or AI, indicating a significant "shortage of technical expertise" (Rantala et al., 2020). As a result, advanced technologies are often underused or applied inconsistently.

Capacity-building programs are frequently project-based and short-term, rather than integrated into institutional structures. This creates dependency on external consultants or donor-funded projects. Universities and technical institutes have begun to introduce courses in forest informatics, but integration into professional forestry education remains limited. Long-term capacity building—through continuous learning, open training materials, and international collaboration—is essential for sustainable digital adoption.

4.3 Culture

Institutional and organizational culture plays a critical role in shaping how technology is perceived and adopted. Forestry is traditionally a conservative sector, built on hierarchical structures and long-established routines (Ferrari et al., 2022; Leonard & Tyers, 2021), with much of the industry operating on traditional practices such as emails and phone calls rather than structured data (Jäntti & Aho, 2022). Decision-making is often based on expert judgment and field experience (Lämås et al., 2023), with many forestry disciplines still relying on traditionally collected, resource-intensive data rather than advanced analytical tools (Borz et al., 2022). This professional identity can sometimes clash with data-driven or automated approaches (Kocak & Pawlowski, 2023; Leonard & Tyers, 2021).

Resistance to change also arises from concerns about data reliability, loss of control, or fear of redundancy among staff (Konovalova et al., 2023). Workers may express fear for their jobs, and advisors question their value as machines increasingly make autonomous decisions, leading to potential deskilling or dehumanization (Leonard & Tyers, 2021; Rose et al., 2020; Woodruff et al., 2024). Concerns about the reliability of technology, security, and privacy also act as significant barriers to adoption, alongside the perceived complexity of digital tools (Andreasen et al., 2023; Dibbern et al., 2024). Building a digital culture therefore requires leadership that values innovation and transparency, with successful organizational culture development depending on leaders driving a strong digital culture and breaking down communication barriers (Butt et al., 2024; Kocak & Pawlowski, 2023). Success stories—such as participatory monitoring platforms or open-data initiatives—can help demonstrate the benefits of digital tools while fostering co-creation and acknowledging local expertise (Rantala et al., 2020; Urzedo et al., 2022). A balanced approach that combines traditional forest knowledge with digital evidence is crucial for cultural acceptance, as understanding forest owners' perceptions of new technologies is essential for their societal benefit (Wising et al., 2024).

4.4 Cost

Financial constraints remain a major bottleneck for digitalization (Konovalova et al., 2023). Although cloud services, drones, and sensors have become cheaper, the initial investment for equipment, software licenses, and training can still be high, especially for developing countries or small forest enterprises (Teixeira et al., 2021). Many digital forestry projects depend on external funding, leading to sustainability issues once the project ends (Arts et al., 2020; Hsu et al., 2019).

Maintenance and data storage costs are often underestimated. Subscription-based software, licensing fees, and the continuous need for system updates can strain limited budgets. Moreover, there is still limited evidence on the direct economic returns of digitalization in forestry compared to traditional methods. Demonstrating clear cost–benefit outcomes—such as savings from optimized road networks, improved inventory efficiency, or reduced fire losses—could encourage more sustained investment. Partnerships with the private sector and integration into broader digital-economy strategies may also help overcome financial barriers.

4.5 Synthesis: Interlinkages Among the 4Cs

The four dimensions—Connectivity, Capacity, Culture, and Cost—are deeply interconnected. Poor connectivity limits capacity building and increases costs, while cultural resistance can undermine both infrastructure investments and skill development (Figure 6). Effective digital transformation therefore requires a holistic approach. Technical solutions must be accompanied by institutional reforms, financial mechanisms, and cultural adaptation strategies.

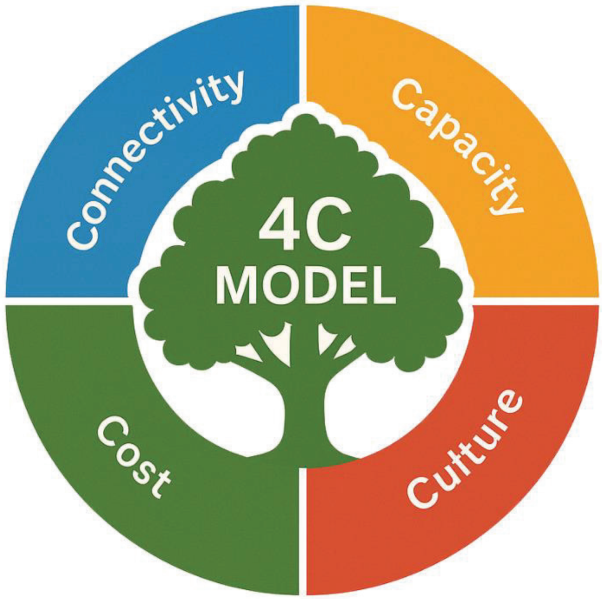

Figure 6. The 4C Model of barriers to digital transformation in forestry. Connectivity, Capacity, Culture, and Cost represent interrelated challenges spanning technical, institutional, social, and economic dimensions. Effective digitalization requires addressing these barriers collectively through integrated policy and capacity development.

Addressing these barriers collectively can help forestry transition from isolated pilot projects to systemic digital integration. The next section explores the opportunities and pathways that can emerge once these constraints are recognized and strategically addressed. Recognizing these interlinkages is essential for transforming the 4C constraints into the 4O opportunities explored in the next section.

5. Opportunities and Emerging Pathways

While forestry faces multiple technical and institutional barriers to digital transformation, it also holds significant opportunities for innovation, efficiency, and sustainability (Palander et al., 2024; Picchi et al., 2021; Sommer et al., 2024). As digital tools mature and data infrastructures improve, new possibilities are emerging for more transparent, adaptive, and ecosystem-oriented forest management (Catalli et al., 2024; Ferretti et al., 2024; Holm & Schweier, 2024; Zweifel et al., 2023).

Building on the previous 4C framework that identified the key barriers to digitalization—Connectivity, Capacity, Culture, and Cost—this section introduces a complementary perspective: the 4O model, which outlines the principal opportunity pathways for digital forestry. These are Optimization, Observation, Openness, and Orchestration, representing the transition from constraint to potential.

Accordingly, these opportunities can be grouped around four major themes (Figure 7):

(1) efficiency and sustainability gains (Optimization) (Picchi et al., 2021),

(2) ecological monitoring and resilience (Observation) (Ferretti et al., 2024),

(3) participation and transparency (Openness) (Holm & Schweier, 2024; Nitoslawski et al., 2021),

(4) integration with the circular bioeconomy and climate policy (Orchestration) (Sommer et al., 2024; Wang et al., 2024).

Together, these dimensions define how digital transformation can move forestry from isolated innovation to systemic, data-driven sustainability.

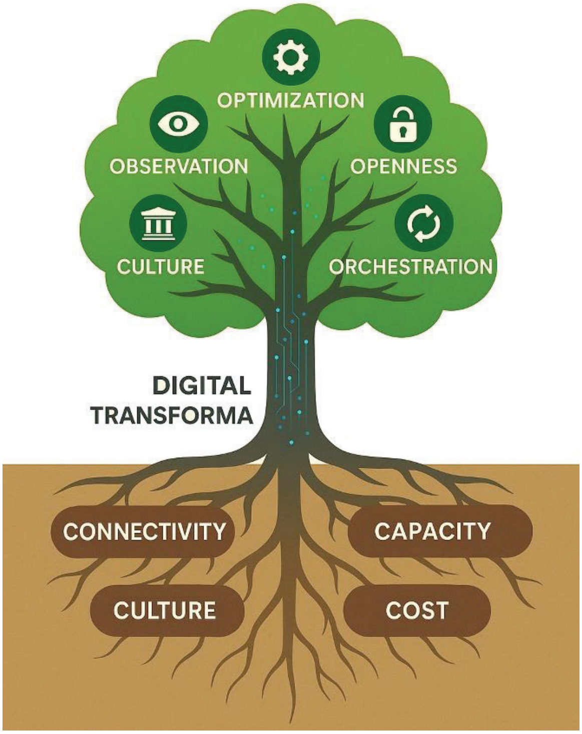

Figure 7. From 4C Barriers to 4O Opportunities in Digital Forestry. The conceptual tree illustrates the transformation from the 4C barriers—Connectivity, Capacity, Culture, and Cost—rooted in institutional and technical constraints, toward the 4O opportunities—Optimization, Observation, Openness, and Orchestration—that define the growth and maturity of digital forestry. The trunk symbolizes the digital transformation process connecting these two dimensions.

5.1 Efficiency and Sustainability Gains

Digital technologies can substantially increase operational efficiency and resource sustainability across all stages of forest management—from inventory and harvesting to logistics and restoration. Automated data collection through drones and IoT sensors reduces fieldwork time and improves measurement accuracy (Buchelt et al., 2023; Cui et al., 2022; Haq et al., 2024). These sensor-based data acquisitions are pivotal in smart forestry, ensuring high-quality data for artificial intelligence applications (Sommer et al., 2024). Machine-learning algorithms can optimize harvesting schedules, predict road wear, or identify the most efficient transport routes based on terrain and weather conditions (Almeida et al., 2022, 2023; Zhao et al., 2024).

Such optimizations translate into lower fuel consumption, reduced soil disturbance, and better use of human and financial resources. Decision-support systems, which integrate data sources, modeling, analytical tools, and optimization algorithms, can combine ecological, economic, and technical indicators to help balance production with conservation objectives (Lämås et al., 2023). In particular, integrating digital road network optimization, which is crucial for reducing environmental impacts and production costs, with environmental impact models can simultaneously reduce operational costs and ecological footprints (Silva et al., 2020). As sustainable forest certification increasingly depends on traceable digital evidence, facilitated by technologies like blockchain for secure and transparent tracking, efficiency-oriented digital tools also support compliance and market competitiveness (He & Turner, 2022).

5.2 Ecological Monitoring and Resilience

Digital technologies are redefining how forests are monitored for ecological health, biodiversity, and climate resilience (Nitoslawski et al., 2021). Remote sensing and AI-based classification enable near-real-time mapping of forest disturbances, such as deforestation, fire, or pest outbreaks (Carter et al., 2024; Francini et al., 2020; Haq et al., 2024). Continuous data streams from ground sensors and satellite observations feed early-warning systems that improve preparedness and reduce response times (Torresan et al., 2021; Zeuss et al., 2023).

Beyond disturbance detection, digital systems also support long-term ecosystem monitoring. LiDAR and hyperspectral imagery can capture changes in canopy structure and species composition, offering valuable insights into forest regeneration and habitat dynamics (Almeida et al., 2021; Tusa et al., 2020). Integrating these observations with climate models allows better forecasting of drought stress, carbon sequestration, and ecosystem resilience (Norman et al., 2016; Stenzel et al., 2023; Thomas et al., 2017; Zavala et al., 2024).

Ultimately, digital ecological monitoring contributes not only to scientific understanding but also to adaptive governance. By linking data to transparent dashboards, policymakers can identify priority areas for intervention, track restoration progress, and evaluate the effectiveness of conservation measures (Viti et al., 2024).

5.3 Participation, Transparency, and Social Inclusion

Digital transformation also creates opportunities for broader participation and accountability in forest governance. Web-based platforms (Akın et al., 2025), mobile applications, and open-data portals enable citizens, local communities, and NGOs to contribute to monitoring efforts (Arts et al., 2020; Nitoslawski et al., 2021; Torresan et al., 2021; Haq et al., 2024; Holm & Schweier, 2024; İnanç Özkan & Aksu, 2025a, 2025b). Examples include participatory forest mapping, community-driven reporting of illegal logging, and public access to environmental impact assessments (He & Turner, 2022; Komdeur & Ingenbleek, 2021).

Such systems can increase transparency in decision-making and strengthen trust between authorities and stakeholders (Holm & Schweier, 2024). They also empower marginalized groups by providing access to information and tools that were previously restricted to technical experts. In developing countries, mobile-based forest monitoring applications have proven effective for involving local communities in data collection and enforcement (Arts et al., 2020; Torresan et al., 2021).

However, inclusive digitalization requires attention to equity and accessibility (Arts et al., 2020). Training, user-friendly design, and multilingual interfaces are essential to ensure that digital participation does not reproduce existing social inequalities. When implemented carefully, participatory digital tools can bridge the gap between local knowledge and formal forest policy (Fagerholm et al., 2017).

5.4 Integration with the Circular Bioeconomy and Climate Policy

Forestry's digital transformation aligns closely with the broader global shift toward the circular bioeconomy and climate-neutral development, aiming to enhance forest management while minimizing environmental impact and reducing greenhouse gas emissions (Picchi et al., 2021; Wang et al., 2024). Digital data can improve the traceability and lifecycle assessment of forest products, enabling certification systems that guarantee sustainable sourcing. Blockchain-based ledgers, for instance, can verify the origin of timber and prevent illegal trade, providing a secure and transparent method of tracking forest products and minimizing illegal logging (Komdeur & Ingenbleek, 2021; Stopfer et al., 2023).

At the policy level, digital monitoring systems support national reporting obligations under international climate agreements. Accurate, transparent data on forest carbon dynamics are essential for climate action mechanisms such as REDD+, Nationally Determined Contributions, and carbon offset markets, helping to predict forest vulnerability and carbon fluxes (Fagerholm et al., 2017; Thomas et al., 2017; Toksoy, Öztekin & Bayramoğlu, 2020; Bayramoğlu & Küçükbekir, 2022). Furthermore, integrating forestry datasets with agricultural and energy systems helps design cross-sector strategies for carbon neutrality, promoting a sustainable bioeconomy and reducing GHG emissions (Poulsen & Stigsdotter, 2014; Zhao et al., 2024). For example, digital decision-support tools can optimize land-use allocation to balance timber production, bioenergy supply, and biodiversity conservation by integrating data sources with modeling and analytical tools to evaluate trade-offs between production and conservation (Fagerholm et al., 2017; Lämås et al., 2023; Marano et al., 2019). In this way, digital forestry becomes a key enabler of the green transition.

5.5 Case Illustration: Digital Forestry Initiatives in Türkiye

Türkiye offers an illustrative example of how emerging digital technologies are being integrated into forest management. The General Directorate of Forestry has developed several platforms for real-time monitoring and spatial analysis, leveraging technologies for forest assessment and planning (Ercan & Toker, 2021). Systems such as ORBIS and OGM Atlas consolidate forest inventory data, satellite imagery, and management plans into a unified digital environment, aligning with broader trends in digital forest management and the use of web-based GIS tools for natural resource assessment (Malkoç, 2024).

Drone-based surveillance (Gülci et al., 2017), early-warning fire detection systems, and mobile data collection applications have significantly improved the timeliness and accuracy of forest assessments (Çolak & Sunar, 2018; Sandim et al., 2023). The integration of LiDAR and AI-based analysis is gradually expanding, particularly in projects focused on forest road planning and efficiency assessment, contributing to more precise measurements and improved decision-making (İnan et al., 2017; Seyrek et al., 2025; Vatandaşlar & Zeybek, 2021). These advanced remote sensing and AI techniques enhance the accuracy of estimations for various forest parameters, which can surpass traditional manual methods (Guirado et al., 2020).

Türkiye's experience highlights that digital transformation in forestry is feasible even under resource constraints—provided that institutional commitment, cross-sector collaboration, and capacity building are aligned (Ercan & Toker, 2021). While challenges such as high implementation costs, regulatory frameworks, limited information access, and a shortage of skilled specialists can impede digital transformation (He & Turner, 2021; Konovalova et al., 2023), these national efforts demonstrate how such barriers can be mitigated through strategic investments and clear governance frameworks.

5.6 Synthesis: The Path from 4C to 4O

The opportunities outlined above suggest that digitalization is not merely a technological upgrade but it signifies a paradigm shift from data collection to data collaboration, from reactive management to co-adaptive governance. When applied responsibly, digital tools can make forestry more efficient, resilient, and inclusive. They enable a transition from reactive management to proactive stewardship, where decisions are informed by continuous learning and transparent data flows.

Yet realizing these opportunities requires persistent effort to bridge digital divides, strengthen institutional capacity, and embed ethical standards into design and implementation. The next section explores these forward-looking dimensions by outlining future research directions and governance priorities for digital forestry.

6. Future Directions and Research Needs

Digitalization in forestry is still in an early and uneven stage of development. Yet, the speed of innovation in artificial intelligence, remote sensing, and data infrastructure indicates that the next decade will bring transformative changes. Future research must therefore move beyond technical implementation to explore how digital systems reshape the governance, ethics, and social dimensions of forest management. Several emerging directions are particularly important: AI-driven decision ecosystems, standardized digital infrastructures, human–machine collaboration, and automation ethics (Figure 8).

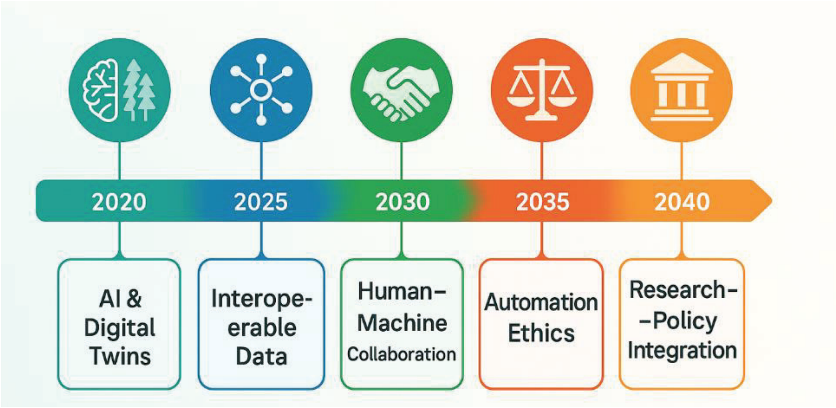

Figure 8. Evolution of the Digital Forestry Ecosystem (2020–2040). The timeline illustrates projected technological and governance milestones—spanning from AI-driven decision systems to integrated research–policy–practice frameworks in digital forestry.

6.1 Artificial Intelligence and Digital Twins in Forest Governance

The next frontier of digital forestry lies in the creation of intelligent decision ecosystems that integrate AI, simulation, and real-time data streams. Digital twins—virtual representations of forest ecosystems that update continuously—are expected to become central to future forest planning. They will allow managers to simulate alternative interventions, predict outcomes, and test "what-if" scenarios before implementing real-world actions (Catalli et al., 2024; Holm & Schweier, 2024; Sasaki & Abe, 2025).

AI-driven governance systems could synthesize data from multiple scales—satellite imagery, IoT sensors, socio-economic databases—to support adaptive and transparent decision-making (Haq et al., 2024; Sasaki

& Abe, 2025). For example, reinforcement-learning algorithms might optimize harvest schedules under changing climate and market conditions (Shavazipour & Engberg, 2024), while multi-agent systems simulate the behavior of stakeholders and ecosystems simultaneously (Campo et al., 2009).

However, the rise of autonomous decision systems also raises critical governance questions. Who defines the parameters of optimization? How do we ensure that algorithmic decisions remain aligned with social and ecological values? Future research should explore frameworks for AI accountability (Aranda et al., 2023), model explainability (Ezhova et al., 2025), and stakeholder oversight (Kawakami et al., 2024) to ensure that artificial intelligence enhances, rather than replaces, human judgment in forest governance.

6.2 Toward Standardized and Interoperable Data Ecosystems

A sustainable digital transition requires a common data language across institutions and borders. At present, forestry data are fragmented across multiple agencies, stored in incompatible formats, and governed by inconsistent metadata standards. This fragmentation limits large-scale analysis and hinders international collaboration.

Developing standardized digital ecosystems—with harmonized taxonomies, open APIs, and FAIR data principles—should be a top priority for research and policy (Sasaki & Abe, 2025; Wang et al., 2025). International coordination bodies, such as FAO, UNECE, and the Global Forest Observations Initiative, can play a key role in aligning definitions and protocols.

Research should also focus on semantic interoperability, ensuring that different datasets convey the same meaning across contexts. Advances in ontologies, knowledge graphs, and machine-readable metadata can enable automated data integration across forestry, agriculture, biodiversity, and climate domains. The goal is to create a “digital commons” for forestry—an open and transparent infrastructure where information flows freely but securely among all stakeholders (Sasaki & Abe, 2025).

6.3 Human–Machine Collaboration and the Role of Expertise

As automation expands, the human role in digital forestry will shift from manual execution to strategic oversight and interpretation (Nitoslawski et al., 2021; Sommer et al., 2024). Rather than replacing foresters, intelligent systems should augment their decision-making capacities (Holzinger et al., 2022). Future research must therefore examine how human–machine collaboration can be designed to combine computational precision with experiential knowledge.

Participatory modeling environments and visual decision dashboards can support this collaboration by allowing experts to interact with AI-generated scenarios, adjust parameters, and validate outcomes (Catalli et al., 2024; Santos & Carvalho, 2025; Shavazipour & Engberg, 2024). Such systems could promote learning-by-doing, helping professionals understand both the potential and the limitations of automated reasoning.

Equally important is the preservation of local ecological knowledge. Indigenous and community-based management practices offer insights that cannot be captured solely by data models. Incorporating such qualitative knowledge into digital systems will require new forms of co-design and interdisciplinary research bridging social sciences, ecology, and computer science (Matuk et al., 2020; Rakova & Winter, 2020; Robinson et al., 2022).

6.4 Automation Ethics and Socio-Ecological Responsibility

Digitalization in forestry is not only a technical challenge but also an ethical one. The automation of decision-making introduces risks of data bias (Frazier & Song, 2024), algorithmic opacity (Ezhova et al., 2025), and technological dependency. Future research should critically assess how digital systems influence power relations, resource access, and the distribution of benefits (Frazier & Song, 2024).

Ethical frameworks for digital forestry must address questions of data sovereignty, privacy (Frazier & Song, 2024), and consent—especially when community-level information or biodiversity data are involved (Robinson et al., 2022). Transparent data governance (Choung et al., 2024), open auditing of algorithms, and the inclusion of ethical impact assessments in digital projects can help mitigate these risks (Santos & Carvalho, 2025).

At a broader scale, the ethics of automation must also consider the ecological consequences of optimization (Frazier & Song, 2024). For instance, maximizing short-term efficiency may conflict with long-term ecological stability (Rosa et al., 2024). Responsible digital forestry will require balancing innovation with restraint—ensuring that technologies serve sustainability, not just productivity (Yadav et al., 2024).

6.5 Bridging Research, Policy, and Practice

Bringing these future directions to life will depend on stronger links between research, policy, and practice (Nordin & Sandström, 2016; Weiss et al., 2018). Pilot projects and living labs can provide testbeds for integrating AI, IoT, and cloud systems into operational forestry (Sasaki & Abe, 2025). Cross-sector partnerships—between universities, government agencies, and private technology firms—can accelerate innovation while maintaining public accountability (Klenk & Hickey, 2012; Urzedo et al., 2022).

Moreover, policy frameworks must evolve to reflect the realities of digital ecosystems (OECD, 2020). This includes revising data regulations (Rantala et al., 2020), supporting open-source development, and incentivizing digital literacy in forestry education (Konovalova et al., 2023). International collaboration will be essential to ensure that digital transformation benefits both technologically advanced and developing countries, avoiding new forms of digital inequality (Nesse et al., 2025).

6.6 Synthesis: Toward an Integrative Vision for Digital Forestry

The future of digital forestry will depend on how well technological innovation is balanced with ethical governance and social inclusion. Artificial intelligence and automation hold tremendous potential for understanding and managing forests as complex adaptive systems. Yet, they must be guided by transparent standards, participatory design, and ecological wisdom.

Future research should not only refine algorithms but also reimagine relationships—between humans and machines, data and knowledge, and technology and nature. This integrative vision extends the 4O model into future governance, linking Optimization, Observation, Openness, and Orchestration to research, ethics, and policy.

7. Conclusion

The digitalization of forestry represents both a remarkable opportunity and a profound challenge. As this chapter has shown, digital technologies—from remote sensing and artificial intelligence to cloud platforms and data infrastructures—are transforming how forests are observed, managed, and governed. Yet, this transformation is neither uniform nor inevitable. It unfolds unevenly across regions, institutions, and forest types, shaped by variations in infrastructure, capacity, culture, and cost.

The analysis throughout this chapter highlights a paradox at the heart of digital forestry: the sector most dependent on natural systems has been among the slowest to digitalize. This paradox reflects the unique complexity of forest ecosystems—living, dynamic, and deeply intertwined with social and ecological processes. It also reveals that digital transformation in forestry cannot be understood merely as a technical progression but must be seen as a socio-ecological transition requiring institutional adaptation, ethical reflection, and long-term commitment.

The conceptual framework presented in Section 2 established that digitalization proceeds through distinct but interconnected stages: digitization, digitalization, and digital transformation. Forestry, in many contexts, remains between the second and third stages, where digital tools are increasingly integrated but full systemic change has yet to be realized. Sections 3 and 4 demonstrated that technological advancements—such as AI-driven analytics, IoT-based monitoring, and cloud-enabled data sharing—are pushing the sector toward greater efficiency and transparency. However, barriers captured by the 4C model (Connectivity, Capacity, Culture, and Cost) continue to constrain this progress, particularly in developing regions.

At the same time, Section 5 introduced a conceptual transition—from the 4C barriers that hinder transformation to the 4O opportunities that enable it: Operational efficiency, Observational intelligence, Open participation, and Organizational integration. These four dimensions define the pathway toward mature digital forestry. The shift from 4C to 4O represents not merely the overcoming of constraints but a reorientation of forestry toward openness, adaptability, and data-informed stewardship. In this vision, technology becomes a facilitator of ecological understanding, participatory governance, and circular bioeconomic value creation.

Efficiency gains improved ecological monitoring, participatory governance, and integration with the circular bioeconomy illustrate how digital tools can make forestry both more sustainable and more equitable. The case of Türkiye showed that even under resource constraints, strategic investments and institutional leadership can yield tangible progress toward a digital forestry paradigm.

Looking forward, Section 6 emphasized that the future of digital forestry will depend not only on technology but on how it is governed and integrated into society. The emergence of AI, digital twins, and standardized data ecosystems points to a future of intelligent, adaptive management. Yet, these systems must be guided by ethical standards, transparent data governance, and active human participation. Responsible digitalization means ensuring that technology enhances, rather than replaces, human stewardship of forest ecosystems.

Taken together, the findings of this chapter suggest that digitalization in forestry is possible—but only under specific ecological, institutional, and ethical conditions. It requires investments in digital infrastructure and education, open and interoperable data systems, and inclusive governance that values both technological innovation and local knowledge. The goal is not a fully automated forestry, but a digitally empowered one—where decisions are informed by real-time data, guided by ecological principles, and shared transparently across stakeholders.

Ultimately, the digitalization of forestry is more than a technical evolution; it represents a cultural and epistemological shift. It challenges us to rethink how we measure, value, and care for forests in the digital age. The question "Is digitalization in forestry possible?" therefore has a nuanced answer: yes, but only when technology serves the forest, not the other way around. In this sense, digital forestry must balance innovation with empathy, precision with wisdom, and data with ethics—recognizing that the future of forests depends as much on how we design our technologies as on how we nurture our ecosystems.

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Chapter VI - Rewilding: An Opportunity for Nature Conservation and Climate Change Mitigation?

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1. Introduction

Anthropogenic impact on the world's ecosystems through land use dates back very far. However, the extent to which this has occurred has increased over the last few decades (Meyfroidt et al., 2022). Subsequently, about 25% of ice-free terrestrial ecosystems have been converted by humans into croplands, pastures, and settlements (IPBES, 2018). In addition, about 50% of ice-free ecosystems have been modified by humans to varying degrees—without completely changing ecosystem types, but with significant effects on the environment and biodiversity. Therefore, approximately 75% of the Earth's terrestrial ecosystems are managed or used by humans (Ellis et al., 2008). These human-driven land conversions affect the stability and productivity of ecosystems worldwide. This land conversion leads to a serious decline in the Earth's biodiversity (Lanters 2023).

WWF's 2024 Living Planet Report summarizes this poor situation very clearly. The report draws attention to the 73% decline observed in the average size of monitored wildlife populations in just 50 years. It indicates that, in a world approaching irreversible thresholds driven by nature loss and climate change, the system is under threat. Freshwater ecosystems suffered the heaviest loss with an 85% decline, followed by terrestrial ecosystems with a 69% decline and marine ecosystems with a 56% decline (WWF, 2024). Biodiversity also directly affects ecosystems' resistance to pests and environmental change. For this reason, the decline in biodiversity affects not only ecosystems but also the ecosystem services required for human existence. There has been a growing effort worldwide since the early 20th century to take effective measures to halt further biodiversity loss and to secure ecosystem services (Kurdoğlu, 2008). International agreements such as the United Nations Convention on Biological Diversity (CBD), and even conservation organizations such as the World Wide Fund for Nature (WWF), were established for the conservation of biodiversity (Bellard et al., 2022). In developed parts of the world, of course, there are far too many conservation organizations and many similar and different conservation approaches to list here. These modern conservation approaches and their relationships with rewilding are summarized in Table 1 (Lanters 2023).

Table 1. Similarities and differences between conservation approaches

	Land sharing/ land sparing	Ecosystem management	Coexistence of humans and wildlife	Social-ecological resilience	Rewilding
Conservation aims	Sparing: conservation of biodiversity and species by creating segregated nature habitats and areas of high-yielding agriculture Sharing: Biodiversity conservation in low-yielding agricultural areas)	Regulate the use of ecosystems to preserve ecosystem functions by maintaining ecological processes, maintaining ecological integrity, conserve biodiversity in complex systems (Mori, 2011). Ecological integrity entails: maintaining viable populations, ecosystem representation etc.	Humans and wildlife can coexist in human-dominated Landscapes with help of appropriate tools, right governance and societal support	Enhancing resilience of ecosystem services by: maintaining diversity and redundancy; managing connectivity, slow variables and feedbacks; supporting complex adaptive systems thinking; encouraging learning and experimentation; increasing participation; and supporting polycentric governance systems	Restoring functional ecosystems, natural disturbance regimes, and ecological processes. Reducing human influence. Restoring biodiversity, species interactions and wilderness

Role of humans	Sparing: biodiversity conservation measures of humans in nature areas. Sharing: humans influence biodiversity through wildlife-friendly farming	Active role of humans in the success of ecosystem management. Humans can't be separated from nature entirely.	Humans are included in conservation.	Social system with humans is intertwined with the ecological system and its processes	Depends on whom you will ask. Reducing human control and dominance. Eventually no influence of humankind and nature in its autonomous state

Rewilding is a forward-looking conservation approach based on strengthening self-regulating natural processes rather than returning ecosystems to a specific historical reference point. In this respect, rewilding differs from classical restoration ecology and particularly aims to ensure the continuity of future-oriented ecological functions (Corlett, 2016). Behind the concept's rapidly growing global interest in recent years are multifaceted factors such as the acceleration of biodiversity loss, changes in land use, abandonment of rural areas, the rising importance of nature-based solutions, and the increasing pressure of climate change on ecosystems (Bayramoğlu & Demir, 2018).

One of the most important reasons why rewilding has become increasingly debated in the context of climate change is that the critical roles animals play in the carbon cycle have been scientifically demonstrated. Studies in recent years have shown that large mammals and other key species can increase carbon storage capacity by creating profound impacts on plant composition, soil processes, nutrient cycles, and fire regimes in ecosystems (Schmitz et al., 2023). This framework, called "Animating the Carbon Cycle (ACC)," points to strong, often overlooked reciprocal relationships between animal diversity and the carbon cycle. This approach positions rewilding as a strategic instrument in climate policies and expands the scope of nature-based solutions. In the case of Türkiye, it can be said that rewilding practices are still at an early stage. Nevertheless, rural population loss, abandonment of traditional agricultural lands, expansion of forests, and the partial recovery of some large mammal populations (for example, brown bear, wolf, roe deer, and deer species) offer important opportunities for natural processes to become functional again. In this context, rewilding has the potential to be an innovative nature conservation approach in a landscape in Türkiye shaped by both ecological and socio-economic transformations. Bringing wildlife back closer to historical levels can make contributions to biodiversity and the climate crisis that are not often considered. Revitalizing the carbon cycle may be one of the notable and reliable natural solutions for the climate.

1.1. Conceptual Framework

It should be noted that the common denominator of the ecological restoration versus rewilding dilemma is ecosystem management. In this respect, ecological restoration is also a part of ecosystem management. Ecological restoration is "the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed" (SER, 2004). A form of ecological restoration that has gained great popularity is rewilding. This concept originates from North America, where rewilding focuses on the restoration of large-scale wildlife reserves and the restoration of trophic interactions with keystone species, mostly carnivores (Lorimer et al., 2015). However, in Europe this restoration approach is less traditional than in North America and has been adapted to more cultural landscapes (Mikołajczak et al., 2022). Although rewilding and ecological restoration overlap, there are also important differences between the two concepts that are not easy to define. Moreover, projects currently seen as rewilding projects began as restoration projects; for example, Yellowstone Park, Pleistocene Park, Oostvaardersplassen, and the reintroduction of wolves to Mauritius and neighboring islands (Lorimer et al., 2015; Hayward et al., 2019).

The concept of rewilding has diversified over time through contributions from different researchers, organizations, and practitioners in the field; accordingly, its definitions have also evolved. Most definitions accept as common ground the strengthening of natural processes, reducing human intervention as much as possible, and increasing ecosystem autonomy. Anderson et al. (2019) state that rewilding is a subset of restoration ecology, but that it directs its focus toward future ecological functions rather than a past reference state. They even report that while every rewilding is a restoration, not every restoration can be called rewilding. According to them, rewilding is a subfield under the broader umbrella of restoration practices: all rewildings are restorations (of species, but especially of ecological processes), but not all restoration is rewilding. The term "rewilding" aims to clarify and specify—reducing confusion rather than creating it. Recent studies on rewilding have encouraged such clarity, including further specifying various subcategories of rewilding itself.

Another topic that should be mentioned here is wildernesses. In fact, this was the name given to certain protected areas declared in the United States at the end of the 19th century (Kurdoğlu 2008). In medieval Europe, parks were feudal institutions, and they ensured the existence of "wildernesses" in which grazing and cutting were strictly prohibited and which privileged persons used as hunting reserves (Coolidge, 1965). Again in America, in the early 1900s, about 500 wildlife protection reserves—

each smaller than 2,500 hectares—were set aside where public entry was restricted or completely prohibited. Given the social climate of those eras, the pioneering protected areas in both America and Europe were managed only for the recreation and use of the upper classes (Wright, 1996). With the work carried out by the 1st International National Parks Committee convened in the United States in 1962, definitions were made for five classes covered by national parks and similar areas. One of these was Strict Wilderness Reserves (Bayer, 1968). Wilderness is a landscape that has not been altered by humans. This is more of a landscape approach to wilderness. In these wilderness landscapes, fundamentally there is no human intervention. That is: "no agriculture, no forestry, no mining, no oil and gas, no energy infrastructure, and no transportation infrastructure."Wilderness areas are fully functioning ecosystems. Despite issues related to the concept of wildlife, there is some consistency among researchers regarding its definition and characteristics. Many researchers agree that wilderness can be defined as "a natural area where there is no human intervention, that is free-flowing, and where processes dominate" (Lanters, 2022).

In contrast, Hayward and some other researchers argue that the concept of rewilding has become too ambiguous and that the term restoration is more comprehensive (Hayward et al., 2019). The dominant view in the literature, however, shows that rewilding is a strong, process-focused complement rather than replacing restoration.

Among rewilding approaches, three models stand out:

- Trophic rewilding aims to re-establish the ecosystem-engineering roles of species such as predators and large herbivores.
- Passive rewilding is based on allowing natural succession to continue uninterrupted in areas where human use has been abandoned.

- Pleistocene rewilding is a more controversial approach that argues for reviving the ecological roles of extinct megafauna through closely related species.

The main differences among these three approaches appear in the level of intervention and ecological targets; however, the shared aim is to enable ecosystems to reach a self-sustaining equilibrium.

1.2. Historical Development and Inter-Biogeographical Approaches

The concept of rewilding first emerged in North America within efforts to create networks of large and connected wilderness areas. In this region, reintroducing predator species that provide top-down control mechanisms in ecosystems, strengthening movement corridors, and conserving broad habitat integrity developed as core components of rewilding. This movement, pioneered by Michael Soulé and Dave Foreman, found a strong early field of application due to North America's vast geography and the historical distribution of wildlife. Donlan et al. (2005)'s study proposing the revival of Pleistocene megafauna brought the concept to the center of both scientific and ethical debates.

In Europe, the concept of rewilding emerged within a different socio-ecological context. Because the continent's cultural landscapes—shaped by thousands of years of human use—do not contain large-scale, intact wilderness areas, rewilding there more often means making natural processes functional again within cultural landscapes. Rural population loss and the abandonment of agricultural lands accelerated passive rewilding dynamics in Europe; reassessing the effects of large herbivores on landscapes also strengthened a process-based conservation understanding. Lorimer and Driessen (2016) argue that European rewilding is a "post-natural" form of conservation oriented not toward the past but toward the future. Türkiye's landscape structure and socio-ecological process are closer to European examples than to those of North

America. Mosaic habitat structures shaped by long-term human use, empty spaces created by rural outmigration, and processes such as forest expansion create a suitable context for rewilding in Türkiye. Therefore, it can be said that the most rational approach applicable in Türkiye is compatible with Europe’s process-based rewilding model.

1.3. The Relationship Between Rewilding and Restoration, and Debates on Intervention

The relationship between the concept of rewilding and restoration ecology has been a topic of debate at both scientific and philosophical levels since the concept first emerged. Restoration ecology is one of the oldest and most institutionalized sub-disciplines of conservation science and essentially aims to return degraded ecosystems to a certain reference state (Corlett, 2016). Rewilding, on the other hand, represents a more dynamic understanding that questions this historically reference-focused approach of restoration and instead emphasizes strengthening ecosystem processes. Anderson et al. (2019) argued that rewilding is not completely outside restoration; on the contrary, it is a more process-focused subset of restoration. According to them, while every rewilding initiative has the character of restoration, only a small portion of restoration practices can be defined as rewilding. This is because restoration often pursues a particular historical or compositional target; whereas the focus of rewilding is not recreating the past, but increasing ecosystems’ capacity to self-regulate despite future uncertainties.

Within this framework, rewilding can also be considered a complementary phase of restoration. Many restoration initiatives initially require intensive human intervention: planting saplings in degraded forest areas, erosion control practices (Gümüş, Hatay & Ünver Okan, 2019; Mısırlıoğlu, Gümüş & Yoshimura, 2022; Mısırlıoğlu & Gümüş, 2024; Hatay et al., 2024), engineering interventions in river rehabilitation, or clearing invasive species, for example. Rewilding represents a longer-term phase that, after this initial stage, allows ecosystem processes to take over again. Therefore, in many cases restoration and rewilding can be thought of as sequential yet integrated processes. Especially under climate change, the increasing difficulty of restoration's goal of reaching a particular historical reference makes the process-based structure of rewilding both more applicable and a more ecologically realistic solution. The philosophical depth of rewilding becomes clearer in debates about the level of human intervention. When the concept first emerged, it was associated with the idea of extensive wilderness areas from which human influence had been completely withdrawn; some researchers interpreted rewilding as a movement of "retreating back into the wild" against all forms of human intervention. Over time, however, this approach was seen as problematic both ecologically and socio-politically; contemporary understandings of rewilding have begun to argue, rather than rejecting human intervention entirely, for intervention to be carried out in a "strategic in temporal and functional terms" way. Corlett (2016) emphasized that practices such as controlling invasive species, recovering vegetation in degraded ecosystems, reconnecting fragmented wildlife populations, and reintroducing species are necessary for rewilding. This approach shows that rewilding is not a romantic movement of "spontaneous return to nature"; rather, it consists of practices that require active intervention at certain points.

At the center of these intervention debates lies the issue of timing. When the rate of degradation and environmental change in ecosystems is very high, ecosystem succession left to a passive process may not progress in the desired direction. In that case, active intervention becomes a necessity to reactivate processes in an ecosystem that is collapsing. For example, in coastal ecosystems where invasive species rapidly become dominant, passive rewilding does not produce the desired results. Without intensive and long-term species removal, it is not possible for natural succession to follow a healthy course. Similarly, in forest ecosystems where predators disappeared many years ago and prey populations have increased in an unbalanced way, active rewilding practices aimed at re-establishing trophic relationships may be necessary instead of a passive approach (Corlett 2016; Anderson et al., 2019).

In this context, while rewilding is not an approach wholly opposed to human intervention, it positions intervention as a limited, purpose-oriented, and withdrawable tool—designed to make natural processes functional again. Although reducing intervention is a fundamental principle of rewilding, this reduction is only possible once the ecosystem reaches the capacity to self-regulate. Reducing intervention before ecological autonomy is achieved may prevent the long-term sustainability that rewilding aims to secure. One of the points that clarifies the difference between rewilding and restoration is the debate on the reference state. Restoration projects generally define an intact historical reference period; this reference period is often an ecosystem composition or habitat structure from before modern human impacts. Rewilding, however, argues that the reference state should not be sought in the past (Lorimer & Driessen, 2016). The reason is that it is not possible to reverse the transformations that climate change has created in ecosystems. A past temperature, precipitation regime, or species composition cannot be targeted, because future ecological conditions deviate completely from these references. For this reason, rewilding aims not to reach a fixed ecological state, but to ensure the continuity of functional processes under variable conditions. In this respect, rewilding provides a more adaptable framework than restoration in terms of managing uncertainty in the context of global change (Carrol & Noss, 2021).

A significant part of the rewilding literature focuses on the question of how humans should evaluate their historical impact on nature.

This debate has been especially concentrated in the European context. On the European continent, imagining a landscape without human influence is considered by many researchers to be far from ecological reality. Lorimer et al., (2015) concept of the "wildness of the future" interprets rewilding as an effort to create new ecological complexity in cultural landscapes. This perspective emphasizes that rewilding is not only a biophysical but also a cultural process. Thus, rewilding becomes a more flexible approach that does not sharply separate the human–nature dichotomy; on the contrary, it accepts human existence as part of ecosystem processes. This perspective is particularly important for landscapes like Türkiye's, shaped by thousands of years of human use. The Anatolian peninsula's historical intensity of land use, grazing regimes, forestry practices, and settlement patterns show that rewilding requires a distinctive framework in the Turkish context. Therefore, it seems more realistic that the rewilding model applicable in Türkiye should adopt a process-based approach compatible with cultural landscapes, as in Europe. In cases where certain species have disappeared or where populations have been severely weakened, species-based rewilding may come onto the agenda in Türkiye; however, this should not mean bringing in exotic species, but should aim only at restoring the ecological roles of native species.

Conceptual ambiguities regarding the scope and form of application of rewilding have at times led to criticisms in academia. Hayward et al. (2019) argue that the concept has been expanded too much to encompass all kinds of conservation practices and that the definition has become dysfunctional. According to them, rewilding has lost its conceptual boundaries relative to restoration. However, the majority of researchers involved in the debate do not agree with this criticism. Because the flexibility of rewilding provides conservation science with significant adaptive capacity under rapidly changing environmental conditions. Therefore, the breadth of the concept can be considered not a weakness, but one of the elements that constitute the strength of rewilding in terms of practical applications (Corlett 2016; Anderson et al., 2019).

In current rewilding literature, the increasingly adopted approach is to treat rewilding not as something reduced to passive processes, but as a holistic model in which active intervention and passive processes are used together in harmony. Within this framework, intervention is carried out only to the extent necessary, and withdrawal is essential once ecosystem processes regain a natural rhythm. Therefore, it is not correct to associate rewilding with a wilderness ideal in which human activity is completely ignored. On the contrary, rewilding often requires serious technical, logistical, and managerial interventions in its initial phases. This can be seen clearly in practices such as invasive species control, establishing habitat connectivity, stabilizing areas degraded by erosion, restoring river regimes, and reintroducing species. The main point that emerges at the end of these discussions is this: rewilding is not an approach that replaces restoration; it is a framework that focuses on revitalizing ecosystem functions from a broader perspective than restoration. The reactivation of ecological processes—especially interspecies interactions and trophic relationships—is the most distinctive feature of rewilding. In this respect, rewilding can also be interpreted as a more holistic evolution of restoration ecology, taking into account the critical effects of biotic processes in ecosystems on the carbon cycle, fire regimes, soil formation, and hydrological dynamics (Carrol & Noss, 2021; Lorimer & Driessen, 2016).

1.4. Rewilding and Climate Change Mitigation: The ACC Framework, Trophic Interactions, and the Carbon Cycle

In recent years, the relationship between rewilding and climate change has increasingly come to the fore in the scientific literature and has become an important topic within the framework of nature-based solutions (Nature-based Solutions, NbS). Traditional climate policies long focused on the physical and chemical components of the carbon cycle; however, biotic processes in ecosystems—especially the effects of animals on carbon storage and cycling mechanisms—were largely overlooked. This can be considered an area where climate science has had a relatively incomplete understanding of ecosystems. Recent studies have shown that large vertebrates, in particular, play a much greater role in ecosystem carbon dynamics than previously assumed. These findings have led rewilding to intersect with a new scientific framework related to the carbon cycle, namely the "Animating the Carbon Cycle (ACC)" approach (Carrol & Noss, 2021).

The ACC approach argues that animals are not merely an outcome of ecosystem functioning, but also a driving force that directs ecosystem carbon flows. From this perspective, the circulation of carbon in ecosystems should be viewed not as a consequence of vegetation alone, but as an integrated product of trophic interactions between plants and animals. The amount, diversity, spatial distribution, and regeneration rate of plant biomass are directly intertwined with herbivore pressure, seed dispersal, feeding behaviors, and the regulatory role of predators in ecosystems. Therefore, increasing carbon storage cannot be reduced to one-dimensional practices such as afforestation or reforestation; rather, animals' roles in activating the carbon cycle must be addressed holistically. A comprehensive synthesis by Schmitz et al., (2023) has shown that, in ecosystems where animal populations function healthily, carbon storage capacity can increase by between 15% and 250%. This study demonstrates that, if just nine key species or species groups fulfill their ecological roles, it would be possible to sequester 6.41 gigatons of carbon-equivalent CO_2 per year globally. This amount corresponds to approximately 95% of the total CO_2 that must be removed from the atmosphere by 2100. These species include gray wolves, African forest elephants, sea otters, bison, antelope species, and great whales—species with broad trophic impact ranges. These findings show that rewilding is not only a biodiversity-based conservation strategy but also a carbon-management approach of critical importance in combating climate change (URL-1; Raupach et al., 2014).

One of the main reasons behind the emergence of the ACC approach is that the ecosystem engineering effects of animals were systematically ignored for a long time. For example, the impacts of large herbivores' grazing behaviors on vegetation species composition, biomass distribution, and fire regimes have been studied less than the physical aspects of the carbon cycle. Yet grazing pressure is a fundamental process that determines vegetation's sensitivity to fire and the amount of carbon retained in soils. Studies in the Serengeti ecosystem have shown that, following the collapse of antelope populations, excessive increases in plant biomass made fires more frequent and more severe; this, in turn, caused the ecosystem to become a carbon source. When those populations recovered, however, fire frequency decreased; grazing pressure shifted the ecosystem toward younger, rapidly growing plant communities; and the ecosystem was once again observed to become a carbon sink. This example strikingly demonstrates the extent to which trophic processes affect carbon storage capacity (Schmitz et al., 2023 ; Donlan et al.,2025). Similarly, sea otters' control of sea urchin populations prevents the loss of giant kelp forests along the Pacific coast and increases these habitats' carbon storage capacity. In this process, the presence of a predator species directly affects not only biodiversity but also carbon sequestration in the oceans. Great whales, through both their physical presence and their feeding cycles between the surface and deeper waters, support CO_2 capture by phytoplankton in the oceans via the process known as the "whale pump." The role of elephant populations in forests is similar; their selective consumption reshapes forest structure, supporting the development of large trees with higher carbon-carrying capacity and increasing carbon storage potential (Raupach et al., 2014; (Schmitz et al., 2023). These examples show that it is insufficient to address the relationship between rewilding and climate change solely within the frameworks of afforestation or natural succession; instead, the biotic components of the carbon cycle must be evaluated through a holistic understanding. The ACC approach is one of the first comprehensive frameworks to provide such a holistic evaluation. Through this framework, animals' role in the carbon cycle is treated not merely as indirect, but as a direct instrument of climate intervention.

Another important contribution offered by rewilding in climate change mitigation is increased landscape-scale connectivity and ecosystem integrity. Connected habitats make species more resilient to environmental changes, preserve populations' genetic diversity, and enable ecosystems to sustain their functions. This is also critical for the long-term continuity of carbon storage processes. While carbon sequestration becomes fragile in fragmented habitats, the residence time of carbon in storage is extended in large and connected ecosystems. For this reason, rewilding can be described not only as a species-based approach, but also as a practice that provides carbon management at the landscape scale. One of the most important points emphasized by the ACC framework is that the collapse of large animal populations should be evaluated not only as biodiversity loss, but also as a reduction in carbon sequestration capacity. This perspective makes it necessary to integrate wildlife conservation strategies with climate policies. Protecting animal diversity in ecosystems and strengthening population dynamics can become a complementary component of climate policies. Indeed, the increasing emphasis on animals' role in the biosphere in the latest IPCC assessment reports indicates that the scientific basis for this integration is becoming more solid.

Despite the critical role of animals in the carbon cycle, many ecosystems today—especially regions where large mammal populations have collapsed or trophic relationships have been disrupted—have weakened in terms of carbon management. This explains why rewilding carries great potential for climate policies. Restoring animals can not only revitalize ecosystem processes, but also rebalance the carbon cycle. In this context, rewilding can be considered an approach that bridges climate change adaptation and mitigation (Donlan et al., 2005).

When considered in the context of Türkiye, the ACC approach is especially noteworthy. In Türkiye, processes such as the rapid decline of rural populations in recent years, abandonment of agricultural lands, changes in rangeland use, and expansion of forest areas are laying the groundwork for natural succession and biotic processes to strengthen again. This dynamic creates important opportunities for passive rewilding. In addition, the fact that Türkiye's large mammal populations are recovering in some regions (for example, wolf, bear, deer, and roe deer populations) is promising in terms of re-establishing trophic relationships. If these processes are managed correctly, it is possible to benefit from the positive effects of biotic interactions on the carbon cycle. Türkiye's habitat diversity, high topographic gradients, climatic differentiation, and biogeographic position can make the effects of rewilding on carbon management even more meaningful. Because trophic interactions' effects on the carbon cycle differ across ecosystems, scientific studies in Türkiye have the potential to make important contributions to the ACC approach. In particular, forest–rangeland transition zones, mountainous areas, wetlands, and coastal ecosystems could be priority research areas in this context.

In conclusion, the relationship between rewilding and climate change mitigation shows that not only the physico-chemical aspects of ecosystem processes, but also their biotic dimensions, are fundamental determinants in the carbon cycle. The ACC approach has elevated rewilding to a strategic position in climate policies by placing these biotic processes within a scientific framework. In this regard, rewilding can be considered a powerful tool that may sit at the center of ecosystem-based carbon management, rather than merely a complementary instrument in future climate solutions.

2. The Socio-Economic Dimensions of Rewilding, Its Political Context, Risks, and an Assessment in Terms of Türkiye

In addition to its potential to revitalize ecological processes, it is known that rewilding generates significant socio-economic and political debates in every geography where it is implemented. The return of large mammals, changes in land-use practices, transformations in the economic activities of rural communities, and the redefinition of governance responsibilities show that rewilding is not only an ecological initiative but also a social one. For this reason, applying rewilding successfully requires a holistic approach that addresses ecological planning together with social acceptance, economic sustainability, and the political framework.

Rewilding can increase the risk of social conflict, especially when it involves the reintroduction of large mammal species or strengthening their populations. The return of species such as wolves, bears, and lynx can lead to economic losses and concerns about asset security for communities engaged in livestock farming. Therefore, the success of rewilding is directly linked to ensuring local communities' participation in processes and managing potential damages in a fair manner. In rewilding projects carried out in Europe, conflict management is often achieved through compensation mechanisms, protective fencing systems, community-based monitoring programs, and the development of wildlife-compatible economic models. Social acceptance of rewilding depends not only on the ecological benefits of species' return, but also on creating alternative economic activities that contribute to the quality of life of local people (Donlan et al., 2005)..

In this context, ecotourism emerges as an important tool for the economic sustainability of rewilding. The presence of large mammal species can increase visitor interest in a region and offer new income sources for rural economies. However, if ecotourism is not planned properly, it can create pressure on ecosystems or cause social tensions between local communities and visitors. Therefore, while ecotourism potential is seen as an opportunity in rewilding projects, it is essential to manage this potential within a sustainable framework. The political context of rewilding is also a critical factor affecting implementation success. Land-use policies, wildlife management, forestry practices, grazing rights, and rural development policies play a determining role in the feasibility of rewilding. For example, in some countries, large-scale rewilding projects have been directly incorporated into national policy frameworks. While the European Union's "Green Deal" framework encourages ecosystem revitalization and nature-based solutions, it makes it possible for some rewilding practices to receive direct financial support. Similarly, in Latin America, policy-based corridor projects supporting the return of large herbivores and predators have made important contributions to the development of a rewilding approach. This policy environment shows that rewilding is not only a scientific issue, but also a topic intertwined with governance and public policies. Bringing rewilding to life successfully requires the collaboration of different stakeholders—state institutions, local governments, communities, academic institutions, and civil society organizations. If such partnerships cannot be established, rewilding projects may face social resistance or become unimplementable due to political tensions. Indeed, in some regions, social reactions against species' return have led to the suspension of rewilding projects or the narrowing of their areas. This once again shows that rewilding cannot be addressed independently of the social context.

The risks of rewilding are not limited to the social and political spheres; ecological risks are also significant and cannot be ignored. Species reintroductions, establishing habitat connectivity, and reactivating ecosystem processes can lead to unintended outcomes where ecological predictability is limited. Rapid population growth of some species can cause overgrazing or vegetation degradation in sensitive habitats. The return of predators can rapidly change prey species' behavior and distribution dynamics, leading ecosystems to respond in unexpected ways. In addition, in areas dominated by invasive species, the success of rewilding practices may require intensive and long-term struggle. Therefore, rewilding applications must be supported by long-term monitoring and adaptive management strategies that take ecological risks into account.

In the context of Türkiye, evaluating the socio-economic and political conditions of rewilding is important for addressing implementation in a realistic framework. In Türkiye, the loss of population in rural areas and changes in traditional land-use forms create important opportunities for rewilding. Abandoned agricultural lands, rangelands, and areas around rural settlements have become places where passive rewilding processes accelerate. In these areas, natural succession produces outcomes such as the rapid development of young forests and increased habitat connectivity. Especially in some districts of Central Anatolia, Eastern Anatolia, and the Black Sea region where rural outmigration is intense, it is observed that large areas have begun to rewild spontaneously. It is also known that some large mammal populations in Türkiye have begun to recover. The increasing presence of brown bears, wolves, roe deer, and deer species in certain regions is promising for strengthening trophic relationships again. However, the return of these species also brings social conflict risk. Especially the interaction of wolves and bears with livestock activities can lead to social tension in some regions. Therefore, implementing rewilding in Türkiye requires developing compensation mechanisms, expanding wildlife education and awareness programs, and including local communities in decision-making processes.

Another important dynamic for rewilding in Türkiye is the protected-area management system. Türkiye's protected areas are mostly under state control, and local communities' participation can be limited. Recent empirical studies from the Eastern Black Sea/Artvin context, focusing on local perception and traditional knowledge–policy links, also underline the need for participatory governance in conservation and climate-oriented interventions (İnanç Özkan & Aksu, 2025a, 2025b). Rewilding success, however, depends on local participation and co-management mechanisms. Therefore, it is clear that rewilding projects to be implemented in Türkiye will require re-evaluating the protected-area system, developing co-management models, and resolving land-ownership issues. Türkiye's land-use policies also significantly affect the feasibility of rewilding. The Rangeland Law, Forest Law, National Parks Law, and other relevant legislation determine the legal framework for rewilding projects. While some of this legislation supports strengthening ecosystem processes, some parts may, in certain cases, encourage management approaches in which human activities remain dominant. For example, in some regions, allocating rangelands for grazing purposes may affect the natural dynamics of herbivore populations. Therefore, implementing rewilding successfully in Türkiye may require reinterpreting existing legislation with an ecosystem-process perspective, or in some cases, updating it. As an example, Figure 1, depicts a sustainable, resilient, and biodiversity-rich forestry transformation for ideal rewilding.

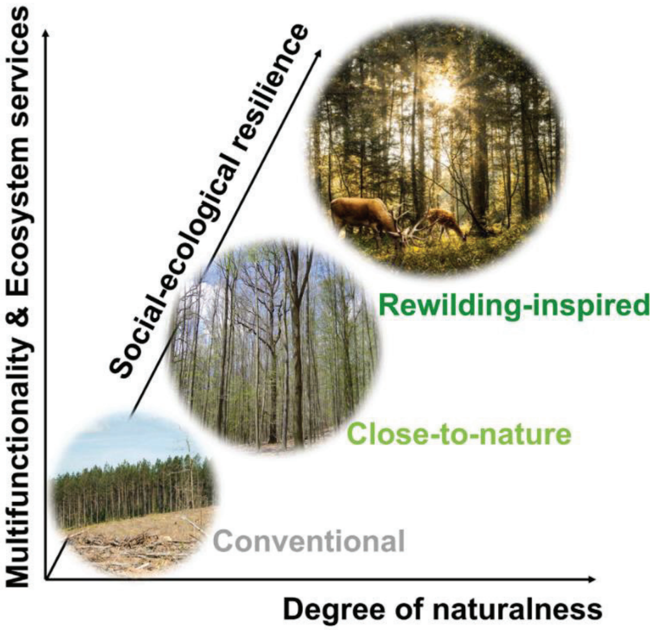

Figure 1. A conceptual framework for rewilding-inspired forestry as a nature-based solution for biosphere sustainability (Wang et al., 2025)

The figure positions rewilding-inspired forestry within a three-dimensional space that distinguishes it from traditional and other green forestry paradigms such as close-to-nature (or continuous-cover) forestry. The framework is defined by three axes: the degree of naturalness, representing the restoration of and dependence on natural processes such as trophic interactions, stochastic disturbances, and species dispersal; the multifunctional provision of ecosystem services, including biodiversity conservation, climate change mitigation, and socio-economic benefits; and socio-ecological resilience to global change (e.g., climate change, pest invasion). Traditional forestry is located at the lower left and focuses on intensive management for timber production, with minimal reliance on natural processes and lower resilience. Close-to-nature forestry occupies a mid-level position, reflecting moderate reliance on natural processes, ecosystem service provision, and resilience. Rewilding-inspired forestry, located at the upper right, emphasizes very high naturalness through trophic complexity, natural stochastic disturbances, and long-distance dispersal, promoting biodiversity-rich, resilient forest landscapes that adapt to climate change and provide multifunctional ecosystem services. The framework highlights rewilding-inspired forestry as a nature-based, holistic, and forward-looking approach with the greatest potential (represented by the size of circular drawings) to promote biosphere sustainability under global change. Copyright of the image showing rewilding-inspired forestry: mixed reality.

While opportunities for rewilding in Türkiye are broad, strengthening the scientific data infrastructure is important for assessing feasibility. Species distribution models, carbon maps, land-use change trends, habitat connectivity analyses, and sociological research measuring levels of social acceptance are critical for planning rewilding. The lack of such studies can constrain rewilding implementation or lead to faulty planning. Therefore, academic studies supporting rewilding research in Türkiye must be increased, and a national monitoring system should be established.

In conclusion, rewilding has a strong nature-based solution potential that sits at the heart of Türkiye's ecological and socio-economic transformations. However, realizing this potential requires addressing not only ecological processes, but also social dynamics, the political framework, and economic requirements holistically. The future of rewilding in Türkiye will depend on the trust relationship established with local communities, the correct management of ecosystem processes, and developing public policies in harmony with this approach.

3. Discussion

What rewilding implies is that, rather than an increasing dichotomy between nature and human culture, human values can coexist with the practical needs and ethical desire to conserve biological populations, even under the shadow of modern human pressures. Rewilding is not compatible with an absolute wilderness concept, because that concept assumes it would exist only in the absence of human interventions. On the other hand, it is closely related to reconciliation ecology. It is also similar to the debate between the land sparing and land sharing approaches in land conservation. Ideally, it might be thought that rewilding would favor land sparing, since it requires restrictions against human use. However, as Hayward et al. (2019) note, the recreation of extinct species (de-extinction) would perhaps take place in highly managed environments such as agricultural lands. This suggests that rewilding may be more suitable for land sharing. Within this framework, interpreting the concept of "wildness" not as mere "absence of humans" but as "species and processes being able to have agency/subjecthood" requires accepting that, in practice, rewilding is often carried out with the logic of "controlled decontrolling." This also makes it necessary, at the points where rewilding meets climate mitigation goals (e.g., the ACC approach), to systematically include not only biophysical outcomes but also dimensions of social acceptance, governance, justice, and risk management (IUCN, 2020).

If large areas of former agricultural land are simply left alone (passively rewild), can large-scale rewilding be successful? There are many such abandoned, rewilded areas in Türkiye. How will we measure the "success" or "degree of wildness" of different rewilding practices? To intervene or not to intervene: one of the main discussion topics of rewilding concerns the level of intervention. In particular, the diversity of attitudes toward invasive species creates uncertainty related to different viewpoints on effectiveness and the correct approach (Corlett, 2016) (Figure 1). In addition, it reveals that the future of rewilding includes significant debates in terms of restoration, species reintroductions, ecosystem functionality, and both ethical and socio-economic dimensions. The crux here is that the claim of "non-intervention" itself is actually a choice of intervention:

decisions such as what we monitor and what we do not, what threshold we consider “acceptable change,” and which species/trophic role’s return we target inevitably carry rewilding into the realm of governance (Corlett, 2016). Therefore, phenomena such as abandoned agricultural lands, rangeland transformations, rural abandonment, and afforestation trends in Türkiye offer a “window of opportunity” for rewilding; at the same time, they necessitate risk and justice assessment on issues such as species conflicts (human–wildlife), fire regimes, invasives, transition zones at rangeland/forest boundaries, and livelihoods in production landscapes. The “Animating the Carbon Cycle” approach, while underlining urgency, argues that a shift is needed in policy thinking: wildlife’s critical impact on the global carbon cycle should be integrated into holistic strategies for combating the climate crisis. This approach aims to strengthen the solutions provided by nature in order to achieve greenhouse gas reduction targets. As a result, the low-intervention principle that is a core tenet of rewilding supports the idea that the protection and restoration of wildlife becomes a strategic element in combating climate change within the ACC framework.

In the ACC/rewilding nexus, the most critical issue scientifically and in terms of policy is that claims of “climate benefit” must be constructed by considering measurability, permanence, leakage/displacement, and double counting risks; otherwise, the credibility of nature-based solutions may be undermined (IPCC, 2022). For this reason, when rewilding-based climate mitigation claims are tied to frameworks such as the IUCN Nature-based Solutions Standard across the design–verification–scaling steps, both scientific consistency and social/ecological safety increase. Daniel Allen (2022), one of the authors, emphasizes that achieving climate targets is also possible through biodiversity and ecosystem restoration: “Bringing wildlife populations back to meaningful levels close to historical levels has the potential to significantly accelerate climate mitigation." It is stated that, in line with the 1.5°C target, approximately 500 gigatons of CO_2 need to be "mined" from the atmosphere. However, at present, only 3% of terrestrial surfaces are functionally undisturbed and 97% of the oceans are open to fishing, which reveals the scale and urgency of rewilding. This emphasis shows that rewilding can be considered not "only biodiversity," but also a strategic lever in managing multiple crises (climate–nature loss–welfare); indeed, perspective studies suggesting that trophic rewilding can expand natural climate solutions also strengthen this line.

However, Pleistocene rewilding is also subject to criticism. If this is true, Pleistocene rewilding becomes indistinguishable from nature conservation and thus undermines itself (Popov, 2025). This objection further sharpens the "level of intervention" debate in the context of climate mitigation: trying to maximize climate benefit by increasing management intensity (and thus expanding the burden of cost, energy, labor, and legitimacy) may erode the distinguishing claim of rewilding. Over the last 100 years, the megafauna of the boreal zone in Eurasia has been enriched through the introduction of non-native species and the northward spread of southern species. This development offers some ideas regarding the concept of Pleistocene rewilding. However, the presence of these additional species is very limited in terms of both population size and available habitat. In addition to ecological constraints, large-scale rewilding efforts are labor-intensive, expensive, and not popular enough to attract significant support; therefore, their implementation is currently problematic (Popov, 2025).

These debates need to be addressed more comprehensively in the future, and better criteria and a scientific conceptual framework must be developed to increase the applicability of rewilding.At this point, countless questions can surely be compiled and new debates opened: If large areas of former agricultural land are simply left alone (passively rewild), can large-scale rewilding be successful? What are the principles that will guide us in our rewilding efforts? On what criteria should our decision to intervene be based? How can land sharing—where settlements and agriculture both align with rewilding and obstruct rewilding efforts—be addressed on common ground? Can we achieve meaningful improvement at the regional or global level using these techniques in small areas? How can restoration techniques used in small areas be adapted to landscapes and regions? Can rewilding be downscaled (We have no chance other than being small!) and if it can be connected with ecological corridors, will it become the sum of its parts? How will we measure the "success" or "degree of wildness" of these efforts? How can new molecular technologies contribute to conservation goals? Should we genetically "modify" species?

Where these questions intersect with climate mitigation, an additional "measurement and evidence" layer comes into play: (i) demonstrating through which mechanisms species restoration affects carbon–nutrient–water cycles, (ii) accepting that this effect may shift direction depending on context (e.g., the same predator can produce different net effects in different biomes), and (iii) establishing a threshold/implementation set that accounts for social impacts (conflict, livelihoods, cultural values)

4. Conclusion

When rewilding is associated with climate change mitigation targets, it shifts the discussion away from merely "returning nature to its former state" and toward "responding to multiple crises by restoring functional processes." The strong point of your draft is that it combines rewilding's claim to "break the dichotomy" (nature–culture, wild–human-made, protected–used landscapes) in its philosophical/ethical background with the urgency of the climate agenda. The main synthesis that emerges from the discussion in this chapter is this: rewilding's contribution to climate mitigation is strengthened not by “absolute non-intervention,” but by an implementation spectrum that increases the numbers of species and processes while limiting intervention with transparent principles and producing verifiable evidence. The ACC approach makes the climate dimension of this spectrum visible; frameworks such as the IUCN Nature-based Solutions Standard can secure the claim–design–verification–scaling chain.

In the context of Türkiye, “passive rewilding” opportunities such as rural abandonment/secondary succession areas—if supported by proper measurement and governance (especially regarding human–wildlife conflict and invasives)—can produce meaningful gains both in biodiversity and in terms of the carbon cycle and climate resilience. For this, the next step is to transform the questions you pose at the end of your chapter into a “research and implementation agenda”; tie intervention decisions to criteria; clearly define success/wildness metrics (ecological processes, trophic function, social acceptance, long-term monitoring); and support climate claims with strong evidence standards.

In this framework, one of the key policy recommendations that would increase the applicability of the rewilding approach in Türkiye is the combination of “protection status + zoning.” A study states that, if the Arhavi Kamilet Valley[1] is granted an appropriate protection status, it would be possible—through zoning—to create sub-zones such as strict protection, traditional use, buffer, and special use; and that the core section offers opportunities for sustaining ecosystem services and conservation (Kurdoğlu & Akbulut, 2015). This approach produces an applicable framework to manage the social acceptance and subsistence-use pressures frequently encountered in rewilding in the field (strict protection in the core, controlled/nature-compatible use in surrounding areas).

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[1] The characteristics of this area and its status as a wild area were presented at the Austrian Wilderness Academy 2014 Workshop under the title "A potential wilderness area in Turkey".

The Kamilet–Durguna Valleys example clearly shows that rewilding and climate mitigation goals in Türkiye should be conceived with the sequence “first protect what remains, then improve and restore function.” It is emphasized that the core area at the center of this basin, due to its naturalness and untouched character, has the quality of a true refugium; and that the core section—located in the central region where edge effects are geomorphologically minimal—offers unparalleled opportunities to protect wildlife and ecological processes. In the context of climate change, protecting such refugia safeguards not only species, but also carbon stocks, water cycles, and natural disturbance/recovery processes.

In addition, it is proposed that the Kamilet–Durguna basin should be designated as a “Strictly Protected Sensitive Area” according to the relevant legislative criteria; that the approximately 19,000-hectare area forming the strict protection zone should be protected as an investment in the country’s future; and, if possible, that it should first be declared a national park. In terms of rewilding and climate mitigation goals, this proposal is directly aligned with (i) strict protection of high-carbon-density habitats such as old-growth forests and peatlands, (ii) limiting fragmentation pressures such as roads and hydropower plants (HPP), and (iii) the principles of basin integrity and uninterrupted ecological processes.

Finally, like the Kamilet–Durguna example, many other sites—such as the Kaçkar Mountains, Hatila Valley, Papart Valley, the natural old-growth forests of the Camili Biosphere Reserve, Munzur Valley, Küre Mountains, and many more—concretize the “co-benefits for climate mitigation” of rewilding: when the exceptional carbon storage capacity of peatlands; the accumulated biomass and soil carbon stocks of natural old-growth forests; alpine meadows; rich flora and fauna; geomorphological richness; glacial lakes; water production and flow-regulation functions;

and topographic–hydrological processes that balance flood/erosion risk are evaluated together, a strong scientific rationale emerges for integrating rewilding strategies in Türkiye with climate policies (especially along the axis of land use and ecosystem-based solutions).

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Chapter VII - The 16th Additional Article of Forest Law No. 6831 from the Perspective of Constitutional Justice

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1.Introduction

The Constitution of the Republic of Türkiye (Constitution) delineates the limits of authority of the legislative, executive, and judicial branches, guarantees fundamental rights and freedoms, and occupies the highest level in the hierarchy of norms. The hierarchy of norms is a constitutional principle that preserves the logical structure of the legal order and regulates the superiority-inferiority relationship between norms (Gözler; 2013). The proof of the hierarchical relationship is that a norm is subject to invalidity if it conflicts with a certain norm. *"Being subject to the penalty of invalidity means that a certain body is vested with the authority and/or duty to repeal the conflicting norm"* (Gülgeç, 2024). In Türkiye, this authority belongs to the Constitutional Court of the Republic of Türkiye (AYM) and is based on two fundamental procedures, namely "abstract norm control" and "control by way of objection," particularly with regard to the review of the constitutionality of laws (Özkul, 2015).

In this context, Additional Article 16, added to the Forest Law No. 6831 by Article 17 of Law No. 7139, has sparked significant debate in terms of both legal and environmental impacts, as it introduces provisions regarding the status and usage of areas removed from forest boundaries. The relevant regulation has been criticized in terms of the right to the environment, the protection of natural resources, and the principles of public interest, particularly Article 169 of the Constitution; criticisms that the integrity of forests would be compromised have been widely discussed in the public sphere.

In light of these debates, the claim that Additional Article 16 was unconstitutional was brought before the Constitutional Court; however, the Court rejected this claim in its decision numbered E.2018/104, K.2020/39 and ruled that the regulation in question was not unconstitutional. Although the legislative body's discretionary power and legislative acts are "acts of will" (Gözler, 2006), the review of a law's provision is conducted solely in terms of its constitutionality, without the judicial body determining whether it is in the public interest. This is because legislative acts, although based on democratic legitimacy, cannot be considered an absolute expression of will; their constitutionality is reviewed by the Constitutional Court, and this review demonstrates the Court's power of legal interpretation (Kaboğlu, 2007). The decisions of the Constitutional Court contribute to constitutional law not only in terms of their outcome but also in terms of their constitutional interpretation (Çakmaz, 2025). At this point, it should be strongly emphasized that the normative boundaries of constitutional adjudication should be expanded by adopting the principle of expansive interpretation, not only based on the technical logic of law but also in relation to the protection of constitutional values (e.g., environmental rights, sustainability, intergenerational justice) (Akıncı, 2022).

In this study, the Constitutional Court's reasoned decision on Additional Article 16 will be discussed in the context of constitutional norm control theory; the claims of unconstitutionality directed at the article in question and the normative interpretation put forward by the Court will be evaluated together. In this context, a two-way assessment will be made around fundamental constitutional concepts such as the legitimacy of legislative acts and the function of the hierarchy of norms.

2.Material and Method

The material for this study consists of Additional Article 16, added to the Forest Law No. 6831 by Article 17 of Law No. 7139, and the Constitutional Court's decision E.2018/104, K.2020/39, which resulted from an application alleging the unconstitutionality of this provision. The study also draws on constitutional principles, the hierarchy of norms, legislative authority, and the concept of public interest, as well as constitutional law sources and judicial decisions relevant to the subject matter.

The study adopted a qualitative research method and proceeded with a normative approach. In this context, the relevant constitutional provisions and articles of law were first analyzed based on the text, and then the reasons set forth in the Constitutional Court's decision were evaluated. The extent to which the interpretation coincided with the general principles of constitutional adjudication was analyzed, and the allegations of unconstitutionality directed at the article were addressed comparatively. The constitutional assessments presented in the Constitutional Court's reasoned decision were discussed in the context of opposing views. In this way, the study attempted to comprehensively evaluate the meaning of the relevant regulation within the constitutional framework.

3.Findings and Discussion

3.1.Oversight of the Legislative Branch

Article 2 of the Constitution, which defines the characteristics of the republic, requires the state to be a social state governed by the rule of law, thereby imposing on the state the duty to take the necessary measures to ensure social justice. Article 5 of the Constitution stipulates that among the aims and responsibilities of the state are providing the peace, happiness, and welfare of individuals and society; removing political, economic, and social obstacles that restrict the fundamental rights and freedoms of individuals in a manner inconsistent with the principles of the social state governed by the rule of law and justice; and taking the necessary measures to ensure the material and spiritual development of individuals.

The Constitutional Court's decision E.1963/336 and K. 1967/29 and dated 26-27.09.1967 defines the requirements of being a social state governed by the rule of law as follows: "*Respecting human rights and freedoms, realizing and guaranteeing the peace and welfare of the individuals, establishing a balance between the individual and society, regulating labor and capital relations in a balanced manner, ensuring that private enterprise operates with security and stability, and taking social, economic, and financial measures to ensure that workers live humanely and that working life develops with stability. These include economic and financial measures to protect workers, taking steps to prevent unemployment, and ensuring the equitable distribution of national income. Additionally, establishing a just legal system and committing to its continuation, along with applying a realistic regime of freedom with determination and adherence to the law.*" In this regard, the authority granted to the legislative body by the constitution is to ensure social justice and social security (Gören, 2014), to create living conditions for individuals that are consistent with human dignity (Azrak, 1962), and to support material and spiritual development in line with evolving social and technological conditions. Therefore, in reviewing the constitutionality of laws, the Constitutional Court's consideration of these matters plays a crucial role in protecting the constitutional order. In this regard, the constitutional court is expected to review not only the literal constitutionality of laws but also their conformity with the spirit and purpose of the constitution (Azrak, 1962). In its decision E. 2007/51, K. 2007/56 and dated May 15, 2007, the Constitutional Court stated that constitutionality review is a requirement of the rule of law in order to "ensure legal legitimacy." It is anticipated that failure to ensure legal legitimacy will undermine the principle of the rule of law and erode trust in the law. Therefore, it is stated that the primary duty of each of the legislative, executive, and judicial organs of the rule of law is to purge the legal order of actions contrary to the general principles of law, the constitution, and the laws, and to protect the rights of the state and individuals from the effects of such actions that are impossible to remedy. In its decision E.1996/72, K.1997/51 dated May 15, 1997, defines the rule of law as "a state that establishes and is committed to maintaining a fair legal order that respects and protects human rights, and whose all actions and acts are subject to judicial review." The same decision emphasizes that the principle of the rule of law requires "the absolute supremacy of law over all organs of the state and the legislature to always consider itself bound by the Constitution and the supreme rules of law."

In the Republic of Türkiye, a social state governed by the rule of law, legislative power belongs to the Grand National Assembly of Türkiye (TBMM) and is non-transferable (Constitution, Article 7). The Grand National Assembly of Türkiye must act in accordance with the Constitution when exercising this power. However, considering social needs and conditions, there is no legal regulation that prevents the enactment of laws on any subject. Therefore, the decisive criterion for whether laws are valid is whether the law was enacted by the TBMM in accordance with the process (Gözler, 2006).

The legislative body can enact laws on any subject, but according to the theory of the hierarchy of norms, the laws enacted cannot be contrary to the Constitution (Constitution, Article 11). This also arises as a requirement of the principle of the supremacy of the Constitution (Yılmazoğlu and Perdecioğlu, 2021). The review of the constitutionality of laws is carried out by the Constitutional Court within the scope of *"constitutional justice,"* which was first accepted with the 1961 Constitution. Granting the Constitutional Court the authority to review the constitutionality of laws is considered a very important step in terms of the rule of law. The aim is to protect the Constitution and the constitutional order, as well as fundamental rights and freedoms, and to prevent legislative activity, which is political in nature, from exceeding constitutional limits (Azrak, 1962).

3.2.Constitutional Justice

Constitutional review, which first emerged in the Turkish legal system with the 1961 Constitution, was also regulated in the text of the 1982 Constitution. The duty assigned to the Constitutional Court by Article 148 of the 1982 Constitution is defined as reviewing the constitutionality of laws only in terms of form and substance. The establishment, duties, and powers of the Constitutional Court, whose boundaries and framework are defined in the Constitution, are regulated under Law No. 6216 *on the Establishment of the Constitutional Court and Judicial Procedures*. Pursuant to Article 36 of the aforementioned law, the power of review in terms of form is limited to whether the final vote was carried out with the required majority. Cases for annulment based on procedural irregularities are examined and decided by the Constitutional Court with priority. The period for filing a case requesting the annulment of laws on procedural grounds is ten days from the date of their publication in the Official Gazette, while the right to file a case directly requesting annulment on substantive grounds expires within sixty days from the date of publication in the Official Gazette (Article 37). The right to file a lawsuit for annulment on the grounds that laws are unconstitutional in terms of form and substance is granted to the President, the two political party groups with the largest number of members in the Grand National Assembly of

Türkiye, and members representing at least one-fifth of the total number of members (Article 35).

The substantive review of laws is carried out after the "*Principles of Representation and Compliance in Filing an Action for Annulment"* listed in Article 38 of the aforementioned law are replaced by . Accordingly, an action for annulment is filed upon a decision taken by the general assemblies of the two political parties with the largest number of members in the Grand National Assembly of Türkiye, by an absolute majority of the total number of members. If the case is filed by members representing one-fifth of the total number of members in the Grand National Assembly of Türkiye, the names of two members to be notified by the court must be specified. The annulment case is deemed to have been filed on the date the petition, containing the request for annulment on the grounds of the law's unconstitutionality, is referred by the general secretariat to the office of the director of administrative affairs. The General Secretariat informs those who filed the case that the request for annulment has been registered. If the case is filed by one-fifth of the total number of members of the Grand National Assembly of Türkiye, the petition must be accompanied by the numbers, names, surnames, information about the regions they were elected from, and signatures of those who filed the case. Each page of the petition bearing signatures must be certified by the Speaker of the Grand National Assembly of Türkiye or an authorized official with their signature and seal, confirming that the names, surnames, and signatures of the members of parliament appearing on that page are authentic, and then submitted to the General Secretariat. If the case is filed by political party groups, certified copies of the group general assembly decision and certified documents proving that those who signed the petition are the group chair or deputy must also be submitted to the General Secretariat with the petition. Finally, it is essential to specify which articles of the Constitution the provisions alleged to be unconstitutional violate and the reasons for this. However, the Constitutional Court is not obliged to rely on the reasons put forward. The Court has the authority to rule on unconstitutionality based on other reasons, provided that it remains within the scope of the request for annulment (Article 43).

The Constitutional Court examines whether the requirements set forth in Article 38 of the aforementioned law have been fulfilled within ten days from the date of registration. If deficiencies are identified following the examination, the parties concerned are notified that the deficiencies determined by the decision must be remedied within at least fifteen days. If the deficiencies are not completed within the specified period, the case is deemed not to have been filed and the parties concerned are notified. If it is decided to examine the merits, the petition and its attachments are sent to the Presidency of the Grand National Assembly of Türkiye, the President, and the political party groups entitled to file an annulment case.

The constitutionality of laws is reviewed not only through annulment proceedings but also through appeals. Appeals may be lodged with the judicial authority (Borrego, 2013). During the hearing of any case, if the court finds that the provision or provisions of the law applicable to the case are unconstitutional or finds the claim made by one of the parties to be valid, it may file an objection application by sending the original of the application decision, stating the reasons why it finds the provision or provisions to be unconstitutional, to the Constitutional Court. If the Constitutional Court finds the application made by the court to be valid, the process of norm control begins. The Constitutional Court has the authority to conduct its review based on other rules or regulations, without being bound by the reasoning of the court that filed the objection. Therefore, the legal facts and assessments on which the court using the objection route bases its reasoning are not binding on the Constitutional Court (AYM., E.2020/22, K. 2020/34, Decision dated 25/06/2020). If the Constitutional Court does not issue a decision within five months, the court hearing the case is expected to conclude the case by deciding it within the framework of the provisions in force. However, if the Constitutional Court issues its decision before the decision on the merits becomes final, the court must comply with this decision (Article 40).

3.3.Constitutional Interpretation

The protection of the legal order is possible through the predetermination of legal rules and the regulation of behavior within the framework of these rules, which are known to everyone (Gözler, 2013). The concept of interpretation is encountered in the concretization of legal provisions and principles, i.e., their application to specific cases. The judge must understand the essence, meaning, and spirit of the legal rule rather than its wording. Therefore, interpretation emerges as the fundamental activity of the judge (Keskinsoy and Kaya, 2021).

In some cases, it is necessary to establish a connection between the purpose of the law at the time it was enacted by the legislature and the purpose at the time the rule is applied. In its decision E.1997/1 K.2000/1 and dated 18/2/2000, the Supreme Court of Appeals defined purposive interpretation as a form of interpretation required by the times. Therefore, contemporary interpretation is an interpretation that considers the objective purpose of the law at the time it is applied rather than at the time it was created. The aforementioned decision emphasizes that the scope of contemporary interpretation is limited to the framework of the law's wording. Therefore, it is emphasized that the expressions and/or concepts in the wording can be interpreted broadly or narrowly within the objective purpose, but meaning cannot be attributed to the law by going beyond the framework outlined by the law. Similar statements are found in the Constitutional Court's decision E.1994/76, K.1994/73, dated October 13, 1994 ( ). *"The text of the law must be understood according to the meaning of the words used in legal language. Even if a legal rule is thought to* *conflict with the social and economic requirements of the day, it must be applied as long as it remains in force, as required by law. Deviating from this rule for certain reasons, interpreting the texts in ways other than their meaning, attempting to amend the text, actually attributing to the law what is not in the law, changing its purpose through interpretation, or taking the place of the legislator."*

High courts are obliged to interpret the provisions of the law in accordance with the reasons, wording, and spirit of the law (YİBBGK., E.1997/1 K.2000/1, Decision dated 18.2.2000). However, in some cases, the same provision of the law is interpreted in different ways. In particular, there are complaints that members of the constitutional court interpret constitutional provisions according to their own desires, beliefs, opinions, and ideologies (Gözler, 2013). The principles of interpretation put forward in case law and doctrine do not have binding qualities for the interpreter (judge) because they are not presented as any legal rule (Gözler, 2006). Therefore, it is possible that a legal provision may contain more than one norm, and it is also possible for these norms to be interpreted in different ways. It is not possible to scientifically establish that one interpretation is more valid than another (Gözler, 2006). The fundamental issue that comes to the fore in all countries that accept constitutional adjudication is whether judicial review by a court composed of a certain number of judges appointed by a parliament consisting of members of parliament is compatible with democratic principles (Metin, 2012).

Gözler (2006) outlines the framework for the constitutional interpretation of constitutional justice as follows: "*The raison d'être of constitutional justice is that, given the hierarchy between laws and the Constitution, the function of constitutional justice is nothing other than enforcing this hierarchy. If constitutional courts review the conformity of laws with something other than the Constitution, they lose their legitimacy. What gives legitimacy to the review of the conformity of laws with the*

Constitution is that the standard for this review is the Constitution itself. Therefore, constitutional courts must be very careful when reviewing the constitutionality of laws and must use exclusively "constitutional norms" as the standard for this review. Constitutional courts lose their legitimacy if they use general, abstract concepts such as "justice" or "social solidarity" or principles lacking a positive basis, such as "supra-constitutional principles" or "general principles of law," as a standard instead of constitutional norms" (Metin, 2012). The principle adopted regarding interpretation is referred to in the decision of the Tenth Chamber of the Court of Cassation, E.1988/2165, K.1988/2355, dated 11/04/1988. Accordingly, the "essence" that carries the purpose of the ruling and the "wording" that forms its form are identical, and in case of a discrepancy between them, the essence of the ruling must be taken into account.

In its decision E.2018/104, K.2020/39 dated 16.7.2020, the Constitutional Court states that:

In the petition for the annulment of the first paragraph of the 16th additional article of the Forest Law No. 6831, it is summarized as follows: *"The Constitution stipulates that the date of December 31, 1981, is the date for determining the loss of forest status and, consequently, for removing an area from forest land. For a place to lose its forest status and be removed from forest land, the loss of status must have occurred before this date. However, the rule in question allows areas that have been destroyed or built upon to be excluded from the forest boundary without considering this date. The fundamental reason for setting such a date in the Constitution is to prevent forests from being excluded from the forest area by burning, cutting, or other forms of destruction. the protection of forest resources serves to fulfill environmental-ecological, socio-cultural, and economic functions of vital importance for human life and the future of the planet, the application of the rule would lead to developments that restrict the forest regime, and it is necessary to take the necessary steps for the* *areas evaluated under the rule to regain their forest ecosystem characteristics, that treeless rocky areas within forests are also an important part of the forest ecosystem and are particularly important for wildlife, that it takes a long period of time, such as 300 years, for certain Treasury lands that are not considered forests to acquire forest status, Therefore, it cannot be said that allocating land to the General Directorate of Forestry (OGM) for forest establishment in exchange for areas removed from forest boundaries will not lead to a reduction in forest boundaries. Moreover, the Constitution assigns the state the task of increasing forest areas, and incorporating areas that should be used as forests into the forest regime is already part of the state's duty without any conditions or compensation. the destruction of another forest area cannot be a compensation for the reduction of another forested area, forests are not only composed of trees, and areas considered marginal in terms of tree cover are important areas of biological diversity, it has been argued that the rule is contrary to Article 169 of the Constitution.*

Case law and legal rules related to the grounds for annulment;

The established view of the Court of Cassation regarding forest soil and/or forest clearings is as follows: "*Even if the forest vegetation cover on a site that was previously a forest has been destroyed, the forest soil alone should be considered a forest."* (8th Civil Chamber, E. 2021/13831- K. 2021/11337; 8th Civil Chamber, E. 2021/16003-K. 2021/12578; 8th Civil Chamber, E. 2021/12718- K. 2021/12121). As stated in the Constitutional Court's decision dated 10/3/1966, E. 1965/44, K. 1966/14, *"naturally growing or cultivated trees and shrubs, together with their locations, are considered forests."* The legislator has included *"land"* in the definition of forest. Therefore, it is accepted that if trees are destroyed for any reason, their land continues to exist as another element of the forest.

The 20th Civil Chamber of the Court of Cassation, in its decision E. 2013/898 and K. 2013/1500, referring to the second paragraph of Article

17 of Law No. 6831, emphasizes that forest clearings cannot be used for agriculture, animal husbandry, or construction for any reason, nor can they be acquired as private property. The decision also states that immovable properties with the nature of forest clearings do not necessarily have to have been forests in the past. The purpose of prohibiting the acquisition of forest clearings in any way is to protect the integrity of the forest (Y.H.G., 1997/20-830/1034; 1997/20-808/1039; 1999/7-22-43; 1999/8-689-822; 2002/8-230-261; 2003/20-665/614). It is clear that forest clearings cannot be acquired through adverse possession, even if the forest cadastre has been completed and more than 20 years have passed since the date of finalization (Y.H.G.K., 2004/7-531-582).

The conditions necessary for acquiring ownership of rocky or scrubby areas are addressed in the decision of the 12th Civil Chamber of the Supreme Court of Appeals, E. 2010/8-219, K. 2010/273. According to the decision, these areas, which are not considered forests under Article 1 of Forest Law No. 6831 and do not have the characteristics of agricultural land, are under the control and disposal of the State and can be acquired by possession through development and improvement in accordance with Article 17 of Cadastre Law No. 3402. However, these areas must not be allocated for public service, must have been made suitable for agriculture through development and reclamation work involving expense and labor, and must not fall within the boundaries of the development plans for the area to be acquired through possession. However, until the forest cadastre is completed, rocky areas and shrubbery that are considered forests under Article 1 of Law No. 6831, and scrubland, which are considered forests until the forest cadastre is completed, cannot be acquired through development and rehabilitation, based on the opinion emphasized in the forest demarcation minutes finalized by cadastral surveys and expert reports that these areas are "not considered forests but cannot be excluded from forest boundaries due to loss of quality."

Similarly, in its decision E. 2021/8118, K.2021/11690, the 8th Civil Chamber of the Court of Cassation ruled that scrubland with a slope of between 10% and 30% located within a forest area that has been cleared and converted into agricultural land, and the remaining part consisting of rocky and scrubby areas ( ), cannot be considered forests under Article 1/j of Law No. 6831 and cannot be distributed through allocation. Therefore, the title deed acquired through allocation has no value for the administrations, and it is emphasized that it is not possible to acquire forest land through title deeds and possession.

In addition, regulations regarding the rehabilitation and afforestation of barren, degraded areas that are rocky, stony, barren, and do not actually have forest characteristics are included in the Forest Law No. 6831. According to the provision of the 12th additional article of the aforementioned law*, "Damaged or infertile forest areas shall be subject to afforestation, erosion control, and rehabilitation works. In these areas, the necessary existing species shall be protected, grafted, and/or rehabilitated. In addition, vacant areas within forests shall be filled by planting, sowing, and grafting with species that grow naturally in the region, thereby restoring and/or rehabilitating them."* Similarly, pursuant to Article 57 of the aforementioned law, *"In order to increase the forest area, in areas within forest boundaries that have become vacant due to fire and various other reasons, and which are unproductive, degraded, and designated for conservation in management plans despite not having soil conservation characteristics, as well as on state-owned land suitable for forest growth conditions, afforestation may be carried out by village legal entities and other real and legal persons according to plans deemed appropriate by the General Directorate of Forestry."*

The Türkiye Forest Resources Report 2020, published by the General Directorate of Forestry, includes definitions of functional productivity/inefficiency for the first time. Functional productivity means "the *production and benefit* status *per unit area in terms of product or protection and service quantity required by the management objective and protection target of the areas allocated in the plan unit (forest types and land use types)*." Functional inefficiency, on the other hand, refers to *"the situation where the product or service required by the management objective and conservation target is not provided."* In numerical analyses of forest resources, functionally productive/unproductive forest areas are separated based on forest district directorates. Gap-closed forest areas can be included in either group depending on their status within areas with operational and conservation objectives.

Apart from this distinction, forests are evaluated in two groups: protected forests and coppice forests. According to the provision in Article 20 of the Regulation on the Establishment and Duties of the Provincial Organization of the General Directorate of Forestry, "It is the duty of the forest management chief to carry out *the necessary silvicultural work to ensure that degraded protected forests and coppice forests are converted into productive forests"* . According to the wording of the article, degraded forests and woodlands are considered unproductive forests.

The "Regulation *on Removal from Forest Boundaries under* Article 16 of *the Forest Law No. 6831" published* in the Official Gazette dated 7/1/2021 and numbered 31357 regulates the details of the application of Article 16. The criteria set forth in Additional Article 16 regarding removal outside forest boundaries are defined in Article 4 of the implementing regulation. Accordingly, it refers to "*places where it is not considered beneficial to preserve as forests from a scientific and technical standpoint: places where there are no tree communities and where it is not beneficial to establish forests in terms of forestry activities and economics."* The aforementioned high court decisions state that an area that was previously a forest does not lose its forest status with the disappearance of the tree communities on it.

Although trees and shrubs form the basic elements of the forest ecosystem, they are not sufficient to explain the system within the forest. Trees and shrubs gain meaning together with other living and non-living elements that make up the forest. Other living and non-living elements within the forest ecosystem maintain their existence in relation to trees and shrubs. Any change in environmental components leading to the extinction of one species will cause the extinction of other species that are dependent on it (Gümüş, 2021). Therefore, forests have much more value than just being a collection of trees. Nearly all terrestrial life on Earth is hosted by forests. The ecosystem diversity of forests is related to the complex network of organisms such as plants, animals, fungi, and bacteria. Forests are also the habitat of many undiscovered plant and animal species (WWF, 2024). The most fundamental component to consider within the forest ecosystem is soil. Soil is the most complex and comprehensive ecosystem on Earth. It is teeming with life, and thousands of different species can be found in every square meter of soil. Proper management of the requirements of living soil will provide better ecosystem services such as water retention, prevention of nutrient loss, and ensuring the continuity of underground life (Coyne, 2018). Soil, one of the largest carbon storage pools on Earth, also increases its water retention capacity thanks to the carbon it contains (Rawls et al., 2003). Forest clearings also have an indispensable value within the ecosystem. Forest clearings formed as a result of temperature inversion are irreplaceable areas rich in biological diversity and of vital importance for wildlife (Yılmaz et al., 2021). Dense forests without clearings are not suitable for the survival of some wild animals (Sevgi, 2013).

The constitutional interpretation that the clause requested to be annulled by the Constitutional Court raises the issue of unconstitutionality;

"The first paragraph of Article 169 of the Constitution states: 'The State shall enact the necessary laws and take the necessary measures for

the protection and expansion of forests. New forests shall be cultivated on the sites of burned forests, and no other type of agriculture or animal husbandry may be carried out on these sites. The supervision of all forests belongs to the State.' The fourth paragraph of the aforementioned article states: "In areas where there is no scientific or technical benefit to preserving them as forests, but where it has been determined that there is a definite benefit in converting them to agricultural land, as well as in fields, vineyards, orchards, olive groves, or for livestock farming, except in areas where urban, town, and village structures are concentrated, forest boundaries cannot be reduced." The remainder of the first sentence of the paragraph states that areas to be excluded from forest boundaries are those where there is no benefit in preserving them as forests from a scientific and technical standpoint and which cannot be converted into agricultural land; are divided into two categories: rocky, barren, and unproductive areas that do not actually have forest characteristics, and areas that have settlements on them or are suitable for settlement as of April 28, 2018, when this article came into force. For areas falling under the first category, the phrase "where there is no scientific or technical benefit in preserving them as forests..." in the fourth paragraph of Article 169 of the Constitution allows for the exclusion of these areas from forest boundaries, and no time limit is specified in the relevant constitutional provision in this regard.

The second group of areas also stipulates that, as of the date this article enters into force, not all rocky, barren, or infertile areas that are currently inhabited or suitable for habitation, but only those that possess these characteristics and at the same time do not actually have forest characteristics, may be excluded from the forest boundary. Therefore, it is understood that the phrase "areas that do not actually have forest characteristics" in the paragraph refers to areas corresponding to the phrase "... that have completely lost their forest characteristics in terms of *science and technology" in the aforementioned provision of the Constitution. Within this framework, in accordance with the rule, rocky, barren, and infertile areas that have settlements on them or are suitable for settlement on the date this article enters into force may be excluded from forest boundaries only if they have completely lost their forest characteristics in terms of science and technology, in accordance with the aforementioned provision of Article 169 of the Constitution. Areas that do not possess this characteristic cannot be excluded from forest boundaries under the rule.*

The second sentence of the paragraph stipulates that immovable property under the control and disposal of the state or in the special ownership of the Treasury, amounting to at least twice the area excluded from forest boundaries, shall be allocated to the General Directorate of Forestry for the establishment of forests.

The rule stipulates that areas that are generally unsuitable for preservation as forests from a scientific and technical standpoint, and that judicial remedies exist to prevent arbitrary use of the rule outside its intended purpose. The rule does not violate Article 169 of the Constitution. The request for annulment must be rejected."

Additional Article 16 introduces important regulations regarding the nature and use of areas removed from forest boundaries. However, the claims that this article is contrary to the Constitution have been evaluated by the Constitutional Court, which ruled in its 2020 decision that the regulation in question is not contrary to the Constitution (AYM, E.2018/104, K.2020/39). The Constitutional Court's decision is based on the principle that the judicial branch cannot determine whether legislative acts are in the public interest or not; it can only review their constitutionality. Within the framework of this decision, the constitutional norm review process is an evaluation mechanism based on the court's interpretation.

This study aims to evaluate, within the scope of constitutional adjudication, the constitutionality of Additional Article 16, added to the Forest Law No. 6831 by Article 17 of Law No. 7139, in terms of its compliance with the fundamental norms of the Constitution, particularly Article 169. Based on the Constitutional Court's decision numbered E.2018/104, K.2020/39, the analysis emphasizes that the function of norm control must be carried out in light of the principles of interpretation consistent with the spirit, purpose, and context of constitutional norms, not limited to the literal content of laws.

The reasons stated in the application for annulment focus on the inadequacy of evaluating forest areas solely on the basis of tree cover and the need to take into account the multidimensional functions of the forest ecosystem in terms of biological diversity, soil integrity, wildlife, and ecological cycles. In this context, it was argued that Additional Article 16 contained provisions that could open the door to narrowing the boundaries of forest areas ( ) and, in this respect, could conflict with the provisions of the Constitution imposing positive obligations regarding the protection and expansion of forests.

However, the Constitutional Court viewed the scope of the specific regulation as limited to areas that *"do not actually have the characteristics of a forest*," *"are not considered beneficial to preserve as forests from a scientific and technical perspective,"* and *"cannot be converted into agricultural land*," drawing attention to the existence of structural mechanisms and public oversight channels that prevent the arbitrary application of the regulation. Furthermore, it was assessed that the provision requiring the allocation of an area at least twice the size of the areas removed from forest boundaries for reforestation purposes provides a guarantee mechanism in terms of compensating for environmental loss.

From the perspective of constitutional adjudication, the decision in question demonstrates that the court considers not only the formal constitutionality of legal norms but also the contextual meaning of constitutional norms and their reflection within the framework of the social state principle. However, it should not be forgotten that the limits of constitutional adjudication must respect the delicate balance between judicial activism and the democratic legitimacy of the legislature. This is because constitutional courts, while ensuring the supremacy of the constitution, should not expand constitutional interpretation in a way that replaces political decision-making processes.

4.Conclusion

In conclusion, the Constitutional Court's decision on Additional Article 16 reveals the function of constitutional adjudication and the limits of constitutional interpretation within the framework of the principle of the hierarchy of norms. It also raises the need to expand environmental constitutional interpretation in future similar regulations to include a more holistic ecosystem approach. The assessment of forests not only as economic resources or areas for development but also as natural assets protected by the constitution is important in terms of restructuring constitutional adjudication with environmental sensitivity.

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Chapter VI - The Ecological and Cultural Value of Honey Forests: Community Perpectives, Biodiversity, and Conservation Challenges

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1. Introduction

Honey forests, characterized by their rich floral composition and ecological functions, provide critical support for beekeeping, biodiversity conservation, and traditional land-use systems in many rural regions. In Turkey, particularly in the Eastern Black Sea Region, honey forests hold significant cultural and economic importance for local communities. These forests serve not only as essential habitats for wild pollinators and native flora but also as traditional sources of organic honey production, forming part of the region's intangible cultural heritage (Kaya et al., 2020; Tunalı, 2016).

From a biodiversity perspective, honey forests sustain a diverse range of species, including endemic plants and insect pollinators such as bees, butterflies, and beetles. The ecological services offered by these forests—such as pollination, soil stability, microclimatic regulation, and carbon sequestration—are vital for the sustainability of both natural ecosystems and rural livelihoods (IPBES, 2019; Kremen et al., 2007). Recent studies highlight the increasing vulnerability of these systems due to land-use changes, climate variability, and insufficient conservation frameworks (FAO, 2019; Potts et al., 2016; Seyhan & Bayramoğlu, 2021).

Despite their ecological richness, honey forests remain under-recognized in national biodiversity and forest management policies. Local communities, especially small-scale producers and women beekeepers, possess valuable traditional knowledge related to sustainable forest use and conservation. However, changing socio-economic dynamics, weak institutional support, and declining intergenerational knowledge transfer pose significant threats to the sustainable management of these landscapes (Çelik & Erdoğan, 2019; Meinzen-Dick et al., 2019).

In the case of Artvin—a biodiversity hotspot in northeastern Turkey—honey forests represent a socio-ecological system where ecological values and cultural meanings intersect. Understanding how local people perceive these forests, and identifying the challenges they face in their protection and utilization, are essential for designing inclusive and effective conservation strategies (Bayram & Erkan, 2017; Öztürk & Yılmaz, 2020).

This study aims to explore the ecological and cultural significance of honey forests, focusing on local perceptions, biodiversity functions, and emerging conservation challenges in the Artvin region. Specifically, the study seeks to:

(i) assess local knowledge and perceptions regarding honey forests;

(ii) identify the ecological roles these forests play, especially in relation to pollinators and native vegetation; and

(iii) examine the socio-institutional factors influencing conservation outcomes.

2. Material And Methods

2.1. Study Area

The study was conducted in Artvin Province, located in northeastern Türkiye within the Eastern Black Sea Region. Artvin is distinguished by its extensive forest cover, including numerous honey forests that are notable for their rich floral diversity and favorable conditions for organic beekeeping. The province represents a unique socio-ecological landscape where traditional agricultural practices and forest-based livelihoods coexist with cultural traditions linked to honey production. The region's humid and temperate climate supports a wide variety of flora and fauna, which are essential for maintaining ecosystem services (Eminağaoğlu, 2018; Eminağaoğlu & Kaya, 2021).

2.2. Sample Selection and Data Collection

The target population of the study consisted of local beekeepers and ecological farmers operating within honey forests in Artvin Province. The estimated size of this population ranged between 1,500 and 2,000 individuals. The appropriate sample size was calculated using Cochran's (1977) formula with a 95% confidence level, a 10% margin of error, and an estimated proportion of 50%:

The calculated minimum sample size was approximately 96 participants. However, in order to enhance representativeness and adapt to field conditions, 150 to 200 participants were included in the study. A purposive sampling method was employed, prioritizing producers with experience in organic beekeeping and ecological farming, and representing various production scales.

Data collection was carried out during the summer of 2024 through face-to-face surveys and structured interviews. Informed consent was obtained from all participants prior to data collection.

The collected data were analyzed using SPSS software. Where appropriate, descriptive statistics, independent samples t-tests, one-way ANOVA, and correlation analyses were applied. These analyses aimed to evaluate the effects of honey forests on organic beekeeping and ecological agriculture, as well as to assess producers' attitudes and levels of satisfaction.

3. Results

The study sample consisted of 200 participants engaged in organic beekeeping and ecological agriculture in the Artvin region. Table 1 presents the demographic distribution of respondents according to gender, age, and education level. Female participants comprised 40% of the sample, while males accounted for 60%. The age distribution showed that 25% of respondents were between 18 and 30 years old, 45% between 31 and 45, and 30% aged 46 or above. Regarding education, 20% had completed primary school, 35% high school, and 45% held university degrees or higher qualifications. (Table 1).

Tablo 1. Socio-demographic characteristics of participants

Variable	Category	Frequency (n)	Percentage (%)
Gender	Female	80	40
	Male	120	60
Age	18–30 years	50	25
	31–45 years	90	45
	46 years and above	60	30
Education	Primary school	40	20
	High school	70	35
	University or above	90	45

This demographic profile reflects a diverse participant group, allowing for comprehensive analysis of how perceptions and practices related to honey forests vary across different socio-demographic segments. Subsequent analyses examine the influence of these demographic factors on attitudes toward organic beekeeping and ecological farming within honey forest contexts.

The survey aimed to assess perceptions of honey forests in relation to ecological functions, cultural significance, and conservation challenges. Data were collected using a 5-point Likert scale (1 = Strongly Disagree, 5

= Strongly Agree), and both descriptive and inferential statistics were applied.

The data reveal insights into how ecological and cultural dimensions of honey forests are perceived and highlight the major threats and barriers faced in sustainable management. Table 2 summarizes the main categorical findings derived from both quantitative and qualitative data sources.

Table 2. Summary of local perceptions, biodiversity awareness, cultural values, and conservation challenges related to honey forests in Artvin

Category	**Key Findings**	**Percentage (%)**	**Description**
Perceptions of Ecological & Cultural Values	Positive effects on honey quality and bee health	85+	Majority of producers acknowledge the ecological importance of honey forests.
Biodiversity Awareness	Recognition of native flowering plants and wild pollinators	70+	High awareness of flora and pollinator diversity associated with honey forests.
Awareness of Pollinator Decline	Observation of decreasing pollinator populations	40	Mixed levels of ecological knowledge or environmental awareness among producers.
Cultural Traditions	Honey harvest rituals, traditional hive making, oral knowledge transfer	-	Cultural practices tied to honey forests are actively maintained.
Women's Roles in Culture	Medicinal honey products, community festivals	-	Women play key roles in cultural heritage and traditional practices.
Conservation Challenges – Women's Participation	Limited involvement of women in decision-making	60	Gender disparities affect management and conservation processes.

Category	Key Findings	Percentage (%)	Description
Conservation Challenges – Legal Protection	Inadequate legal status and protection of honey forest areas	72	Legal frameworks are insufficient for forest conservation.
Conservation Challenges – External Threats	Mining, land conversion, and other pressures	68	External threats pose significant risks to honey forests and their ecosystem services.
Economic & Technical Barriers	Difficulties accessing markets and technical support, especially for women and smallholders	-	Economic sustainability is challenged by limited access to resources and services.

The findings of this study reveal a generally positive perception of honey forests among local beekeepers in the Artvin region. Over 85% of respondents acknowledged the significant contributions of honey forests to honey quality and bee health, highlighting the integral role these ecosystems play in sustaining organic apiculture. This strong ecological appreciation extends to biodiversity awareness, with more than 70% of participants demonstrating familiarity with native flowering plant species and recognizing the presence of diverse wild pollinators, such as bumblebees and solitary bees. However, only 40% reported observations of declines in pollinator populations, indicating a potential gap in ecological knowledge or varying levels of environmental awareness within the community.

Cultural dimensions associated with honey forests emerged prominently in qualitative data. Traditional practices, including seasonal honey harvest rituals, indigenous hive construction methods, and the oral transmission of beekeeping knowledge, were frequently cited by participants. Notably, women's roles in these cultural practices were emphasized, especially concerning the preparation of medicinal honey products and the organization of community festivals celebrating the honey harvest. This underscores the gendered nature of cultural heritage linked to honey forests and highlights women as key custodians of both ecological and cultural knowledge.

Despite widespread recognition of ecological and cultural values, several conservation challenges were identified. A majority of participants (60%) pointed to the limited participation of women in decision-making processes related to forest and apiculture management. Moreover, 72% emphasized the inadequate legal protection afforded to honey forest areas, while 68% reported external threats such as mining activities and land conversion pressures. Similar shortcomings in legal status, zoning, and long-term management effectiveness have been widely documented in the development and current governance of protected areas both globally and in Turkey (Küçükbekir & Bayramoğlu, 2022). Economic and technical barriers were also significant, with many small-scale producers—particularly women—facing difficulties in accessing markets and technical support services. These multifaceted challenges underscore the need for inclusive policies that integrate gender considerations, strengthen legal frameworks, and enhance support mechanisms to ensure the sustainable management of honey forests and the livelihoods dependent upon them.

The survey aimed to assess local producers’ perceptions regarding the ecological and agricultural benefits provided by honey forests. Participants were asked to rate their agreement with a series of statements reflecting different aspects of honey forests' contributions, including their impact on honey quality, bee health, floral diversity, and sustainability factors. Responses were recorded on a 5-point Likert scale, where 1 indicated strong disagreement and 5 indicated strong agreement. Table 1 summarizes the mean scores, standard deviations, and percentage distributions of positive (4–5), neutral (3), and negative (1–2) responses (Table 3).

Table 3. Local producers' perceptions of the ecological and agricultural contributions of honey forests

Survey Statement	Mean	SD	% Positive (4–5)	% Neutral (3)	% Negative (1–2)
Honey forests improve honey quality.	4.35	0.65	82	10	8
Honey forests support bee health.	4.10	0.80	75	15	10
Honey forests increase floral diversity.	4.28	0.70	80	12	8
Absence of pesticide use is an advantage.	4.22	0.75	78	14	8
Honey forests positively affect soil health.	3.90	0.85	70	18	12
Honey forests enhance pollination services.	3.85	0.90	68	20	12
Honey forests contribute to biodiversity conservation.	4.00	0.80	73	17	10
Honey forests provide advantages for sustainability in agricultural systems.	3.85	0.95	65	25	10
Economic and technical difficulties are encountered.	3.40	1.10	55	20	25

The results indicate a generally positive perception among local producers regarding the multiple ecological and agricultural benefits of honey forests. The statement "Honey forests improve honey quality" received the highest average score (Mean = 4.35), with 82% of participants expressing agreement or strong agreement. This finding underscores the perceived direct impact of honey forests on product quality, a critical factor in organic beekeeping.

Other highly rated items include the enhancement of floral diversity and the advantage of pesticide-free environments, reflecting the ecological importance of honey forests. However, challenges remain evident, as indicated by the relatively lower score for economic and technical difficulties, with 25% of respondents expressing disagreement or dissatisfaction.

These insights highlight the multifunctional value of honey forests and the need for targeted interventions to address technical and economic barriers, thereby maximizing their contribution to sustainable rural development and organic agricultural practices (Bayramoğlu & Toksoy, 2017).

4. Discussion

The results confirm that honey forests significantly support organic beekeeping and ecological agriculture in Artvin by enhancing ecological functions such as pollination, biodiversity conservation, and soil health. The strong positive perceptions of local producers regarding honey quality and bee health correspond with recent findings emphasizing the critical role of natural habitats in maintaining pollinator populations and sustaining high-quality apiculture products (Garibaldi et al., 2020; Klein et al., 2021).

Moreover, the high appreciation for pesticide-free environments within honey forests reflects the global shift toward chemical-free agricultural practices that safeguard ecosystem and human health (Smith et al., 2022). However, the moderate ratings on soil health and pollination suggest potential gaps in local awareness or variability in forest management practices that merit further investigation. In forest landscapes, soil-related outcomes (e.g., surface stability and erosion control) can also be influenced by land-use pressures and infrastructure-related slope disturbances, which highlights the need to interpret 'soil health' perceptions together with local disturbance processes (Gümüş, Hatay & Ünver Okan, 2019; Mısırlıoğlu, Gümüş & Yoshimura, 2022; Hatay et al., 2024; Mısırlıoğlu & Gümüş, 2024).

Economic and technical difficulties highlighted by respondents align with global challenges faced by organic farmers and beekeepers, such as limited access to technical expertise, infrastructure, and reliable markets (FAO, 2021; IPBES, 2023; Bayramoğlu et al., 2025). Addressing these constraints through targeted extension services and inclusive policies is critical to fully harness the multifunctional benefits of honey forests.

The observed demographic differences, especially gender disparities, reflect broader structural inequities documented in rural agricultural systems worldwide (Meinzen-Dick et al., 2021). Women's greater reporting of challenges underscores the need for gender-responsive interventions (Seyhan & Bayramoğlu, 2023), including tailored training programs and equitable resource allocation, to empower female producers and enhance their participation in sustainable forest-based livelihoods.

Overall, the study aligns with contemporary sustainability frameworks advocating for integrated socio-ecological approaches that balance conservation goals with local development needs (IPCC, 2022; FAO & UNEP, 2020). Strengthening participatory governance and fostering collaboration between scientific and indigenous knowledge systems are essential for adaptive management and resilience in honey forest landscapes.

5. Conclusion

Honey forests are indispensable for sustainable organic beekeeping and ecological agriculture in Artvin, offering multiple ecosystem services that directly benefit local producers and contribute to biodiversity conservation. The positive perceptions regarding honey quality, bee health, and pesticide avoidance highlight the environmental and economic potential of these forests.

Nevertheless, ongoing economic and technical challenges must be addressed through comprehensive support programs focusing on capacity building, market integration, and gender inclusivity. Policymakers and practitioners should prioritize equitable access to resources and strengthen extension services tailored to diverse producer needs.

Future research should adopt interdisciplinary and participatory methodologies to capture the dynamic interactions within honey forest systems and evaluate the long-term impacts of management interventions. Such efforts will support evidence-based policy and contribute to achieving global sustainability targets related to climate action, life on land, and sustainable livelihoods.

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Chapter VII - The Interaction of Land Change at the Basin Scale on Natural Resources and the Socio-Economic Structure

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1. Introduction

Global climate change is one of the most pressing environmental issues of our time, having profound impacts on both natural ecosystems and human life. The accelerated use of fossil fuels since the Industrial Revolution, combined with increasing energy demand and rapid urbanization, has led to a significant rise in the concentration of greenhouse gases in the atmosphere, resulting in a notable increase in global average temperatures (IPCC, 2022). Temperature increases have led to irregularities in precipitation patterns, more frequent droughts, floods caused by sudden and heavy rainfall, and disruption of ecosystem balance (Bayramoğlu & Demir, 2018) . Climate change has not only environmental but also social and economic impacts (Bayramoğlu et al., 2025a). The depletion of water resources, the decline in agricultural land productivity, and the fragmentation of forest ecosystems have led people to rely more heavily on natural resources. River basins, in particular, have historically been attractive areas for both agricultural production and settlement, and have therefore been under pressure due to natural resource use.

Agricultural production is one of the sectors most directly affected by climate change. Rising temperatures and irregular rainfall patterns reduce crop yields, alter agricultural production seasons, and threaten global food security. Additionally, communities in rural areas that rely on agriculture for their livelihoods are experiencing economic losses. Declining incomes, unemployment, and rural prosperity are triggering migration over time, leading to increased social inequalities (Abbass et al., 2022). This situation causes social and economic pressures not only in rural areas but also in cities.

Population growth in Turkey is a key factor contributing to increased pressure on natural resources (Seyhan & Bayramoğlu, 2021; Bayramoğlu et al., 2025b). The growing population has necessitated the opening up of new areas to meet basic needs such as housing, food, energy, and transportation. This has led to the expansion of agricultural areas, the establishment of industrial facilities, the emergence of new settlement areas, and accelerated infrastructure investments (Öztürk et al., 2015). Basins with fertile soils have been the areas most affected by this process.

Basins have become areas of intense economic activity due to the opportunities they offer, including extensive agricultural land, abundant water resources, and efficient transportation. However, increasing population pressure, rapid urbanization, and industrial investments in recent years have led to a rise in non-agricultural land use in these regions, resulting in the shrinking of forest areas and the fragmentation of ecosystems (Gülersoy, 2013; Şen, Bayramoğlu & Toksoy, 2015; Sarı, 2025).

Forest ecosystems play a crucial role in mitigating the adverse effects of climate change by storing carbon, while also being of great importance in terms of biological diversity. They also have ecological functions such as preserving soil fertility, preventing erosion, and regulating the water cycle. Additionally, they offer economic benefits, including fuel, pasture, and non-timber products, to people living in rural areas. However, increasing population and uncontrolled urbanization have led to the shrinking and fragmentation of these ecosystems, as well as the socio-economic vulnerability of rural areas (Bayramoğlu & Toksoy, 2017).

Assessments conducted at the watershed scale provide a robust framework for understanding the interplay between land use and socio-economic structures. Watersheds are natural units where water, soil, vegetation, and human activities coexist. With these characteristics, they allow for the joint analysis of both ecological processes and socio-economic transformations. Basin-based studies provide a holistic approach to natural resource management and contribute to the development of sustainable development policies.

Overall, global climate change and rapid population growth in Turkey have resulted in significant changes in land use within watersheds. The shrinking of forested areas, the spread of non-agricultural use, and the increase in industrial activities have caused both losses in ecosystem services and transformations in the socio-economic structure. Therefore, a detailed examination of watersheds is of great importance for both sustainable natural resource management and the development of regional development policies (Küçükbekir & Bayramoğlu, 2022).

2. Land Use Changes

Land is one of the most fundamental components of natural resources and is indispensable for the sustainability of human life. Land assets, which include soil, water, vegetation, and biodiversity, have historically been at the center of settlements, agricultural production, transportation, and industrial activities. However, population growth, rapid urbanization, diversification of economic activities, and global environmental changes have led to fundamental transformations in land use patterns. These transformations not only alter the physical structure of the area but also directly affect the functioning of natural ecosystems, socio-economic balances, and regional development policies.

The concept of land change is generally expressed in the literature as land cover/land use change, referring to the transformations created by humans on the Earth's surface (Ellis, 2007). The fact that this situation has taken on a global dimension also profoundly affects the world's ecological functioning (Lambin & Meyfroidt, 2001). The conversion of forests into agricultural land, the draining of wetlands, the opening up of pastures for settlement, or the shift of agricultural land to industry are among the most common examples of land change. These processes disrupt the natural balance of ecosystems, reduce biological diversity, and make human-environment interactions fragile.

The conversion of forests into agricultural land, the draining of wetlands, the conversion of pastures into settlements, or the shift of agricultural land to industrial use are among the most common examples of land change. The common point of these changes is the disruption of the natural balance of ecosystems, the reduction of biological diversity, and the fragility of the relationship between the natural environment and human activities (Bağcı & Bahadır, 2019).

Land use in our country is constantly changing. The rapidly growing population in Turkey, urbanization, and the associated increase in industrial activities are causing significant changes in land cover/land use. The destruction of forests and pastures, particularly the inappropriate use of Class I agricultural areas and their uncontrolled and unplanned use, is a clear example of this, leading to irreversible damage to the land and ultimately resulting in its degradation. The total area of land lost in this manner (Class I, II, and III) has reached 573,239 hectares (Cangir et al., 1998; Dengiz & Özcan, 2006). At the same time, the expansion of agricultural production to meet the food needs of the growing population has led to the reduction of forests and pastures in rural areas. During the same period, with the acceleration of urbanization, the pressure to develop non-agricultural areas increased, and fertile agricultural lands began to be replaced with industrial facilities, roads, and settlements. Large-scale infrastructure investments have also been effective in land change.

Large-scale investments, such as dam projects, hydroelectric power plants, the expansion of transportation networks, and mining activities, are also key elements of land change (Kurdoğlu, 2016; Ustaoğlu, 2019). One of the areas experiencing the most intense land change is river basins. Basins are dynamic systems where water resources, agricultural areas, and settlements coexist. Therefore, they are among the most transformed geographies, under pressure from population growth and economic activities. The Kızılırmak and Yeşilırmak basins, as Turkey's largest and most important basins, are areas where this process is most clearly observed. Historically attractive for agricultural production, these basins are now under intense pressure for both settlement and industrial activities. The expansion of agricultural land has led to a decline in forest areas. At the same time, some parts of the basins have lost their natural structure due to the effects of intensive urbanization. Economic activities, which have accelerated particularly in the last half-century, have fundamentally changed land use patterns in these basins. The environmental impacts of land changes are widespread. The reduction of forest areas leads to a decrease in carbon storage capacity, thereby accelerating climate change (Toksoy, Öztekin & Bayramoğlu, 2020;

Bayramoğlu & Küçükbekir, 2022; Küçükbekir, Bayramoğlu & Bulut, 2024). At the same time, it causes disruptions in the water cycle, decreases in groundwater levels, and increased soil erosion. The intensive use of chemical fertilizers and pesticides in agricultural areas causes pollution of water resources (Yavuz et al., 2024). The impermeability of soils, resulting from settlement and industrial activities, increases surface runoff and multiplies flood risks. These environmental changes have a profoundly negative impact on human life and quality of life.

From a socio-economic perspective, land conversion has a profound impact on the livelihoods of rural populations. The income sources of people living in forest villages, which are based on agriculture, livestock, and forest products, have been reduced, thereby increasing rural migration trends. The fragmentation of agricultural land has led to a reduction in rural employment, while in cities, rapid migration has resulted in increased infrastructure, housing, and environmental problems. Thus, land change has become a factor that reshapes socio-economic balances in both rural and urban areas (Güloğlu et al., 2021).

Land changes in watersheds are a typical reflection of Turkey's overall land use trends. In addition to agriculture, industrial, energy, and transportation investments have intensified in these watersheds, and the integrity of natural areas has been disrupted with the increase in settlements.

Land change causes the loss of forests and biological diversity from an ecological perspective, while creating effects such as rural migration, employment problems, and income distribution imbalances from a social perspective (Küçükbekir & Bayramoğlu, 2021). Therefore, it is seen that land change is not only a physical transformation but also a multidimensional socio-economic process.

Land change is one of the most pressing issues today, with its significant environmental, social, and economic implications. The effects of global climate change, combined with population growth and uncontrolled urbanization, increase pressure on land, disrupting the natural balance, especially in strategic areas such as watersheds, and changing the way of life of communities. The effects of land changes are not limited to ecological boundaries but also fundamentally transform socio-economic structures. Therefore, the accurate analysis of land changes at the watershed scale is crucial for the development of sustainable natural resource management and regional development policies.

3. The Impact Of Land Use Change On Natural Resources

The impact of land use changes on natural resources is considered one of the most significant processes threatening environmental sustainability by causing visible disruptions in the functioning of ecosystems. Natural resources are not only the foundation of ecological balance but also the basis of human societies' economic and social existence. However, land use changes, which have accelerated in the last century, have led to severe losses in the quantity and quality of these resources. Studies conducted worldwide reveal that land use changes disrupt ecological balances, particularly in developing countries, and threaten the sustainability of natural resources (Foley et al., 2005).

One of the most apparent effects of land change is seen on water resources. The draining of wetlands for intensive agricultural activities and excessive groundwater extraction have led to significant declines in freshwater reserves. Increased construction and industrial activities have led to surfaces becoming impervious, disrupting the natural water cycle, lowering groundwater levels, and increasing the risk of flooding (Scanlon et al., 2007). In Turkey, excessive groundwater use, particularly in areas such as the Konya Closed Basin and the Gediz Basin, has led to the rapid depletion of water resources. The Kızılırmak and Yeşilırmak basins are also among the areas where irrigation water demand has increased due to growing agricultural activities, leading to a deterioration in water balances (Kibaroğlu, 2019). The excessive use of agricultural chemicals causes pollution in lakes, rivers, and groundwater and limits the capacity of ecosystems to renew themselves. This situation poses significant challenges to both the drinking water supply and agricultural production, ultimately affecting the quality of life for local communities.

Soil is another fundamental natural resource that is directly affected by land-use changes. The conversion of forests to agricultural land or the overuse of pastures has left the soil surface unprotected, resulting in rapidly increasing erosion rates. Soil loss, especially on sloping land, has led to the erosion of fertile topsoil, resulting in a long-term reduction in agricultural production capacity (Montgomery, 2007). Studies conducted in Turkey indicate that the misuse of agricultural land results in the loss of millions of tons of soil annually through erosion (Çepel, 1997). Chemicals used in intensive agricultural activities reduce the organic matter content of the soil, increase salinity and desertification problems, and negatively affect the biological diversity of soils. At the basin scale, erosion processes associated with land-use change can be further intensified by infrastructure-related surface disturbances, and such effects have been quantified using erosion modeling approaches developed for forest road slopes and similar land-use contexts (Mısırlıoğlu, Gümüş & Yoshimura, 2022; Mısırlıoğlu & Gümüş, 2024).

Biological diversity is one of the elements most affected by land changes. The shrinking of forests, wetlands, and pastures has led to the loss of habitats for many species. The fragmentation of natural habitats has weakened interactions between species, leading to a decline in genetic diversity and a reduction in the resilience of ecosystems (Sala et al., 2000).

Rapid changes in land use pose a serious threat, particularly to endemic species, and make it challenging to conserve biological diversity. The Yeşilırmak Basin, located in the Black Sea Region of Turkey, is home to many endemic plant species. However, forest fragmentation and agricultural expansion are reducing the habitats of these species. Species loss directly affects societies not only ecologically but also in terms of medical, economic, and cultural values (Cardinale et al., 2012).

The effects of land changes on natural resources in Turkey between 2000 and 2020 are clearly visible in data from TÜİK, FAO, CORINE, and DSİ. Per capita water resources have decreased by more than 20%, and wetlands have suffered a 15% loss. Agricultural areas have shrunk by 4 million hectares, and pasture areas by 3 million hectares. Although forest areas appear to have increased in official records, there have been qualitative losses and fragmentation. In terms of biological diversity, the number of species on the red list has increased by 20% (TÜİK, 2001–2020; FAO, 2016; EEA, 2017; DSİ, 2020).

Table 1. The effects of land use changes on natural resources in Turkey (2000–2020) (TÜİK, 2001–2020; FAO, 2016; EEA, 2017; DSİ, 2020)

Natural Resources	2000 Status	2020 Status	Results
Water (m³)	Per capita ~1,650 m³ water, wetlands ~1.2 million ha	Per capita ~1,300 m³ water, wetlands ~1.2 million ha	Risk of water scarcity, decline in groundwater levels, floods–droughts
Soil (ha)	27 million ha of farmland, 14 million ha of pasture	23 million ha of farmland, 11 million ha of pasture	Erosion, loss of productivity, desertification
Forest (ha)	20.7 million ha forest	23 million ha of forest (qualitative loss)	Forest fragmentation, weakening of ecosystem functions
Biodiversity	Relatively balanced ecosystem, species under less threat	Habitat loss, 20% increase in red-listed species	Species loss, decrease in ecosystem resilience

The effects of land changes on natural resources are also evident in socio-economic terms. The depletion of water resources threatens food security by reducing agricultural production; the loss of soil fertility limits rural employment opportunities; and the loss of biodiversity leads to a decline in potential economic activities such as ecotourism and non-timber forest products (turner et al., 2007). These processes accelerate rural migration, increasing infrastructure and unemployment problems in cities and reshaping the social structure.

4. Land Use Changes and Forests

Forests play a decisive role in both the natural environment and socio-economic structures as one of the most fundamental components of global ecosystems. They play a critical role in mitigating the adverse effects of climate change due to their regulation of the carbon cycle, their role as hosts for biological diversity, their control of water flows, and their prevention of soil erosion (Kurdoğlu & Avcıoğlu Çokçalışkan, 2011;

IPCC, 2022). However, factors such as industrialization, urbanization, population growth, and the expansion of agricultural activities over the last century have led to fundamental changes in land use, threatening the integrity of forests. These transformations in land use on a global scale have led to the fragmentation of forests, the erosion of their qualitative characteristics, and losses in ecosystem services.

When evaluated in the context of Turkey, although there has been a quantitative increase in forest areas, this increase does not always indicate a qualitative improvement—according to data from the General Directorate of Forestry (OGM), forest cover, which was 20.2 million hectares in 1973, reached 23.36 million hectares by 2023. This increase can be attributed to the combined effects of natural regeneration efforts, afforestation projects, and improvements in inventory methods. However, risks such as closed-area losses in forests, habitat fragmentation, and forest fires bring significant problems, especially at the local level (OGM, 2023).

Human activities, including urbanization, industrial zones, transportation corridors, and energy investments, fragment forest ecosystems, thereby increasing edge effects and putting pressure on biodiversity (FAO, 2024).

Population pressure and the intensity of economic activities in watersheds have accelerated changes in land use, creating intense pressure on forest areas. This situation indicates that, alongside the expansion of agricultural areas and increased irrigation activities in watersheds, there is a trend towards the reduction and fragmentation of forest areas (DSİ, 2020).

Drought management plans and reports prepared at the basin level reveal that indirect pressures are being exerted on forest ecosystems, particularly in areas with intensive agricultural activities, as water withdrawals increase (DSİ, 2020).

Remote sensing and geographic information system (GIS)-based studies conducted in the Kızılırmak Delta reveal significant changes in land use, as well as alterations to the coastline. Analyses conducted between 1987 and 2000 revealed that agricultural areas expanded, resulting in a decrease in wetlands and forested areas (Avcı et al.,, 2003).

Similarly, Landsat analyses conducted in the Black Sea coastal belt (e.g., Rize Province) revealed that transitions between forest, agricultural, and settlement areas could be quantitatively mapped over time, proving this method to be an effective tool for monitoring land change at the watershed scale. The primary drivers of land change include population growth, economic development, agricultural expansion, and infrastructure development. In particular, dam projects, hydroelectric power plants, the development of road networks, and the formation of new settlement areas in the Yeşilırmak and Kızılırmak basins have led to the fragmentation of forest ecosystems (Ceran, 2025). In addition, changes in drought regimes, fire risk, and extreme weather events caused by climate change are creating additional pressures on forests (IPCC, 2022). In this process, the carbon sink capacity of forests is decreasing, their water regulation functions are being disrupted, and the ecosystem services that rural communities obtain from forests are becoming increasingly limited.

The decline in forested areas has not only had ecological consequences but has also profoundly affected the socio-economic structure (Seyhan & Bayramoğlu, 2023). People living in forest villages have been driven into poverty by the decline in their income sources from wood, fuel, pasture, and non-wood products. This situation has increased the migration tendencies of the rural population, and the population moving from rural to urban areas has brought with it the problems of uncontrolled urbanization in cities. Thus, changes in land use have directly affected not only the natural environment but also economic and social balances (OGM, 2023).

Monitoring and analysis studies conducted at the watershed level enable these changes to be identified more clearly. Thanks to remote sensing techniques and GIS-based spatial analyses, the temporal changes and fragmentation levels of forest areas can be determined, and concrete data that guide management policies can be obtained. These methods, as in national inventory studies, also serve as a guide for decision-makers in watershed planning.

Overall, the process of land change in watersheds, combined with the effects of global climate change, has had a significant impact on forest ecosystems. Population pressure, economic activities, and climate change have led to the shrinking and fragmentation of forested areas, resulting in losses of ecosystem services. In this context, studies conducted at the watershed scale will contribute to understanding not only ecological outcomes but also social and economic transformations. At the same time, they will serve as a strategic guide for the development of sustainable natural resource management and regional development policies.

5. The Impact of Land Use Change on the Socioeconomic Structure

Land has played a pivotal role in shaping economic, social, and cultural structures, as one of the most fundamental elements of production throughout human history. Many areas, including agricultural activities, industrial production, urbanization, and transportation networks, are directly related to land use patterns. Therefore, land changes are considered not only as ecological processes but also as factors that transform the socio-economic structure of societies. The increasing population, industrialization, and globalization, primarily since the second half of the

20th century, have led to fundamental changes in land-use patterns and reshaped socio-economic balances (Lambin & Meyfroidt, 2011).

One of the most obvious reflections of land change is on agricultural production. The increasing population and rising food demand have led to the expansion of agricultural areas, which has often been achieved by converting forests, pastures, and wetlands to agricultural land. This has led to losses in soil fertility, a decline in biodiversity, and accelerated erosion (Montgomery, 2007). Overcultivation of agricultural land has reduced the organic matter content of soils, while mistakes in irrigation practices have resulted in poor water management. This process has negatively impacted the livelihoods of people living in rural areas, causing fluctuations in their agricultural income. Therefore, land changes constitute a critical problem area in terms of food security and rural employment (Tilman et al., 2002).

Industrialization and urbanization are also among the powerful determinants of land changes. The opening up of large areas of land for industrial facilities and new settlements has led to the loss of fertile agricultural land. The urbanization process has increased migration pressure on the rural population, and migration from rural to urban areas has resulted in labor distribution imbalances. Rapid population growth in cities has led to infrastructure deficiencies, unemployment, and social integration problems (Seto et al., 2011). Therefore, land-use changes have been a significant factor in reshaping the rural and urban landscapes.

The decline in forest areas has both direct and indirect effects on the socio-economic structure. A significant portion of the rural population derives its livelihood from forests; firewood, non-timber products, pastures for livestock, and ecotourism potential are fundamental components of rural life. Forest loss has led to a reduction in these resources, constricting the rural economy. In addition, the decline of forests has accelerated climate change and increased the frequency of natural disasters (floods, landslides, droughts). Thus, land changes have led to both losses in ecosystem services and an increase in economic risks (FAO, 2016).

The degradation of water resources is also a significant consequence of land changes. Excessive water use for agricultural irrigation, dam construction, urbanization, and industrial activities has negatively affected the quantity and quality of water. The degradation of water resources has resulted in losses in agricultural production, disruptions to energy production, and a decline in the quality of life for the population. These problems have also triggered social conflicts and migration dynamics. Migration is one of the most prominent consequences of land changes on the socio-economic structure. The decline in agricultural and forest resources has limited the livelihoods of rural populations, accelerating migration from rural to urban areas (Black et al., 2011). While migration has led to population decline and labor force loss in rural areas, it has created new social problems in cities, including rapid population growth, infrastructure issues, and unemployment. Thus, land changes have fundamentally transformed the demographic structure.

The effects of land changes on the socio-economic structure are multidimensional. Changes in agriculture, forestry, water, and settlement areas have a direct impact on economic activities, rural and urban lifestyles, migration dynamics, and social welfare. Therefore, the sustainable management of land changes is of great importance in terms of preserving both environmental and socio-economic balances (Ceran, 2025).

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Chapter VIII - The Role of Forest Ecosystems in Carbon Sequestration and Methodological Approaches for Accurate Assessment

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1. Introduction

Accelerating climate change has pushed the regulatory role of forest ecosystems in the global carbon cycle to an unprecedented level of importance. Forests convert atmospheric CO_2 into biomass through photosynthesis, forming the largest component of terrestrial carbon sinks and playing a key role in maintaining the global carbon balance (Friedlingstein et al., 2022; Pan et al., 2011). Accurately quantifying the annual carbon sequestration capacity of forests is therefore not only an ecological necessity, but also a strategic requirement underpinning international climate policy, carbon markets, and national greenhouse gas inventory systems (IPCC, 2021).

Forest carbon sequestration capacity must be understood as the outcome of multiple interacting processes, including annual net carbon uptake, species composition, age-class structure, canopy closure, climatic drivers, and disturbance regimes. Recent ecosystem studies emphasize that robust estimates of carbon sequestration require the joint consideration of both structural properties (e.g., tree height, volume, aboveground biomass) and functional properties (e.g., productivity, phenology, physiological stress) of forests, using complementary lines of evidence (Anderegg et al., 2020; Pugh et al., 2019).

Within this context, three main methodological families have become central to the quantification of forest carbon sequestration capacity: (i) field-based approaches that provide high accuracy at the plot and stand level, (ii) remote sensing techniques employing optical, radar, and LiDAR sensors to achieve synoptic spatial coverage, and (iii) Net Primary Production (NPP)–based productivity models that describe ecosystem carbon uptake as the balance between photosynthesis and autotrophic respiration. The literature shows that each of these approaches, when used in isolation, has important limitations; by contrast, hybrid approaches that integrate field measurements with remote sensing and NPP models tend to yield more accurate and spatially consistent estimates of carbon sequestration (Baccini et al., 2017; Duncanson et al., 2022).

In this chapter, forest carbon sequestration is treated as a complex property emerging from the interaction between ecosystem structure, function, and external forcing. The following sections present the conceptual foundations of forest carbon cycling, describe the main methodological approaches used to quantify carbon sequestration capacity, and discuss their uncertainties and complementarities within a coherent, decision-oriented framework.

1.1. The Role of Forests in the Global Carbon Cycle

Forest ecosystems constitute one of the largest components of the terrestrial carbon cycle, regulating exchanges of carbon among the atmosphere, biosphere and soils. Globally, forests store a substantial fraction of terrestrial carbon in above- and belowground biomass and soils, and they account for a large share of the annual land carbon sink (Friedlingstein et al., 2022; Pan et al., 2011). Through photosynthesis, trees absorb atmospheric CO_2 and convert it into organic matter, while autotrophic and heterotrophic respiration, decomposition, and disturbance processes return part of this carbon to the atmosphere. The net balance between these fluxes determines whether a forest functions as a net carbon sink or a net source.

At the ecosystem level, gross primary production (GPP) represents the total carbon fixed by photosynthesis, whereas autotrophic respiration (Ra) and heterotrophic respiration (Rh) return carbon to the atmosphere via plant metabolism and microbial decomposition, respectively. The difference between GPP and total ecosystem respiration (Ra + Rh) defines net ecosystem production (NEP), which is widely used as an indicator of the net carbon balance of forests (Bowman et al., 2020; Chapin et al., 2006; Luyssaert et al., 2007). This balance is highly sensitive to environmental drivers such as climate, topography, nutrient availability, stand age and species composition, as well as to the frequency and intensity of natural and anthropogenic disturbances.

Recent studies show that under ongoing climate change the role of forests in the global carbon cycle is becoming increasingly dynamic and, in some regions, more fragile. Heat waves, prolonged droughts, altered fire regimes and increasing biotic stress (e.g. insect outbreaks and pathogens) have reduced the net carbon sink strength of several forest biomes and, in extreme cases, have led to temporary or persistent carbon source behavior (Allen et al., 2010; Anderegg et al., 2020; Seidl et al., 2017). For example, severe drought years in parts of Europe and North America have been associated with sharp reductions in NEP and increased tree mortality, weakening the buffering role of forests in the climate system.

Consequently, the contribution of forests to the global carbon cycle must be understood not only in terms of their carbon storage capacity, but also as a dynamic process shaped by climatic variability, disturbance regimes and forest management. Quantifying forest carbon fluxes and stocks with robust, scale-consistent methods is therefore essential for improving global carbon budget assessments, constraining Earth system models and supporting effective climate mitigation strategies.

1.2. Aim, Scope and Structure of the Chapter

This chapter aims to provide a coherent conceptual and methodological framework for quantifying the carbon sequestration capacity of forest ecosystems. Rather than developing a new model or presenting a single case study, the focus is on synthesizing existing knowledge on how forest carbon stocks and fluxes are measured, monitored and modelled across scales—from individual stands to regions and continents. In doing so, the chapter bridges ecological theory on forest carbon dynamics with the practical requirements of climate policy, national greenhouse gas inventories and carbon market mechanisms (IPCC, 2019; IPCC, 2021).

The scope of the chapter is deliberately interdisciplinary. On the biophysical side, it covers the main carbon pools and fluxes in forests, the roles of gross primary production (GPP), net primary production (NPP) and net ecosystem production (NEP), and the key ecological and disturbance drivers that control carbon dynamics (Chapin et al., 2006; Luyssaert et al., 2007). On the methodological side, it reviews three major families of approaches to quantifying forest carbon sequestration: field-based measurements, remote sensing-based techniques and productivity/NPP-driven models. Particular emphasis is placed on hybrid approaches that combine these data sources, reflecting the direction of recent advances in global carbon monitoring (Baccini et al., 2017; Patenaude et al., 2004; Schimel et al., 2015).

The chapter is structured in five main parts. Section 2 introduces the forest carbon cycle, describing the principal carbon pools and fluxes and summarizing the ecological and disturbance processes that regulate them. Section 3 examines the main methodological approaches—field plots and allometry, optical–radar–LiDAR remote sensing, and NPP-based models—highlighting their respective strengths, limitations and domains of applicability. Section 4 discusses the major sources of uncertainty and error in forest carbon assessments, including measurement issues, scale mismatches, model assumptions and the representation of disturbances (Duncanson et al., 2022; Todd-Brown et al., 2013). Building on this, Section 5 proposes a practical decision framework to guide method selection according to study objectives, spatial and temporal scale, data availability and technical capacity. The chapter concludes by outlining key research gaps and future directions for integrating emerging observation systems, process-based models and policy needs in forest carbon sequestration assessment (Friedlingstein et al., 2022; Pan et al., 2011).

2. Forest Carbon Cycle: Processes and Controls

Forest ecosystems sit at the core of the terrestrial carbon cycle, mediating exchanges of carbon among the atmosphere, vegetation, litter, and soils over time scales ranging from hours to centuries. Forests store a substantial fraction of global terrestrial carbon in living biomass, dead organic matter, and soil organic carbon, while continuously cycling CO_2 through photosynthesis, respiration, decomposition, and disturbance-driven losses (Pan et al., 2011). How much carbon a forested landscape can retain at any given time depends not only on the size of these pools but also on the direction and magnitude of the fluxes that connect them.

From a process perspective, forest carbon dynamics are governed by the balance between gross primary production, autotrophic and heterotrophic respiration, and the suite of processes that redistribute carbon among aboveground and belowground pools. Conceptual frameworks developed over the past two decades emphasise that net ecosystem production emerges from the interaction of physiological regulation (e.g.

stomatal control, allocation patterns), stand structure (age, species composition, canopy architecture), and environmental constraints such as climate and nutrient availability (Chapin et al., 2006; Litton et al., 2007). At larger spatial scales, these processes integrate across heterogeneous stands and environmental gradients, producing emergent patterns in the CO_2 balance of boreal, temperate, and tropical forests (Luyssaert et al., 2007).

This chapter section focuses on these process-level foundations. In Section 2.1, we describe the main carbon pools and fluxes in forest ecosystems and clarify key terms such as GPP, NPP, NEP and NBP. Section 2.2 examines the ecological controls on carbon sequestration, including climate, site conditions, stand structure and biodiversity. Section 2.3 then discusses how natural and anthropogenic disturbances—such as fire, storms, insects and drought—alter the forest carbon balance and modulate the long-term sink strength of forests under a changing climate.

2.1. Carbon Pools and Fluxes

Forest ecosystems store and cycle carbon through a set of interconnected pools and fluxes that together define their role as carbon sinks or sources. At any given time, carbon is distributed across five main pools: (i) aboveground biomass (stems, branches, foliage), (ii) belowground biomass (coarse and fine roots), (iii) dead wood (standing and downed), (iv) litter (fresh and partially decomposed plant material on the soil surface), and (v) soil organic carbon (stabilized organic matter in mineral and organic horizons) (IPCC, 2019; Stuart Chapin et al., 2012). The IPCC Guidelines and numerous synthesis studies indicate that, globally, forests contain a substantial fraction of the terrestrial carbon stock, with soil and biomass together accounting for the majority of stored carbon in many biomes (Friedlingstein et al., 2022; Luyssaert et al., 2007; Pan et al., 2011).

Carbon enters forest ecosystems primarily through gross primary production (GPP), the total amount of CO_2 fixed by photosynthesis. A portion of this assimilated carbon is used to meet metabolic demands and is returned to the atmosphere via autotrophic (plant) respiration (Ra). The difference between GPP and Ra is net primary production (NPP), which represents the net annual increment of carbon in plant biomass (Chapin et al., 2006; Litton et al., 2007). Part of NPP is transferred from live biomass to litter and dead wood through leaf fall, branch breakage, root mortality and tree death, forming the input to detrital pools. Within these pools, carbon is further transformed and partly released back to the atmosphere by heterotrophic respiration (Rh) driven by microbial decomposition (Stuart Chapin et al., 2012; Todd-Brown et al., 2013).

From an ecosystem perspective, the balance between carbon gains and losses is commonly expressed as net ecosystem production (NEP = NPP – Rh). Positive NEP indicates that carbon inputs from photosynthesis exceed respiratory and decomposition losses, meaning the forest acts as a net carbon sink; negative NEP indicates a net source (Chapin et al., 2006; Luyssaert et al., 2007). When additional non-respiratory fluxes (e.g. fire emissions, harvest removals, leaching) are included, the balance is often termed net biome production (NBP), which is particularly relevant for management and policy contexts because it integrates both ecological processes and human interventions (Chapin et al., 2006). In managed or disturbance-prone forests, NBP can deviate substantially from NEP, as harvest, fire or storms can rapidly export large quantities of carbon despite high underlying productivity (Pan et al., 2011).

These pools and fluxes are not independent; rather, they form a tightly coupled system governed by climate, site conditions, species composition and disturbance regimes. For example, a warm and moist climate may increase GPP but also accelerate respiration and decomposition, altering NEP and the relative importance of biomass versus soil carbon pools (Beer et al., 2010). Similarly, stand age and structural development influence the partitioning of carbon between aboveground and belowground biomass, while repeated disturbances can gradually shift carbon from long-lived biomass into more labile litter and soil fractions (Litton et al., 2007; Luyssaert et al., 2007). Understanding how carbon moves among these pools, and how the associated fluxes respond to environmental drivers, is therefore a prerequisite for robust quantification of forest carbon sequestration capacity and for the selection of appropriate field, remote sensing and modelling approaches in later sections of this chapter.

2.2. Ecological Controls on Forest Carbon Sequestration

Forest carbon sequestration emerges from the interaction of multiple ecological controls that regulate both carbon inputs through photosynthesis and carbon losses via respiration, decomposition, and disturbance. At broad scales, climate—particularly temperature, precipitation, and atmospheric evaporative demand—sets the upper limit for forest productivity and thus potential carbon uptake. Global syntheses show that terrestrial gross and net primary production covary strongly with climatic gradients; warm, moist regions with long growing seasons generally support higher GPP and NPP, whereas cold or water-limited systems exhibit reduced carbon uptake (Beer et al., 2010; Zhao & Running, 2010). Extreme events such as heat waves and droughts can abruptly reduce carbon assimilation and increase tree mortality, shifting forests from net sinks to temporary carbon sources (Allen et al., 2010; Anderegg et al., 2020).

Water availability and atmospheric demand are particularly important at seasonal to interannual scales. Increased vapour pressure deficit and drought stress reduce stomatal conductance, photosynthesis, and growth even when soil moisture is not yet critically low (Novick et al., 2016). In many mid-latitude and boreal forests, recent increases in atmospheric demand have already weakened the carbon sink despite relatively stable precipitation, highlighting the sensitivity of sequestration to coupled water–energy constraints (Friedlingstein et al., 2022).

Nutrient availability, especially nitrogen and phosphorus, provides a second fundamental axis of control on forest carbon dynamics. Meta-analyses indicate that nitrogen limitation of NPP is globally widespread across terrestrial ecosystems, constraining the capacity of forests to translate additional CO_2 or warmth into sustained biomass accumulation (LeBauer & Treseder, 2008). In nutrient-poor or highly weathered soils, phosphorus can become co-limiting with nitrogen, particularly in tropical and subtropical forests, further restricting carbon sequestration despite favourable climatic conditions (Du et al., 2020). Forest management and atmospheric deposition may partially alleviate nutrient constraints in some temperate regions, but can also create imbalances that alter allocation patterns and carbon residence times in biomass versus soils (Jandl et al., 2007; Lal, 2005).

Stand structure, species composition, and biodiversity shape how forests respond to these climatic and edaphic drivers. Age structure influences the balance between growth and respiration: young, rapidly growing stands often exhibit high NPP but relatively low standing carbon stocks, whereas old-growth forests maintain large carbon pools and can continue to function as persistent sinks over long periods (Luyssaert et al., 2007). Structural attributes such as canopy height, leaf area, and vertical complexity modulate light interception and microclimate, thereby affecting both productivity and decomposition dynamics (Litton et al., 2007). At the same time, increasing tree species richness and functional diversity are associated with higher productivity and more stable carbon sequestration across global forests, likely due to complementary resource use and facilitative interactions among species (Liang et al., 2016; Reich, 2014).

Disturbance regimes interact with these factors to determine whether forests act as carbon sinks or sources over decadal timescales. Fire, windthrow, insect outbreaks, and pathogen epidemics can rapidly release large amounts of stored carbon, followed by multi-decadal recovery phases during which regrowing stands gradually rebuild biomass and soil carbon (Bond-Lamberty et al., 2007; Seidl et al., 2014). The net effect of disturbance on carbon sequestration depends on disturbance frequency, severity, and spatial pattern, as well as on post-disturbance regeneration pathways and management interventions (Pugh et al., 2019; Seidl et al., 2017). Under ongoing climate change, increasing disturbance intensity and extent pose a substantial risk to the long-term stability of forest carbon sinks.

Overall, forest carbon sequestration is controlled by a coupled set of climatic, edaphic, structural, and biotic factors operating across scales. Robust quantification of sequestration capacity therefore requires methods that can represent not only average productivity, but also nutrient constraints, stand development, biodiversity effects, and disturbance dynamics in an integrated way.

2.3. Disturbance and Forest Carbon Balance

Disturbances are a fundamental component of forest dynamics and a key control on whether a forest acts as a carbon sink or a carbon source. Wildfires, insect outbreaks, windthrow, droughts and storms alter stand structure, mortality rates and regeneration trajectories, thereby modifying gross primary production (GPP), ecosystem respiration and net ecosystem production (NEP). When disturbance frequency or severity increases, the balance between carbon uptake and release can shift, sometimes abruptly, from net sink to net source conditions. Long-term assessments for Europe, for example, show that the increasing area affected by fires, wind damage and insects has already reduced the continent's forest carbon storage potential, despite ongoing biomass gains in undisturbed stands (Seidl et al., 2014, 2017).

Fire is often the most immediate and visible driver of carbon loss. High-severity wildfires rapidly transfer large amounts of aboveground biomass to the atmosphere as CO_2 and other trace gases, while also consuming part of the litter and organic soil horizons (Bond-Lamberty et al., 2007; Bowman et al., 2020). Post-fire recovery trajectories depend on fire regime, site conditions and species traits; in some ecosystems, regeneration is fast enough for forests to regain their carbon sink function within decades, whereas in others repeated or unusually severe fires lead to long-term depletion of carbon stocks. Changes in climate and land use are modifying fire regimes in many regions, with more frequent extreme fire seasons projected for the coming decades, which adds further uncertainty to future forest carbon balances (Bowman et al., 2020; Seidl et al., 2017).

Drought and heat waves represent another critical disturbance pathway. Prolonged soil moisture deficits and high vapour pressure deficit reduce stomatal conductance, suppress GPP and increase tree vulnerability to hydraulic failure and biotic agents. A global synthesis of drought- and heat-induced tree mortality has documented widespread dieback episodes across biomes, indicating that even mature forests can rapidly lose large amounts of biomass under extreme climatic stress (Allen et al., 2010; Anderegg et al., 2020). Such events not only release previously stored carbon but can also reduce future sequestration capacity by altering species composition, stand density and age structure, with implications for long-term NEP and regional carbon budgets.

Many disturbance agents interact. Drought-stressed trees are more susceptible to bark beetles and pathogens, while storm damage creates fuel and structural conditions that can amplify subsequent fire severity. Empirical and modelling studies for European and North American forests suggest that, under continued climate change, combined disturbance regimes are likely to intensify, with cascading effects on regional carbon storage and feedbacks to the climate system (Amiro et al., 2010; Kurz et al., 2008; Seidl et al., 2014, 2017) These interactions highlight that disturbances cannot be treated as rare anomalies but must be explicitly incorporated into forest carbon accounting and scenario analysis.

From a methodological perspective, quantifying disturbance impacts on carbon requires integrating multiple data sources and time scales. Field plots and eddy-covariance flux measurements provide detailed information on carbon fluxes before and after disturbance events (Amiro et al., 2010; Baldocchi, 2020), while satellite time series (e.g. Landsat, Sentinel) and emerging Lidar-based products allow reconstruction of disturbance history and structural change across large areas (Kennedy et al., 2018). Robust forest carbon assessments therefore need to combine disturbance detection, severity mapping and post-disturbance recovery analyses with the approaches described in the previous sections, so that both the immediate carbon losses and the long-term regrowth dynamics are adequately captured. In addition to natural disturbances, infrastructure-related interventions such as forest road construction can indirectly affect forest carbon dynamics by altering soil structure, hydrology, and erosion processes, depending on planning and implementation quality (Ünver & Kurdoğlu, 2024).

3. Approaches to Quantifying Forest Carbon Sequestration

Quantifying forest carbon sequestration requires methods that can capture both the structural properties of forest stands and the functional dynamics of carbon fluxes over time. No single approach can fully represent this complexity across all spatial and temporal scales. Instead, a spectrum of methods has emerged—from ground-based measurements at the tree and stand level to satellite observations and process-based productivity models—each designed to address specific questions about carbon storage and fluxes.

At the core of most forest carbon assessments lies the estimation of above- and below-ground biomass from field measurements. Tree-level attributes such as diameter, height and wood density are translated into biomass and carbon using allometric equations, which have been refined for a wide range of forest types and climatic regions (Chave et al., 2014; Feldpausch et al., 2012). These plot-based measurements provide high-accuracy benchmarks and are essential for calibrating and validating large-scale models and remote sensing products.

Complementary to field inventories, remote sensing approaches exploit optical, radar and LiDAR observations to extrapolate carbon-related attributes over large areas, while net primary production (NPP) models use climate and vegetation data to represent carbon fluxes in a process-based framework (Patenaude et al., 2004; Schimel et al., 2015). Recent advances increasingly rely on hybrid approaches that combine these data streams, using field plots as ground truth, satellites for wall-to-wall mapping, and productivity models to represent temporal variability.

In the following subsections, we first introduce field-based approaches, then examine remote sensing-based methods, NPP-driven productivity models, and finally hybrid frameworks that integrate multiple data sources for more robust carbon assessments.

3.1. Field-Based Approaches

Field-based approaches remain the foundation of forest carbon quantification. They rely on direct measurements of tree and stand attributes in sample plots, which are then converted into biomass and carbon using allometric relationships and wood density information. Standard forest inventory variables—diameter at breast height (DBH), total height, species identity and, where available, crown dimensions—are combined with species- or region-specific allometric models to estimate aboveground biomass at the tree and stand level (Chave et al., 2014; Feldpausch et al., 2012). When multiplied by a carbon fraction (typically 0.47–0.50 of dry biomass), these estimates provide robust stand-level carbon stocks in living biomass.

Permanent and temporary plot networks serve different but complementary purposes. Permanent plots allow repeated measurements over time and are therefore crucial for quantifying growth, mortality and recruitment, as well as for deriving stand-level net biomass increment and carbon accumulation rates. Temporary plots, when sampled with sufficient intensity and stratification, can characterise spatial variability in biomass across regions or forest types. In both cases, careful sampling design—accounting for stand structure, species composition, site quality and management history—is essential to ensure that plot-level measurements are representative of larger areas (Chapin et al., 2006; Pretzsch, 2010).

Field-based approaches are not limited to tree measurements. Soil carbon stocks are assessed through soil sampling, bulk density measurements and laboratory analyses of organic carbon content, often stratified by depth. Dead wood, litter and coarse woody debris are quantified using line-intersect or fixed-area sampling methods. Together, these measurements allow a full accounting of major forest carbon pools—living biomass, dead organic matter and soil organic carbon—as defined in international guidelines such as the IPCC inventory framework (IPCC, 2019).

Despite their high accuracy at the plot scale, field-based methods face important limitations when applied to large regions. They are labour-intensive, time-consuming and costly, particularly in remote or topographically complex terrain. Heterogeneous and mixed-species stands require larger sample sizes to capture variability, and uncertainties in allometric equations can become significant when models are transferred beyond the conditions for which they were developed (Réjou-Méchain et al., 2017). As a result, field measurements are increasingly used in combination with remote sensing and modelling approaches—serving as calibration and validation data rather than as the sole basis for regional carbon estimates (Ghosh & Behera, 2018; Schimel et al., 2015).

3.2. Remote Sensing-Based Approaches

Remote sensing has become a core component of forest carbon assessment because it overcomes the spatial limitations of field plots and provides consistent observations across large regions and long time periods. Optical satellite systems such as Landsat and Sentinel-2 supply repeated surface reflectance measurements that can be transformed into vegetation indices (e.g., NDVI, EVI), which are widely used as proxies for canopy greenness, leaf area and photosynthetic activity (Huete et al., 2002). The Sentinel-2 Multispectral Instrument (MSI), with 10–20 m spatial resolution and red-edge bands, is particularly useful for monitoring forest condition, detecting disturbances and parameterizing productivity models in heterogeneous landscapes (Drusch et al., 2012).

Beyond broad-band vegetation indices, time series of optical data underpin many estimates of gross primary production (GPP) and net primary production (NPP). In these approaches, satellite-derived measures of absorbed photosynthetically active radiation are combined with light-use efficiency models to map terrestrial carbon uptake (Zhao & Running, 2010). Optical time series also enable detection of anomalies—such as drought-induced reductions in greenness—that are linked to declines in NPP and shifts in forest carbon balance.

Synthetic aperture radar (SAR) provides complementary information by transmitting microwave signals that interact with forest structure. C-band and L-band SAR backscatter is sensitive to stem volume, canopy water content and surface roughness, allowing biomass and disturbance patterns to be inferred even under persistent cloud cover (Le Toan et al., 2011; Santoro et al., 2011). Upcoming missions such as ESA's

BIOMASS are explicitly designed to retrieve global forest biomass using P-band radar, further strengthening the role of SAR in carbon mapping (Le Toan et al., 2011).

Lidar (light detection and ranging) adds a three-dimensional perspective by directly sampling canopy height profiles and vertical structure. Airborne lidar campaigns have demonstrated that canopy height and gap distribution are strong predictors of above-ground biomass, and a large body of work now quantifies how lidar-based structure metrics reduce uncertainty in biomass estimates compared to models relying solely on optical data (Zolkos et al., 2013). The Global Ecosystem Dynamics Investigation (GEDI) extends this capability to the spaceborne domain, providing footprint-scale lidar waveforms over the world's forests that can be used to derive canopy height, relative height metrics and above-ground biomass density (Dubayah et al., 2020; Duncanson et al., 2022). By integrating GEDI footprints with wall-to-wall optical imagery, global maps of forest canopy height and carbon stocks with substantially improved spatial detail have been produced (Potapov et al., 2021).

Recent syntheses emphasize that no single sensor type is sufficient for robust forest carbon assessment. Optical data capture phenology and canopy condition, radar is particularly valuable in cloudy or high-latitude regions and for dense canopies, and lidar provides the most direct constraints on vertical structure and above-ground biomass (Schimel et al., 2015). Multi-sensor approaches that fuse these data streams—often in combination with field plots and ecosystem models—are therefore increasingly adopted to exploit the strengths of each system and to reduce uncertainties in estimates of forest biomass, NPP and long-term carbon sequestration.

3.3. NPP-Based Productivity Models

Net primary production (NPP)–based models quantify forest carbon sequestration by linking photosynthetic carbon uptake and autotrophic respiration at ecosystem scale. In most satellite-driven frameworks, gross primary production (GPP) is first estimated from absorbed photosynthetically active radiation and a light-use efficiency term, and NPP is then obtained by subtracting maintenance and growth respiration (Beer et al., 2010). These models provide a mechanistic yet tractable way to approximate how climate, canopy structure and physiological constraints jointly determine the annual net carbon gain of forests.

The MODIS MOD17 family of products is the most widely used global implementation of this approach. It combines meteorological data (radiation, temperature, vapour pressure deficit) with land-cover information and biome-specific parameters to generate consistent, wall-to-wall maps of GPP and NPP at 1 km spatial resolution and annual to 8-day temporal resolution (Patenaude et al., 2004; Running & Zhao, 2015). Evaluations against eddy-covariance flux towers and inventory data in temperate and boreal forests have shown that MODIS NPP captures broad spatial gradients in productivity and interannual variability, although performance can vary by biome and climate regime (Beer et al., 2010; Turner et al., 2005).

Climatic extremes represent a major control on NPP-based estimates of forest carbon sequestration. Global analyses have demonstrated that severe droughts and heat waves can substantially reduce terrestrial NPP, temporarily weakening or even reversing the land carbon sink (Zhao & Running, 2010). These events alter stomatal conductance, canopy water status and photosynthetic capacity, leading to sharp declines in GPP and, in some cases, increased mortality that further affects future NPP. As a result, NPP models must be carefully parameterized to represent the sensitivity of forests to water and energy limitations across different regions.

Despite their strengths, NPP-based models also introduce specific uncertainties. Light-use efficiency parameters, temperature and moisture scalars, respiration coefficients and assumptions about carbon allocation all influence the magnitude and spatial pattern of estimated NPP (Patenaude et al., 2004; Running & Zhao, 2015). In addition, the common practice of converting NPP to carbon using a fixed carbon fraction does not fully reflect species- and tissue-specific variability. These limitations underscore the need to interpret NPP-derived carbon sequestration not as an exact measurement, but as a physically consistent, spatially explicit indicator that should be calibrated and validated with field data, biomass inventories and, where possible, independent remote-sensing products.

3.4. Hybrid Models and Data Integration

Hybrid approaches combine field plots, remote sensing data and process- or data-driven models to produce spatially explicit estimates of forest carbon stocks and fluxes. In these frameworks, ground measurements provide the reference information on biomass and carbon densities, while satellite and airborne observations extend this information in space and time. Typically, structural metrics derived from LiDAR or radar (e.g. canopy height, cover, vertical profile) and spectral indices from optical sensors are related statistically or mechanistically to plot-level biomass, and the resulting models are then applied wall-to-wall to generate regional or global maps of aboveground carbon density and its change over time (Baccini et al., 2012; Gonzalez et al., 2010; Zolkos et al., 2013).

A growing body of work illustrates how such integration improves both accuracy and completeness of forest carbon assessments. In tropical forests, for instance, combining plot inventories with LiDAR-derived canopy height and optical imagery has been shown to reduce uncertainty in aboveground biomass estimates compared with single-sensor approaches, particularly in structurally complex and species-rich stands (Baccini et al., 2012; Gonzalez et al., 2010). Meta-analyses of LiDAR-based studies further demonstrate that model performance depends strongly on the choice of structural metrics, plot design and the way field and remote sensing data are co-registered, underscoring the importance of rigorous sampling and model validation strategies (Zolkos et al., 2013).

At larger scales, hybrid models often use Earth observation products not only to estimate biomass but also to drive or constrain productivity and carbon-cycle models. Spaceborne missions and global data streams such as MODIS vegetation indices, Landsat and Sentinel surface reflectance, and LiDAR-based canopy structure from missions like GEDI are increasingly combined with ecosystem models to monitor forest carbon fluxes and their interannual variability (Potapov et al., 2021; Schimel et al., 2015). These integrated systems are particularly powerful for capturing both carbon gains from regrowth and losses from deforestation and degradation, thereby supporting regional-to-global carbon budgeting (Baccini et al., 2017; Duncanson et al., 2022).

Hybrid approaches also provide a pragmatic pathway towards Meeting monitoring, reporting and verification (MRV) requirements in climate policy and carbon markets. By explicitly linking plot-based estimates, satellite observations and model outputs, they enable transparent uncertainty quantification and facilitate updates as new data streams become available. In practice, the design of these systems involves choices about which sensors to combine (e.g. optical + LiDAR, radar + LiDAR), which variables to predict (biomass, canopy height, NPP, NEP) and how to propagate errors from plots, sensors and models. When carefully implemented, however, hybrid models represent the current state of the art for quantifying forest carbon sequestration across scales from individual stands to continents while maintaining a clear connection to field-based ecological understanding (Potapov et al., 2021; Schimel et al., 2015).

3.5. Comparative Assessment of Methods

Field measurements, remote sensing techniques and NPP-based productivity models each capture different facets of forest carbon dynamics, and their relative strengths and limitations are strongly scale- and question-dependent. Plot-based inventories remain the primary benchmark for aboveground biomass and carbon estimation because they directly measure tree dimensions and species identity and can be linked to locally calibrated allometric equations (Chave et al., 2014; Feldpausch et al., 2012). When appropriate allometries are used, aboveground biomass in structurally complex forests can be estimated with relatively low bias; however, uncertainty increases in highly diverse or poorly sampled forest types, and spatial coverage is inherently limited by the cost and logistics of field campaigns (Chave et al., 2014; Duncanson et al., 2022).

Remote sensing approaches address this limitation by providing spatially continuous information over regional to global scales. Optical indices such as NDVI and EVI are effective proxies for canopy greenness and photosynthetic activity, yet they saturate in dense canopies and are sensitive to clouds, aerosols and illumination geometry (Huete et al., 2002; Nemani et al., 2003). Radar systems, particularly at L- and P-bands, penetrate the canopy and are sensitive to forest structure and biomass, but require complex backscatter modelling and are influenced by surface roughness and moisture conditions (Le Toan et al., 2011). Spaceborne lidar, exemplified by NASA's GEDI mission, directly samples the vertical canopy profile and has demonstrated substantial improvements in aboveground biomass density estimates when combined with coincident field plots and airborne lidar (Dubayah et al., 2020; Duncanson et al., 2022). The main limitations of lidar are its sampling footprint (rather than wall-to-wall coverage) and the need for robust upscaling strategies using complementary optical or radar imagery (Potapov et al., 2021; Schimel et al., 2015).

NPP-based models provide a complementary, process-oriented view by quantifying carbon fluxes rather than static stocks. Satellite-driven NPP products, such as those derived from the MODIS MOD17 algorithm, have enabled consistent monitoring of terrestrial productivity over multiple decades and have been extensively evaluated against flux-tower and inventory data (Turner et al., 2005). These models are well suited to analysing temporal dynamics, climatic controls on productivity and interannual anomalies such as drought-induced reductions in carbon uptake (Nemani et al., 2003; Zhao & Running, 2010). However, they rely on parameterisations of light-use efficiency, respiration and stress responses that may not fully capture species-specific physiology or local site conditions, leading to systematic uncertainties in absolute NPP magnitude and its translation into biomass increments (Beer et al., 2010); Schimel et al., 2015).

Taken together, these three approaches form a continuum rather than competing alternatives. Field plots provide ecological detail and calibration data; remote sensing translates this information into spatially explicit maps of structure and, indirectly, biomass; NPP models describe how rapidly carbon is being added to those stocks through time (Schimel et al., 2015). Integrated assessments that fuse plot, lidar and optical/radar data now achieve demonstrably lower uncertainties in aboveground biomass and carbon balance than any single data source alone, especially when disturbance history and regrowth are explicitly represented (Baccini et al., 2012; Duncanson et al., 2022). For operational forest carbon accounting—whether for national greenhouse-gas inventories or project-level monitoring—method selection therefore hinges on the required spatial and temporal resolution, the dominant sources of uncertainty, and the availability of ground data to anchor remote- and model-based estimates.

4. Uncertainty and Error Sources in Forest Carbon Assessments

Assessing forest carbon sequestration inevitably involves uncertainty, because each major approach—field measurements, remote sensing, and productivity-based models—relies on imperfect data, scaling assumptions and model structures. These uncertainties propagate from tree-level measurements to stand, landscape and global estimates, and they directly affect the reliability of carbon budgets and climate policy indicators (IPCC, 2019; Todd-Brown et al., 2013). Recent syntheses of the terrestrial carbon cycle and forest biomass estimation stress that explicit treatment and quantification of uncertainty is now a core requirement for credible carbon assessments (Chave et al., 2014; Schimel et al., 2015).

4.1. Uncertainty in Field-Based Measurements

Field plots are often treated as "ground truth", yet they contain their own sources of error. Measurement uncertainty arises from imprecise diameter and height readings, plot boundary errors and GPS inaccuracies, all of which can bias estimates of stand basal area and volume (Chave et al., 2014). Studies in tropical and temperate forests have shown that tree height measurement errors alone can translate into several percent uncertainty in plot-level biomass (Feldpausch et al., 2012).

Sampling design is another major driver of uncertainty. In structurally heterogeneous or mixed-species stands, sparse or unevenly distributed plots may fail to capture the full range of tree sizes, species and site conditions, leading to biased extrapolations when plot data are upscaled to the landscape or region (Réjou-Méchain et al., 2017). Allometric equations add a further layer of model uncertainty: their parameters may not be fully representative of local species or size ranges, and small differences in allometric form can lead to large differences in estimated above-ground biomass when integrated over extensive areas (Chave et al., 2014).

Taken together, these factors mean that field data provide a high-value but not error-free reference. Robust carbon assessments therefore require explicit reporting of measurement protocols, sampling intensity and the choice of allometric models, as well as, where possible, statistical propagation of these uncertainties.

4.2. Uncertainty in Remote Sensing-Based Estimates

Remote sensing extends carbon monitoring to regional and global scales, but each sensor type introduces its own limitations. Optical sensors such as Landsat and Sentinel-2 provide rich spectral information on canopy greenness and phenology, yet they are sensitive to clouds, shadows, atmospheric aerosols and topographic effects (Zhu & Woodcock, 2014). In dense forests, vegetation indices can saturate at high leaf area, reducing sensitivity to further biomass increases and leading to underestimation of carbon stocks in high-biomass stands (Fensholt & Proud, 2012; Huete et al., 2002).

Radar systems offer all-weather observation capabilities and sensitivity to canopy structure and moisture, but backscatter is influenced by surface roughness, soil moisture and incidence angle, which complicates the inversion from radar signal to biomass (Santoro et al., 2011). Lidar provides the most detailed three-dimensional information on canopy height and vertical structure and is therefore extremely powerful for constraining above-ground biomass estimates; however, sample-based missions such as GEDI do not cover every location continuously, and footprint density, terrain and canopy complexity all influence retrieval quality (Dubayah et al., 2020; Duncanson et al., 2022).

Cross-sensor harmonization is an additional source of uncertainty. Differences in spatial resolution, spectral response and acquisition geometry between sensors make it non-trivial to combine multi-sensor time series or to transfer biomass models from one platform to another (Schimel et al., 2015). As a result, remote-sensing-based biomass maps typically carry significant, spatially varying uncertainty that must be accounted for when they are used in carbon accounting frameworks.

4.3. Uncertainty in NPP and Productivity-Based Models

Net primary production (NPP) products and process-based productivity models estimate the flux of carbon into vegetation, rather than the standing stock. They therefore depend on a suite of biophysical parameters and climate inputs. Satellite-driven NPP algorithms commonly rely on light-use efficiency formulations, which assume relationships between absorbed radiation, temperature, moisture stress and photosynthetic efficiency (Running et al., 2004; Turner et al., 2005). Errors or oversimplifications in these relationships propagate directly into NPP estimates.

Global studies have shown that drought events can cause large, abrupt reductions in NPP that are difficult to capture with simple stress scalars, leading to discrepancies between modelled and observed carbon fluxes during extreme years (Beer et al., 2010; Zhao & Running, 2010). In addition, many models convert NPP to carbon using fixed carbon fractions and root–shoot ratios, despite evidence that these parameters vary among species, climates and site conditions (Litton et al., 2007; Todd-Brown et al., 2013). This structural simplification contributes to systematic biases and inter-model spread in vegetation and soil carbon projections.

4.4. Scale Mismatches

A pervasive source of uncertainty in forest carbon assessments is the mismatch of spatial and temporal scales among different data sets. Field plots typically represent areas of a few hundred to a few thousand square metres; Lidar footprints for space-borne missions are on the order of tens of metres; optical satellite pixels range from 10–30 m for Sentinel-2 and Landsat to 500 m or coarser for many global NPP products (Duncanson et al., 2022; Potapov et al., 2021). When these heterogeneous data sources are combined—such as using plot data to calibrate satellite models—differences in spatial support can introduce “scale bias”, particularly in highly heterogeneous landscapes where a single coarse pixel contains multiple stand structures or land-cover types (Schimel et al., 2015).

Temporal scale is equally important. Plots may be remeasured every few years, whereas satellites acquire data at weekly to monthly intervals but are affected by data gaps from clouds or sensor issues (Zhu & Woodcock, 2014). Aligning these time scales is challenging, especially when assessing the impact of short-lived disturbance events or interannual climate variability on carbon dynamics.

4.5. Parameter and Model-Structure Uncertainty

Many models used to estimate forest carbon stocks or fluxes depend on parameters that are incompletely constrained by observations. Examples include species-specific wood density, carbon fractions in different tissues, allocation patterns between above- and below-ground biomass, decomposition rates and fire emission factors (Chave et al., 2014; Todd-Brown et al., 2013). These parameters are often drawn from limited data sets or transferred from other regions, which may not reflect local ecological conditions.

Model-structure uncertainty arises when the representation of ecological processes differs among models—for instance, how they simulate photosynthetic responses to water stress, mortality under extreme events or the fate of carbon after disturbance. Comparative analyses of terrestrial carbon models show that such structural differences are a major contributor to the spread in simulated vegetation and soil carbon trajectories, even when models are driven by the same climate data (Friedlingstein et al., 2022; Schimel et al., 2015).

4.6. Incomplete Representation of Disturbances

As discussed in Section 2.3, disturbances such as fire, storms, insect outbreaks and drought can rapidly alter forest carbon balances.

However, many carbon models either simplify disturbance regimes or omit certain disturbance types, leading to underestimation of variability and risk (Seidl et al., 2014, 2017). Long-term assessments for Europe, for example, indicate that increases in area affected by wind, fire and bark beetles have already offset part of the carbon sink provided by forest growth, and that continued climate change is likely to amplify this effect (Seidl et al., 2014).

Capturing disturbance dynamics requires detailed information on event timing, severity and recovery, which is only partially available. While high-resolution optical time series and change-detection algorithms based on Landsat data have improved the detection of disturbance events, translating these signals into accurate carbon flux estimates remains a methodological challenge—especially when multiple disturbance agents interact (Kennedy et al., 2018; Zhu & Woodcock, 2014).

4.7. Strategies to Reduce and Communicate Uncertainty

Recent advances offer several pathways to reduce and better characterize uncertainty in forest carbon assessments. First, combining multiple remote-sensing data sources—such as integrating Lidar-derived structure with optical indices and radar backscatter—has been shown to improve biomass estimates and reduce errors compared with single-sensor approaches (Ghosh & Behera, 2018; Gonzalez et al., 2010; Jiang et al., 2022; Zolkos et al., 2013). Second, using field plots explicitly for calibration and validation, rather than as unquestioned "truth", allows for formal propagation of measurement and sampling errors into modelled products (Chave et al., 2014).

Third, ensemble modelling and data-assimilation frameworks can incorporate parameter and structural uncertainty by comparing multiple models or by updating state variables as new observations become available (Friedlingstein et al., 2022; Schimel et al., 2015). Finally, transparent reporting of uncertainty—through confidence intervals, error maps and clear documentation of data limitations—is essential if forest carbon estimates are to be used in national greenhouse-gas inventories, carbon markets and climate-risk assessments in a scientifically robust way (IPCC, 2019).

5. A Decision Framework for Method Selection

Quantifying forest carbon sequestration can be approached through field-based measurements, remote sensing, and productivity or NPP-based models, but in practice the “best” method is always context-dependent. International guidance documents emphasise that countries and research teams should choose methods according to national circumstances, available data, technical capacity and required accuracy, rather than aiming for a single universal protocol. Building an explicit decision framework helps make these choices transparent, repeatable and aligned with both scientific and policy needs.

5.1. Key Decision Axes: Scale, Purpose, Data and Capacity

A useful way to structure method selection is to organise it along four main decision axes:

1. **Spatial and temporal scale.**

The appropriate method strongly depends on whether the assessment targets a stand, a landscape, a region or an entire country, and whether it focuses on a single point in time or on long-term dynamics.

- Stand- and project-scale applications (e.g. afforestation projects, forest management trials) usually require detailed field inventories and, where available, high-resolution airborne or terrestrial Lidar, because project-level MRV often hinges on plot-level accuracy and traceability.
- Regional to national-scale assessments benefit more from wall-to-wall optical and radar satellite data combined with coarser, but well-distributed, field plots (Pan et al., 2011; Schimel et al., 2015). NPP-based models become

particularly relevant when analysing multi-year trends over large areas, for instance in support of carbon budget studies or climate model evaluation (Friedlingstein et al., 2022).

2. **Primary objective of the assessment.**

The choice of methods also hinges on whether the main goal is to estimate:

- **Carbon stocks** (e.g. above-ground biomass, soil organic carbon),
- **Carbon fluxes** (e.g. annual NPP, NEP), or
- **Changes and drivers** (e.g. disturbance impacts, regrowth, management scenarios).

Field inventories and Lidar are particularly strong for stock estimation in above-ground biomass pools, and are therefore central to many MRV systems and REDD+ applications. In contrast, flux-oriented questions (interannual variability, drought impacts, long-term trends) require time-series approaches combining NPP products, meteorological data and, where available, eddy-covariance flux measurements (Baldocchi, 2020; Beer et al., 2010). Disturbance-focused analyses (fire, windthrow, insect damage) rely heavily on dense optical and radar time series (e.g. Landsat, Sentinel-1/2) to detect, map and characterise events over several decades (Kennedy et al., 2018; Zhu & Woodcock, 2014).

3. **Data availability and monitoring infrastructure.**

Many countries have long-running National Forest Inventories (NFIs), meteorological networks and at least some capacity to access and process satellite data. The IPCC Guidelines explicitly distinguish Tier 1, Tier 2 and Tier 3 approaches based on the level of country-specific data and model sophistication used for greenhouse gas reporting (IPCC, 2019).

- **Data-poor situations** often require starting with Tier 1 or simple Tier 2 methods: default emission factors, sparse field plots and freely available satellite imagery.
- **Data-rich situations**—for example where dense plot networks, permanent sample plots, Lidar campaigns and computing infrastructure exist—can implement Tier 3 approaches that integrate spatially explicit models, high-resolution remote sensing and continuous time series (Schimel et al., 2015).

4. **Technical capacity, costs and uncertainty tolerance.**

Method selection must balance desired accuracy with available expertise, budget and institutional stability. Field measurements and Lidar campaigns are comparatively expensive and logistically demanding, but they provide critical calibration and validation information. Satellite-only approaches are cost-effective at large scales, yet they require strong skills in image processing, radiometric correction and statistical modelling.

International experience shows that robust forest carbon monitoring systems usually rely on mixed designs, where a modest but well-maintained plot network is systematically linked to satellite-derived variables, rather than pursuing extremely dense plot networks or purely remote sensing solutions (FAO, 2016; IPCC, 2019; Jandl et al., 2007). Explicit uncertainty analysis—propagating errors from measurements, allometric equations, model parameters and classification steps—is increasingly seen as a non-optional component of method selection and reporting (IPCC, 2019; Schimel et al., 2015).

Taken together, these decision axes help structure the transition from simple, data-limited approaches to more advanced integrated systems as data availability and technical capacity increase. They also make it easier to justify why a given combination of field, remote-sensing and modelling tools is appropriate for a particular application or policy context.

5.2. Typical Application Scenarios

To make the decision framework operational, it is useful to map common forest-carbon applications onto indicative method combinations rather than prescribing a single "best" technique. Four broad scenarios illustrate how different tools can be combined:

1. **National greenhouse-gas inventories and REDD+ reporting.**

Countries preparing Land Use, Land-Use Change and Forestry (LULUCF) or REDD+ reports under the UNFCCC must satisfy transparency, consistency and uncertainty requirements while working within limited budgets and institutional constraints (IPCC, 2019). In this context:

- A sample-based NFI provides plot-level biomass and emission factors.
- Medium-resolution satellite data (Landsat, Sentinel-2) supply wall-to-wall activity data (area change, disturbance mapping).
- Simple biomass or NPP models, calibrated with national plot data, bridge gaps in space and time.

This combination typically corresponds to upper Tier 2 or Tier 3 reporting, and is aligned with guidance from the Global Forest Observations Initiative (FAO, 2025).

2. **Landscape-scale planning and restoration prioritisation.**

For regional planning—e.g. identifying restoration hotspots, assessing trade-offs between timber production and carbon, or designing nature-based climate solutions—relative differences and spatial patterns are often more important than absolute national totals. Here,

- Optical and radar satellite products are used to map canopy cover, disturbance history and regrowth trajectories.

- Field plots and, where feasible, airborne or UAV-Lidar provide structural detail for calibration and local validation.
- Simple productivity indicators (e.g. multi-year NPP averages) help rank areas by long-term sequestration potential (Beer et al., 2010; Liang et al., 2016).

6. Conclusions and Future Perspectives

Forest ecosystems will remain at the core of the global carbon cycle debate for the coming decades. Current estimates indicate that forests account for a large and persistent fraction of the terrestrial carbon sink, despite increasing pressures from land-use change and climate-driven disturbances. This chapter has shown that quantifying forest carbon sequestration is not a single "measurement problem", but a multi-scale, multi-method exercise that must integrate processes from tree-level physiology to continental-scale disturbance regimes.

Three main methodological pillars structure contemporary forest-carbon assessment:

- **Field-based approaches**, which provide the most detailed and accurate information on stand structure, biomass and species-specific allometry;
- **Remote sensing**, which offers spatially continuous observations of canopy properties, forest structure and disturbance history;
- **Productivity models**, especially satellite-driven GPP/NPP products, which translate climate and canopy information into annual carbon fluxes.

Taken in isolation, each pillar suffers from recognisable limitations—sampling costs and representativeness for plots, atmospheric and geometric artefacts for remote sensing, and parameter and structural uncertainties for models. Yet when combined in hybrid frameworks (e.g., plot-calibrated biomass maps, NPP constrained by flux towers and satellite indices, disturbance-aware time-series analyses), these approaches provide a much more robust picture of forest carbon dynamics than any individual method could deliver. This integration is precisely the direction encouraged by recent global carbon-budget assessments and by the emerging generation of space-based observing systems.

From a policy perspective, methodological rigor is not an academic luxury but a formal requirement. The 2019 Refinement to the 2006 IPCC Guidelines explicitly links higher-tier reporting (Tier 2–3) to the use of country-specific data, spatially explicit models and, where possible, remote-sensing-based monitoring of forest carbon stocks and fluxes. National greenhouse-gas inventories, NDC tracking and carbon market mechanisms all depend on MRV systems that can withstand technical scrutiny and political negotiation. In this context, field plots, satellite observations and NPP models should be viewed as complementary building blocks of a single MRV architecture rather than as competing alternatives.

Looking ahead 10–20 years, the role of new satellite missions will be particularly transformative. ESA's BIOMASS P-band radar mission is designed specifically to map global above-ground forest biomass, targeting densely forested regions where optical and shorter-wavelength radar sensors saturate. Together with ongoing and planned lidar and L-/S-band radar missions, these systems will markedly reduce uncertainties in large-scale biomass estimates, improve the detection of degradation (not just deforestation) and allow more accurate tracking of post-disturbance regrowth. Coupled with advances in machine learning and data-fusion techniques, they will support near-real-time, wall-to-wall monitoring capabilities that were not technically feasible when current guidelines were written.

Given this rapidly evolving context, three strategic priorities emerge for future work on forest-carbon assessment and management:

1. **Tight integration of methods across scales**
    - Systematic use of permanent plots and flux towers to calibrate and validate biomass maps and NPP products;
    - Harmonised processing chains that combine optical, radar and lidar data for structure, productivity and disturbance mapping.
2. **Explicit treatment of uncertainty and disturbance**
    - Routine propagation of measurement, model and scaling uncertainties into final carbon estimates;
    - Disturbance-aware modelling that couples long time-series of satellite observations with process-based representations of fire, drought, insects and storms.
3. **Alignment with MRV and carbon-policy needs**
    - Designing assessment frameworks from the outset to satisfy Tier 2–3 IPCC requirements, including transparency, reproducibility and traceability of methods;
    - Using new biomass and canopy-height products (e.g. BIOMASS-derived maps) to support national inventory improvements and credible carbon-crediting schemes.

Ultimately, forests will continue to provide a critical—though not limitless—buffer against anthropogenic CO_2 emissions. The challenge for the scientific community is to refine and integrate the available methods to characterise this buffer with sufficient accuracy, spatial detail and temporal frequency to support both robust climate science and effective decision-making. The framework outlined in this chapter is intended as a step toward that goal, offering a methodological bridge between ecological understanding, Earth-observation capabilities and the stringent demands of contemporary climate policy.

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