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FOREST RESTORATION AND AGROFORESTRY AS NATURAL CLIMATE SOLUTIONS

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Abstract. *The article examines forest-based climate solutions from 2020 to 2050, including deforestation avoidance, forest restoration, and agroforestry. It analyzes regional mitigation potential, carbon sequestration, biodiversity benefits, and socio-economic factors essential for sustainable implementation and climate change mitigation.*
Keywords: *Forest natural climate solutions, Climate change mitigation, Afforestation, Reforestation, Agroforestry, Forest conservation, Carbon sequestration, Sustainable development, Forest management, Greenhouse gas emissions.*

Introduction

In the context of the Paris Agreement, which sets the goal of limiting global warming to well below 2°C above pre-industrial levels, with efforts to limit the temperature increase to 1.5 °C, urgent implementation of climate mitigation measures is critically necessary. Natural Climate Solutions (NCS), which include the conservation, restoration, and improved management of land resources, occupy a special place in this effort [1].

International research has identified twenty natural strategies that could provide up to 37 % of the economically feasible CO_2 emission reductions needed by 2030 to meet the Paris Agreement targets [1]. Approximately two-thirds of the NCS potential comes from forest-related solutions – forest restoration, preservation of existing forests, and improved forest management. These solutions contribute not only to greenhouse gas emission reductions but also to biodiversity enhancement, restoration of degraded lands, and increased ecological resilience of landscapes [1].

Successful achievement of the Paris Agreement's climate goals requires integrating natural solutions into national and international strategies. Research findings have underpinned global initiatives such as the Bonn Challenge and the United Nations Decade on Ecosystem Restoration, which aim for large-scale restoration of degraded landscapes [1, 30].

Analysis by the Intergovernmental Panel on Climate Change (IPCC) indicates that current national commitments under the Paris Agreement are insufficient to meet the set targets, highlighting the need to strengthen adaptation and mitigation measures [3]. Awareness is growing about the potential of forest restoration for climate mitigation and adaptation, biodiversity conservation, and land degradation reversal [31, 5].

At the same time, implementing forest NCS involves challenges such as land-use conflicts and trade-offs between environmental, social, and economic goals. Potential negative side effects arise from competition for land with agriculture and other priorities [6]. Therefore, it is essential to develop integrated approaches that consider local conditions, engage local communities, and ensure a balance between ecological and socio-economic factors.

This article examines the concept of Forest Landscape Restoration (FLR), which includes reforestation, agroforestry, silvopastoral systems, plantation establishment, and restoration of degraded forests but excludes afforestation of natural non-forest ecosystems such as steppes, savannas, or wetlands [7, 8, 32]. This emphasizes the importance of ecologically sound and contextually adapted approaches.

Thus, forest restoration is one of the most promising strategies to combat climate change, significantly enhancing both mitigation and adaptation. Effective implementation requires comprehensive scientific, political, and social measures that account for potential risks and trade-offs.

Literature Review

International researchers strongly support the concept of Natural Climate Solutions (NCS) as a key element in combating climate change. Studies indicate that up to 37 % of cost-effective

CO_2 emission reductions could be achieved through NCS, with forest-based solutions – including restoration, conservation, and improved forest management – playing a central role [1]. Other research confirms that forest restoration not only has substantial potential for climate change mitigation but also contributes to biodiversity preservation, water balance regulation, and overall ecosystem resilience [2, 3].

At the same time, global scholars acknowledge various challenges in the implementation of NCS. The Intergovernmental Panel on Climate Change (IPCC) [4] emphasizes potential trade-offs associated with these approaches, particularly forest restoration. One of the main issues is competition for land resources between forest restoration, agriculture, and other socio-economic needs. This competition can result in social and ecological risks, including restricted land access for local communities, decreased food security, and altered biodiversity patterns [4]. These concerns highlight the importance of a balanced and integrated approach to forest restoration planning and implementation to avoid adverse outcomes and promote system resilience.

Forest restoration must be pursued through a landscape-level approach, known as Forest Landscape Restoration (FLR), which considers ecological, social, and economic dimensions [5, 6]. Major global initiatives such as the Bonn Challenge and the UN Decade on Ecosystem Restoration are grounded in this scientific understanding and aim to restore millions of hectares of degraded land worldwide [7].

In Ukraine, NCS – particularly forest restoration – are also viewed as promising strategies for both climate mitigation and adaptation. Ukrainian ecologists and climatologists, such as Kovalenko et al., highlight the importance of integrating forest-based NCS into national climate policies, noting the carbon sequestration potential of Ukrainian forests and their role in supporting biodiversity [8].

Studies by Bondar I. P. and Stetsenko M. V. emphasize the role of restoring degraded forest areas in conserving water resources and enhancing the resilience of agricultural landscapes under climate change conditions [9]. Ukrainian scientists also point to the necessity of considering local landscape features, historical land use, and socio-economic factors to ensure the success of forest restoration programs [10].

Nevertheless, Ukrainian experts note that current national commitments under the Paris Agreement remain insufficient, and the implementation of NCS requires greater state support, increased investment in scientific research, and the development of integrated strategies [11].

Objective and problem formulation

To better understand the scale of the contribution of forest-based Natural Climate Solutions (NCS) to climate change mitigation, a synthesized assessment of the global potential of five major strategies is presented (Figure 1). The figure illustrates how different approaches – ranging from reduced deforestation to afforestation and agroforestry – can contribute to greenhouse gas (GHG) emission reductions, taking into account technical, economic, and sustainable constraints.

These estimates vary depending on assumptions about contextual conditions, which are shaped by a range of biophysical and socio-economic factors. Our analysis follows a classification of land-based mitigation potential that distinguishes between three categories: technical, economic, and sustainable potential. Technical potential refers to the maximum possible emission reductions achievable using current technologies, without considering practical limitations.

Economic potential accounts for the financial feasibility of measures based on carbon pricing, reflecting the volume of emission reductions that are cost-effective.

Sustainable potential incorporates not only technical and economic considerations but also social and environmental constraints, such as food security and biodiversity conservation. As such, it provides the most realistic estimate of the land sector’s capacity to contribute to climate mitigation [12].

Aim and Objectives

Several strategies fall under the category of forest-based Natural Climate Solutions (NCS); Figure 1 presents climate potential estimates for the five most prominent ones. The NCS strategies "avoided deforestation" and "reduced forest degradation" do not relate to forest restoration. The "forest management" strategy includes the restoration of existing degraded forests – i.e., forested areas that remain classified as forests [13] – and is part of the Forest Landscape Restoration (FLR) concept. The primary focus is on enhancing climate change mitigation in existing natural forests (Griscom, B.W., et al. [1]); only a small portion of this potential relates to forest restoration. The NCS strategy "agroforestry" is a component of FLR, although its potential may also be included in some afforestation/reforestation assessments [12]. For example, agroforestry systems with more than 25 % tree cover and all silvopastoral systems may be categorized under reforestation. Assigning the mitigation potential of agroforestry to forest restoration may result in double counting. The NCS strategy "afforestation/reforestation" refers to the conversion of non-forest lands into forested areas. Forest restoration is often equated with this category in public discourse on climate change mitigation. Therefore, estimates of the potential of this strategy are particularly important in evaluating the contribution of forest restoration to limiting global warming, and this is where the primary attention is focused.

In Ukraine, agroforestry is actively researched and implemented as a strategy for the sustainable development of the agro-industrial sector. In particular, the textbook "Agroforestry: Ecologically Balanced Development" (Urushadze et al., 2019) explores the fundamentals of agroforestry and its role in biodiversity conservation and improving soil fertility. This manual was prepared with the participation of Ukrainian scientists, including O. V. Mudrak, an academician of the National Academy of Agrarian Sciences of Ukraine (NAAS). It highlights the importance of integrating forest and agricultural systems to achieve ecological and economic sustainability in agricultural landscapes [14].

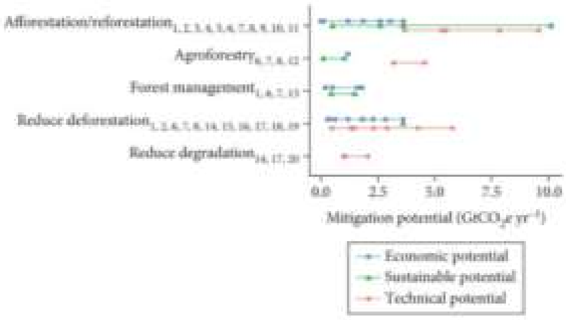

Fig. 1. Climate Change Mitigation Potential of Forest-Based Natural Climate Solutions (NCS) for 2020–2050

Additionally, Ukrainian researchers such as S. A. Koval have studied aspects of forest restoration and afforestation, which are components of agroforestry. For instance, methodological guidelines for practical training for students specializing in "Forestry" and "Park and Garden Management" (Koval, 2019) provide recommendations for incorporating agroforestry into the educational process. These materials help students develop an understanding of the importance of integrating forestry and agriculture for the sustainable development of rural areas.

Thus, in Ukraine, agroforestry is considered an important pathway toward the sustainable development of the agricultural sector, contributing to the preservation of ecological balance and the improvement of productivity on agricultural lands [15].

The figure shows estimates of the carbon emission reduction potential of five main forest-based Natural Climate Solutions (NCS), including afforestation, reforestation, agroforestry, forest management, and reduced deforestation. Different colors represent technical, economic, and sustainable potentials, taking into account ecological and social constraints. The potential range for climate change mitigation through afforestation and reforestation spans from 0 to 10.1 $GtCO_2$ per year during 2020–2050. According to IPCC estimates (2018), the remaining carbon budget to limit warming to 1.5 °C is 420 $GtCO_2$, so forest restoration can significantly contribute to this goal.

Other forest-based strategies, such as avoiding deforestation, have even greater potential – especially in tropical regions [1]. It is crucial to avoid conflicts between afforestation and forest protection. Agroforestry and forest management are attractive because they involve fewer land-use conflicts [12].

The study by Busch et al. examined the potential for greenhouse gas emission reduction through reforestation in the pantropical region during 2020–2050. Under a "business-as-usual" (BAU) scenario, the authors estimated a carbon removal potential of 102.5 $GtCO_2$ through reforesting 387.8 million hectares. The modeling assumes that land use responds to economic incentives, particularly changes in agricultural product and carbon prices [16].

Austin et al. used complex economic modeling that accounts for market feedbacks and projected growth in agricultural demand. For the period 2025–2055, they considered carbon payment scenarios at $20 and $50 per ton of CO_2. The resulting additional CO_2 removal potential ranged from 5.7 to 15.1 $GtCO_2$, while total forest area expansion reached 415–875 million hectares. However, these figures include both avoided deforestation and new forest plantings [17].

Griscom et al. approached potential estimation from a bioclimatic perspective, identifying natural zones where forest cover could exist and excluding urban and cropland areas from the analysis. The study covers both tropical and temperate regions, with potential estimates ranging from 0.1 to 2.6 $GtCO_2$/year depending on the starting carbon price ($5–100/t) and its rate of increase. The BAU scenario provides an annual sequestration of 1.1 $GtCO_2$/year [1].

The most ambitious estimate of potential is provided by Bastin et al., who do not use scenario-based or economic modeling, but instead assess the global biophysical potential of areas where forests could naturally grow. They identified 1,700–1,800 million hectares of potential land for afforestation, which could theoretically absorb 752.4 $GtCO_2$. However, the timeframe for achieving this potential is not specified, and the study does not take socio-economic constraints into account. Therefore, it was not included in the core graphics of the IPCC report [18].

A comparison of results shows that Busch et al. present the largest realistic and scenario-based potential (102.5 $GtCO_2$ by 2050), whereas Bastin et al. offer a highly theoretical estimate, without considering time constraints or economic realities.

Austin et al. and Griscom et al. provide more moderate results that reflect the flexibility of potential depending on carbon pricing.

At the same time, all these studies have significant limitations. Notably, Bastin et al. and Griscom et al. assume a global shift to plant-based diets, which would free up grazing lands in natural forest zones for afforestation. However, Bastin et al. have faced criticism for including afforestation in historically non-forested biomes (Veldman et al., 2019).

Most of the estimates presented in Figure 6.1 illustrate a neglect of social and political constraints, as well as the effects of future climate change [1].

These examples highlight the need for a critical assessment of climate mitigation potential and an understanding of the assumptions behind the estimates. This is especially relevant for upper-bound estimates, which are mostly theoretical, lacking consideration of economic and political feasibility, as well as carbon permanence challenges. Authors must be transparent about these assumptions and clearly communicate both minimum potential carbon removal and risks of failure.

Despite these limitations, most researchers agree that forest restoration holds substantial potential for combating climate change. However, there is a lack of clear, realistic, and convincing implementation pathways for these measures.

The conditions for forest restoration vary significantly between regions, and even within the same region. Differences in biophysical and socio-economic conditions not only present distinct challenges for the development of restoration programs (see Section 5) but also influence the climate mitigation potential. Likewise, variations in restoration approaches – ranging from passive natural regeneration to active interventions, such as planting native or non-native species or implementing agroforestry – come with different challenges and potentials. A better understanding of how these variations affect outcomes is critical for the successful implementation of restoration programs aimed at climate change mitigation.

It should be noted that forest restoration as a climate change mitigation strategy is more focused on tropical and subtropical regions than on temperate and boreal ones. This can be explained by several factors. The rates of carbon accumulation associated with forest restoration vary greatly around the world. For example, Cook-Patton et al. report more than a 100-fold difference in potential rates of aboveground biomass carbon accumulation during the first 30 years of natural forest regeneration, with climatic factors better explaining this variation than land-use history [19]. Trees grow faster in the tropics compared to temperate and boreal regions, so tropical forests have higher carbon accumulation per unit area [20]. This applies to both natural regeneration and intensively managed plantations [21]. Additionally, land in many tropical regions is relatively cheap and accessible. Increasing forest area in tropical regions also increases evaporation and transpiration, causing additional cooling. Conversely, increasing forest cover at high latitudes causes an albedo effect that may lead to overall warming despite carbon uptake by trees. However, forest restoration is also considered relevant for temperate regions, with Russia, the USA, Canada, and China having large areas of potential forest restoration [12, 18–20].

There is scientific debate not only about the overall global mitigation potential of forest restoration but also about the relative contribution of different restoration options [20, 22, 23]. Passive approaches based on natural regeneration, active approaches such as planting native or non-native plantations, and agroforestry differ in how quickly carbon content in stocks changes and in the maximum potential carbon storage per unit area of restored lands. The assessment of mitigation potential depends on methods, timeframes considered for carbon pools, and scenarios of wood use or non-use. For example, Bernal et al., based on an analysis of empirical data from the literature, report that globally, during the first 20 years of growth, plantations have the highest CO_2 removal rates per unit area considering aboveground and belowground biomass (4.5–40.7 t CO_2 per ha per year), followed by mangrove restoration (23.1 t CO_2 per ha per year), natural regeneration (9.1–18.8 t CO_2 per ha per year), and agroforestry (10.8–15.6 t CO2 per ha per year), with some overlap among indicators. Similarly, Bonner et al. (2013), using meta-analysis, report significantly higher aboveground biomass growth rates in plantations than in young secondary tropical forests; these differences are less pronounced in older forests. However, plantation success strongly depends on species selection [24].

A fundamentally opposite view is expressed by Lewis et al., who estimate that in tropical and subtropical regions, natural forests will be six times better than agroforestry and 40 times better than plantations in carbon storage above and below ground in the long term. These estimates are based on several assumptions. First, issues of sustainability and carbon leakage are ignored. It is assumed that natural regeneration is possible on all restoration-eligible lands and that carbon stocks in naturally regenerating forests on degraded lands will recover to their previous high-carbon state. This presupposes that all direct and underlying drivers of forest loss – such as governance failures, poverty, and economic development – will disappear. Second, the wood substitution effect from plantations and agroforestry is not considered. Third, the existing restoration opportunity map used for estimating probable restoration locations includes not only cleared lands but also degraded forests that may retain significant carbon stocks. This allows estimation of initial carbon content on restoration lands. For agroforests and plantations, it is assumed that all initial carbon is lost during establishment, leading to a negative carbon balance for these two options in some countries [20].

Besides this wide range of estimates, there are additional challenges in comparing restoration options. First, many meta-analyses have a positive site selection bias when comparing natural regeneration and active restoration (i.e., studies on plantations are conducted on sites that could regenerate without planting; [25]). Second, both plantations and natural regeneration depend on site conditions, but the importance of different factors is assessed differently across studies [19, 24, 25]. Third, some plantation species may have negative impacts on soil and water resources. Finally, natural regeneration is not always acceptable or achievable, especially due to socio-economic factors (see Section 5). Debates continue that probably the best approach is combining active restoration and natural regeneration, considering local conditions [22, 25].

Wood use can contribute to climate change mitigation by reducing emissions in other sectors. Carbon storage in long-lived forest products (e.g., furniture or construction materials) can replace materials with intensive emissions (e.g., cement or steel), and wood biomass used for energy can replace fossil fuels [4, 26]. There is a trade-off in using wood products or biomass: unmanaged forests usually have larger carbon stocks, but their sequestration potential may saturate over time [27]. In contrast, forests managed for timber production have smaller carbon stocks but, due to the substitution effect, they can be carbon sinks that can be continuously used for mitigation if appropriate silvicultural practices are applied. This ultimately leads to net savings, which can produce a positive net impact of timber production on atmospheric carbon. Precisely defining this impact is complex because it depends on many factors: the materials and/or fuel types being replaced, counterfactual assumptions about forest use, accounting timeframes, forest recovery rates, and other site-specific contexts [4]. Critical methodological differences in the literature result in a wide range of estimates of the substitution impact of wood on greenhouse gas emissions [28].

Global estimates of the potential climate benefits of forest restoration generally do not account for the substitution effect. This is likely due to the overall high uncertainty in the literature regarding the impact of wood use on greenhouse gases, as well as the fact that most substitution studies focus on non-tropical countries, whereas forest restoration as a mitigation strategy is generally focused on the tropics. Ignoring the substitution effect may bias global estimates in favor of restoration options that do not primarily aim at timber production or poverty alleviation, such as passive restoration through natural regrowth [20].

Two more aspects are important for discussing wood use. First, the long-term success of restoration depends on how much restored forests become an economic resource for local communities. Second, global demand for wood products is increasing in line with population and income growth; this trend is expected to continue in the coming decades [29]. Ignoring these two aspects risks focusing exclusively on environmental goals, which may hinder restoration success and thus negatively impact climate mitigation. Recognizing that timber production can positively affect greenhouse gas emissions is important for forest restoration; this may increase the likelihood of successful implementation. Restoration approaches that aim to combine timber production, ecosystem improvement, and socio-economic development, such as FLR and "next-generation plantations", are promising.

Conclusion

Theoretically, forest restoration has the potential to absorb several gigatons of CO2 annually on a global scale in the coming decades, significantly mitigating climate change. To fully realize this potential, forest restoration must be carried out and maintained over areas of hundreds of millions of hectares. However, the feasibility of such large-scale restoration is questioned due to critical issues at local, national, and global levels.

Implementing large-scale forest restoration requires addressing the main economic and social causes of deforestation and forest degradation. These factors have created serious barriers to sustainable development for decades. Although forest restoration is often presented as a win-win solution, it has potential trade-offs and negative consequences. Restored forests can be either a positive or negative resource for livelihoods and accordingly may either help solve socio-economic problems or exacerbate them.

There is potential to strengthen synergies between mitigation and adaptation in the land sector. Understanding these synergies and trade-offs is important for reducing conflicts and increasing policy coherence across all sectors and levels. This will be important not only for climate change but also for sustainable development.

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Відновлення лісів та агролісівництво як природні кліматичні рішення

Проблема. *Посилення впливу змін клімату вимагає ефективних природних рішень, що сприяють поглинанню вуглецю, збереженню біорізноманіття та стійкості екосистем. Відновлення лісів і агролісівництво є перспективними підходами, проте їх потенціал в Україні залишається недостатньо реалізованим через прогалини в політичній підтримці та стратегіях впровадження.* ***Мета****. Проаналізувати роль відновлення лісів і агролісівництва в пом'якшенні змін клімату, оцінити їх переваги як природних кліматичних рішень і виявити можливості для ширшого впровадження в Україні.* ***Методологія.*** *У дослідженні використано огляд наукової літератури з міжнародних та українських джерел щодо відновлення лісів, агролісівництва та пом'якшення кліматичних змін. Аналіз політики та вивчення кейсів проєктів дали уяву про сучасні практики та бар'єри впровадження.* ***Результати.*** *Відновлення лісів та агролісівництво істотно сприяють поглинанню вуглецю, збереженню біорізноманіття та покращенню добробуту сільського населення. Їх інтеграція в просторове планування та кліматичну політику може підвищити кліматичну стійкість України. Проте інституційні, фінансові та інформаційні бар'єри стримують масштабування цих підходів.* ***Наукова новизна.*** *У дослідженні наголошено на екологічному та соціально-економічному значенні поєднання відновлення лісів і агролісівництва як природних кліматичних рішень. Запропоновано рамкову модель для посилення їх реалізації в екологічному й аграрному секторах України.* ***Практичне значення.*** *Результати дослідження можуть бути корисними для розроблення цільових стратегій підтримки відновлення лісів і агролісівництва, сприяючи сталому землекористуванню та адаптації до змін клімату в Україні.*

Ключові слова: *відновлення лісів, агролісівництво, природні кліматичні рішення, поглинання вуглецю, пом'якшення змін клімату, Україна.*

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