

Article

Agroforestry as a Resource for Resilience in the Technological Era: The Case of Ukraine

Sergiusz Pimenow ^{1,2}, Olena Pimenowa ^{1,*}, Lubov Moldavan ³, Piotr Prus ^{4,*} and Katarzyna Sadowska ⁴

¹ School of Business, VIZJA University, Okopowa 59, 01-043 Warszawa, Poland; s.pimenow@vizja.pl

² Department of Social Sciences and Computer Science, Nowy Sącz High School of Business, National Louis University, Grundwalska 17, 33-300 Nowy Sącz, Poland

³ Department of Forms and Methods of Management in Agri-Food Complex of SI, Institute of Economics and Forecasting, National Academy of Sciences of Ukraine, 01011 Kyiv, Ukraine; lmoldavan@ukr.net

⁴ Department of Agronomy and Food Processing, Faculty of Agriculture and Biotechnology, Bydgoszcz University of Science and Technology, Al. Prof. S. Kaliskiego 7, 85-796 Bydgoszcz, Poland; katarzyna.sadowska@pbs.edu.pl

* Correspondence: o.pimenowa@vizja.pl (O.P.); piotr.prus@pbs.edu.pl (P.P.)

Abstract

Climate change is intensifying droughts, heatwaves, dust storms, and rainfall variability across Eastern Europe, undermining yields and soil stability. In Ukraine, decades of under-investment and wartime damage have led to widespread degradation of field shelterbelts, while the adoption of agroforestry remains constrained by tenure ambiguity, fragmented responsibilities, and limited access to finance. This study develops a policy-and-technology framework to restore agroforestry at scale under severe fiscal and institutional constraints. We apply a three-stage approach: (i) a national baseline (post-1991 legislation, statistics) to diagnose the biophysical and legal drivers of shelterbelt decline, including wartime damage; (ii) a comparative synthesis of international support models (governance, incentives, finance); and (iii) an assessment of transferability of digital monitoring, reporting, and verification (MRV) tools to Ukraine. We find that eliminating tenure ambiguities, introducing targeted cost sharing, and enabling access to payments for ecosystem services and voluntary carbon markets can unlock financing at scale. A digital MRV stack—Earth observation, UAV/LiDAR, IoT sensors, and AI—can verify tree establishment and survival, quantify biomass and carbon increments, and document eligibility for performance-based incentives while lowering transaction costs relative to field-only surveys. The resulting sequenced policy package provides an actionable pathway for policymakers and donors to finance, monitor, and scale shelterbelt restoration in Ukraine and in similar resource-constrained settings.

Keywords: agroforestry; shelterbelts; Earth observation; UAV/LiDAR; AI; MRV; payments for ecosystem services; carbon finance; sustainable development



Academic Editor: Eva Pongrácz

Received: 25 June 2025

Revised: 9 September 2025

Accepted: 23 September 2025

Published: 25 September 2025

Citation: Pimenow, S.; Pimenowa, O.; Moldavan, L.; Prus, P.; Sadowska, K. Agroforestry as a Resource for Resilience in the Technological Era: The Case of Ukraine. *Resources* **2025**, *14*, 152. <https://doi.org/10.3390/resources14100152>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Worsening climate change is increasing the vulnerability of agricultural and forestry systems by intensifying droughts, heatwaves, dust storms, and erratic precipitation, reducing stand productivity and regeneration, and increasing the frequency of windstorms and wildfires. Rising temperatures and the increasing frequency of extreme weather events, such as droughts and forest fires, alter disturbance patterns and forest adaptability [1]. These impacts highlight the urgency of treating agriculture and forestry as integral parts of climate adaptation strategies.

Agroforestry—defined as the deliberate integration of trees and shrubs into agricultural landscapes—has long been recognized for its ecological benefits, including enhanced biodiversity, improved soil health, and, critically, carbon sequestration [2]. Recent studies further highlight its capacity to help maintain ecological balance and to shield crops from climate extremes [3,4]. FAO (2024) ranks agroforestry among the most promising climate-adaptation strategies for smallholders [5]. Yet these socio-economic benefits seldom translate into farm-level advantages, as producers face persistent deficits in data, finance, and co-ordination.

The rapid proliferation of sensor networks and low-cost satellites now provides high-frequency measurements of soil moisture, crop stress, and tree growth [6,7]. Systematic reviews demonstrate that AI-IoT combinations substantially improve yield forecasts and optimize resource allocation at small-farm scales [8,9]. In agroforestry settings, deep neural networks can quantify biomass and carbon stocks from multispectral imagery [10,11], while computer vision accelerates disease diagnostics—for instance, detecting coffee rust beneath canopy cover [12]. Consequently, AI is becoming a core element of monitoring, reporting, and verification (MRV) infrastructures. Digital platforms are reshaping value creation and distribution by linking farmers and finance/market actors within data-sharing ecosystems [13]. Supported by agricultural big-data architectures, AI-driven analytics enable a shift from isolated pilots to platform-based services—e.g., yield forecasting and planting-scenario tools—while reducing data fragmentation and improving scalability [14].

Despite technological advances, transition economies confront a dual challenge: legal ambiguity surrounding shelterbelt status and limited telecom infrastructure in rural areas. According to Ukrainian sources, shelterbelts cover approximately 30% of cropland—far below the level required for adequate protection [15]. Similar institutional and technological constraints are evident across other transition economies in Africa and Latin America, limiting the effective adoption of modern agroforestry practices [16]. As a major agricultural economy with severe shelterbelt degradation and ongoing institutional transition, Ukraine serves as a paradigmatic case for exploring digital-empowered agroforestry in fragile contexts.

Progress in AI, IoT, remote sensing, and platform economics is opening pathways for AI-driven agroforestry management capable of attracting “smart” capital, accessing carbon markets, and enhancing farm resilience. Yet institutional failures, low digitalization, and constrained investment continue to impede the large-scale deployment of modern systems in developing regions, including Ukraine—where uneven rural broadband coverage, persistent digital-skills gaps among smallholders, and wartime regulations that restrict civilian UAV operations in many areas slow the roll-out of these technologies.

Existing scholarship typically focuses either on the ecological benefits of agroforestry—such as its carbon-sequestration potential or biodiversity impacts—or on the development of digital tools for precision agriculture in isolation. Only rarely are these strands combined into an interdisciplinary framework that addresses implementation barriers and explores their synergies, leaving the full potential of agroforestry as a digital nature-based solution insufficiently examined, particularly for transition economies and wartime contexts such as Ukraine. In contexts with weak institutions, where conventional support mechanisms are limited, combining AI analytics, satellite monitoring, and innovative ecosystem-service finance can both raise practical efficiency and ensure financial viability at scale.

This study addresses these gaps by presenting a comprehensive analysis of how traditional practices and digital innovations—AI, machine learning, big data, remote sensing—can revitalize agroforest systems under fragile institutional conditions. The objective of this paper is to design and assess an integrated institutional–technological pathway to halt and reverse the degradation of Ukraine’s protective forest belts by combining legal

and financial reforms with AI-enabled MRV and digital platform solutions. Drawing on the scientific literature, regulatory analysis, and international experience, we synthesize promising institutional and technological solutions aimed at mainstreaming agroforestry within climate-adaptation strategies.

Special attention is given to AI-enabled digital technologies for MRV: automated biomass accounting, degradation forecasting, and effectiveness audits of ecosystem measures. Beyond the national case, we highlight the prospective “Ukrainian dataset”—a multi-sensor (EO, UAV/LiDAR, AI-enabled MRV) time series of shelterbelt damage and recovery under conflict, which can inform the parameterization and validation of land-use and climate-risk models used in global assessments, extending relevance to IPCC-type syntheses. We also propose an institutional–technological platform ecosystem that unites farmers, investors, and technology providers. Its core is a digital MRV infrastructure integrated with carbon-market tools, micro-finance systems, and distributed ledgers, opening opportunities for scalable shelterbelt restoration.

Finally, we offer targeted recommendations in policy, digital infrastructure, and capacity development required for wide-scale adoption of AI-driven agroforestry, including clarification of land-use rules and appointment of custodians for shelterbelts through targeted Land Law updates, the creation of a National Carbon Farming Fund, and other measures aimed at strengthening institutional capacity and ensuring financial viability. Accordingly, this article contributes to the scientific and applied discourse on climate-resilient business models, demonstrating how shelterbelt restoration can evolve from a public good into an investment-attractive pathway for sustainable development.

2. Materials and Methods

This interdisciplinary study applies a critical synthesis of the peer-reviewed literature, policy documents, and implemented digital-agroforestry practices worldwide. The analytical approach combines desk-based review, comparative case analysis, and triangulation across ecological, technological, and institutional dimensions. Ukraine was selected as the focal case based on quantitative indicators: in 2024, agriculture, forestry, and fishing altogether accounted for approximately 7.1% of national GDP and nearly 60% of all international trade in 2024, while shelterbelts protected only approximately 30% of arable land compared with the agronomic optimum of more than 50% required for effective erosion control [15,17,18]. These figures underscore Ukraine’s dual position as both a “transitioning agricultural country” and an “ecologically fragile region” with institutional gaps. To strengthen external validity, the Ukrainian case is systematically contrasted with land-restoration and climate-adaptation solutions implemented in the EU, North and Latin America, Asia, and Africa.

Terminology and scope. Internationally, agroforestry is the collective term for land-use systems and technologies in which woody perennials (trees, shrubs, palms, and bamboos, etc.) are used deliberately on the same land-management units as agricultural crops and/or animals in some form of spatial arrangement or temporal sequence. Windbreaks/shelterbelts are defined as single or multiple rows of trees and/or shrubs in linear (or curvilinear) configurations established, enhanced or renovated to reduce wind speed and soil erosion, protect crops and livestock, and to deliver other conservation outcomes [19,20]. In Ukrainian law, protective shelterbelts (*polezachysni lisovi smugy*) are “artificial linear plantings intended to protect agricultural land from adverse natural and anthropogenic factors” [21]. In what follows, we use shelterbelts as an umbrella term and include farm windbreaks/hedgerows when they are designed for wind and erosion control, following FAO guidance.

Peer-reviewed articles were included if they examined agroforestry or shelterbelts together with digital/AI/MRV/remote-sensing components; reports were limited to intergovernmental (e.g., FAO, World Bank/EU bodies) or national authorities to ensure data reliability; Ukrainian legislation was restricted to post-1991 documents reflecting the current institutional context. For the narrative synthesis, we considered publications in English, Ukrainian, and Russian, while the bibliometric figures are based on Scopus records without a language filter (thus predominantly English). We excluded non-peer-reviewed web content, conference abstracts without full texts, duplicates, purely conceptual pieces lacking methods or an agroforestry component, and repealed pre-1991 legal acts.

In synthesizing international cases, we assessed external validity through four comparator dimensions: (i) land-tenure and custodianship arrangements, (ii) farm structure and leasing prevalence, (iii) fiscal/administrative capacity (extension services, stable support programs), and (iv) biophysical context (aridity, erosion risk, temperature/precipitation regimes). Instruments from India, the United States, the EU, China, and LMICs were considered transferable to Ukraine only insofar as they could be adapted to ambiguous shelterbelt tenures, a high share of leased land and agro-holdings, limited extension capacity, and steppe-driven drought/wind-erosion pressures. This framework guided our emphasis on tenure clarification, establishment-phase grants, targeted windbreaks, and phased pilots over wholesale policy transplantation.

In line with this evidence-based approach, references to the “partial” or “complete” degradation of protective forests in Ukraine are used descriptively, reflecting secondary reports and expert assessments rather than standardized thresholds. Unlike formal international forest-health indicators (e.g., canopy coverage, vitality indices, or biodiversity scores), these terms in the present study serve to capture the qualitative extent of vegetation loss and functional decline reported in Ukrainian and intergovernmental documents.

Similarly, we do not consolidate the “efficiency gains” of digital MRV (EO + UAV/LiDAR + AI) into a single percentage figure, since the underlying case studies employ heterogeneous baselines and methodologies. A quantitative assessment of cost and accuracy differentials for Ukraine is therefore reserved for future pilot projects within the proposed MRV architecture.

We placed particular emphasis on AI-enabled tools—remote sensing, MRV platforms, carbon-accounting modules, and stakeholder-interaction models—that underpin data-driven agroforestry. A key methodological step was a bibliometric analysis of scientific publications using the Scopus database (Elsevier B.V., Amsterdam, Netherlands). The initial search query—TITLE-ABS-KEY (“agroforestry” AND (“artificial intelligence” OR “machine learning” OR “digital twin” OR “remote sensing” OR “MRV” OR “carbon farming”) AND “Ukraine”)—returned only one relevant publication [17]. The query was then expanded with additional keywords “Shelterbelt” and “Windbreak”. The revised search—TITLE-ABS-KEY (“agroforestry” OR “Shelterbelt” OR “Windbreak”) AND (“artificial intelligence” OR “machine learning” OR “digital twin” OR “remote sensing” OR “MRV” OR “carbon farming”) AND “Ukraine”)—yielded four relevant publications, two from 2025 [22,23], one from 2024 [24], and one from 2023 [25].

To assess broader academic interest in the topic, a third, geographically unrestricted query was conducted: TITLE-ABS-KEY (“Agroforestry” OR “Shelterbelt” OR “Windbreak”) AND (“artificial intelligence” OR “machine learning” OR “digital twin” OR “remote sensing” OR “MRV” OR “carbon farming”) resulted in 681 documents published between 2000 and 2025. As of 18 June 2025, nearly half of these (338 documents) were published between 2022 and 2025, indicating a sharp rise in scientific attention to this subject in recent years (Figure 1).

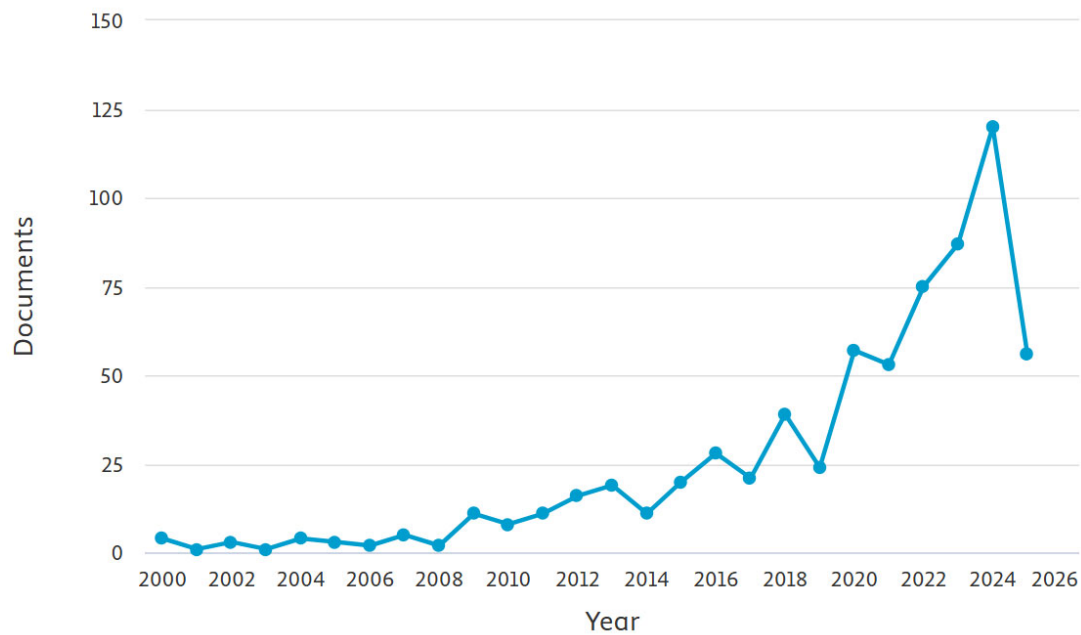


Figure 1. Bibliometric scoping (Scopus Analyzer) of digital / AI-enabled agroforestry literature. Query: TITLE-ABS-KEY (“agroforestry” OR “shelterbelt” OR “windbreak”) AND (“artificial intelligence” OR “machine learning” OR “digital twin” OR “remote sensing” OR “MRV” OR “carbon farming”). Document types: articles, reviews, conference papers. Years: 2000–2025; export date: 18 June 2025. Total $n = 681$; $n = 338$ (2022–2025). Source: Scopus Analyzer (Elsevier B.V., Amsterdam, Netherlands).

In terms of geographic distribution, China leads with 185 publications, followed by India ($n = 95$) and the United States ($n = 89$). Germany ranks fourth ($n = 50$), while other countries among the top 10 include Indonesia, Brazil, the United Kingdom, Italy, Spain, and France, each contributing between 24 and 32 papers (Figure 2).

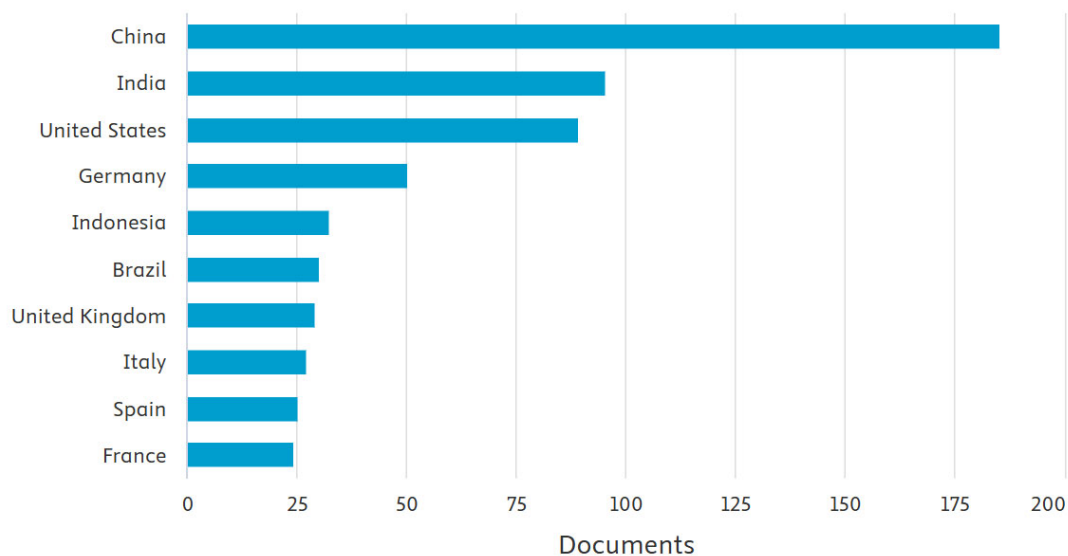


Figure 2. Country-level distribution of publications for the same Scopus query as in Figure 1. Query: TITLE-ABS-KEY (“agroforestry” OR “shelterbelt” OR “windbreak”) AND (“artificial intelligence” OR “machine learning” OR “digital twin” OR “remote sensing” OR “MRV” OR “carbon farming”); document types: articles, reviews, conference papers; years: 2000–2025; export date: 18 June 2025. The top 10 are China, India, United States, Germany, Indonesia, Brazil, United Kingdom, Italy, Spain, France (bar lengths indicate counts; see Section 2 for values: China = 185; India = 95; United States = 89; Germany = 50; others 24–32). Source: Scopus Analyzer (Elsevier B.V., Amsterdam, Netherlands).

These pronounced global interests in digital innovative approaches to agroforestry—contrasted with our bibliometric finding that the initial Scopus query identified only one Ukraine-specific publication (expanded to four after query refinement)—served as a key motivation for this study. Building on this motivation, we structured our methodological approach into several sequential stages designed to capture both the national baseline and relevant international experience.

The methodology consisted of several sequential stages:

Stage one—National baseline. From secondary sources we quantified the area, structural typology, and degradation status of Ukrainian shelterbelts. We assessed drivers such as stand senescence, neglect, fragmentation, fire, and war damage, and traced institutional and socio-economic roots, including legal ambiguity, weak user incentives, rural poverty, and crisis logging. Climate-driven threats—die-back, pest outbreaks, and agro-climatic zone shifts—were also recorded. Finally, we reconstructed the evolution of legal and financial support mechanisms for agroforestry throughout Ukraine's independence period. The national baseline diagnosis draws on three families of sources: (i) post-1991 Ukrainian legislation and executive by-laws governing agricultural land and protective shelterbelts; (ii) reports from intergovernmental and donor organizations (e.g., FAO, World Bank/GEF, European Commission, and affiliated EU bodies) providing inventories, policy assessments, and climate-risk analyses; and (iii) peer-reviewed scientific literature and Ukrainian academic monographs addressing shelterbelts, erosion control, land tenure, and agro-ecological change. Wartime impacts were taken from public assessments by competent authorities and intergovernmental partners. For transparency, while preserving the sequential MDPI numbering, the concrete intergovernmental and national reports underpinning the baseline are cited in situ within the Results (Sections 3.1.1–3.1.5), alongside the corresponding numerical statements.

Stage two—International evidence. Institutional models, climatic and economic outcomes, and incentive schemes were synthesized from more than 20 cases spanning India, the United States, China, and EU Member States. These cases were selected to cover diverse climatic zones (temperate, tropical, arid), economic systems (market-oriented, mixed, state-led), and institutional contexts (mature versus transitioning governance), thereby ensuring breadth in identifying transferable lessons. The review covers national strategies, direct subsidies, payments for ecosystem services (PES), and the embedding of agroforestry within broader climate and agricultural programs, as well as market-based mechanisms such as voluntary carbon markets, sustainable supply chains, and agro-energy solutions. Barriers to diffusion—technical, economic, educational, and regulatory—were catalogued.

Stage three—Digital transferability. Contemporary digital solutions were analyzed for their relevance to Ukraine. The assessment encompassed multi-sensor satellite data (Landsat-8, Sentinel-2, hyperspectral), machine-learning classifiers for vegetation mapping, LiDAR and UAV techniques for 3-D biomass monitoring, and MRV indices (NDVI, NBR) employed in PES verification. Implementation constraints—capital cost, computational load, atmospheric noise, and rural connectivity gaps—were identified.

No primary field data were collected. The study relies on qualitative synthesis and cross-contextual comparison. All information is sourced from authoritative open repositories, ensuring transparency, reproducibility, and relevance for other climate-vulnerable regions with weak institutional capacity. The explicit data provenance underpins the robustness of the results.

3. Results

Agroforestry has been embedded in agricultural traditions across diverse cultures for centuries, consistently contributing to the well-being of rural communities. FAO defines agroforestry as “a collective term for land management systems where woody perennials

(trees, shrubs, palms, bamboos, etc.) are deliberately integrated with agricultural crops and/or animals, in some form of spatial arrangement or temporal sequence” [2].

More than just a cultivation method, agroforestry represents a dynamic and ecologically grounded approach to managing natural resources. By incorporating perennial vegetation into farming systems, it promotes diversification and strengthens resilience, offering tangible social, economic, and environmental benefits to land users [26]. These systems operate through interconnected ecological and socio-economic processes, where the interplay among trees, crops, livestock, and local communities forms the foundation for multi-functionality and long-term sustainability (Figure 3).

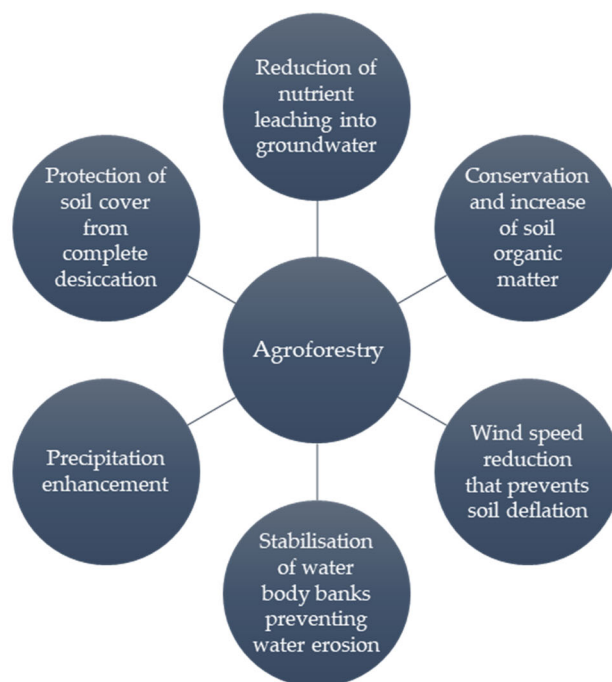


Figure 3. Key effects of agroforestry. Source: compiled by authors.

3.1. Agroforestry in Ukraine: Status and Challenges

3.1.1. Biophysical Condition of Shelterbelts

Ukraine contains roughly 40% of the world’s black soil reserves [27], but decades of intensive cultivation undertaken without sufficient windbreak protection have accelerated soil depletion and erosion. Today, shelterbelts cover only 1.3–1.5% of arable land—far below the agronomic optimum of 3–4.5% required for effective field protection [28].

Official statistics indicate that the area of field and farmstead shelterbelts expanded from about 0.4 million ha in the early 1990s [29] to approximately 0.446 million ha by 2016, equivalent to 1.4% of total farmland [30]. Independent experts, however, considered this figure inflated because no comprehensive inventory has been carried out since 1976 and widespread illegal felling has occurred; the actual area is estimated at roughly 0.35 million ha [31].

Armed conflict has further aggravated the situation: by 2023, an estimated 18% of protective plantings had been damaged [22]. The full ecological cost—loss of ecosystem services and biodiversity—cannot yet be quantified while hostilities continue [32]. Meeting science-based protection targets would require at least 0.7 million ha of new shelterbelts [31]. In their absence, millions of hectares of cropland remain exposed to wind and water erosion, moisture deficits, and yield decline.

Most existing belts were established between the 1950s and 1970s by collective farms. Now 50–70 years old, many stands have reached or exceeded their biological lifespan. Decades without silvicultural care have left trees senescent, weakened, or dead, while numerous belts have become fragmented, particularly in steppe zones where once-continuous

rows have been reduced to scattered tree clusters. Such gaps negate the windbreak function on adjacent fields [25].

Lack of systematic management has also produced overcrowded canopies, litter accumulation, and, conversely, sparse sections where stems have failed. Both extremes violate design parameters and erode protective value. Proximity to settlements encourages the dumping of household waste, which increases fuel loads; during droughts, overgrown, fuel-loaded belts ignite readily, and fire incidents have risen sharply.

As of the early 2020s, Ukraine's agroforestry network can be characterized as being in a state of crisis: shelterbelts are ageing, degraded, partially lost, or war-damaged, and now require urgent restoration themselves. Paradoxically, this critical condition also opens a window of opportunity for large-scale reconstruction and modernization of the protective network. While biophysical degradation is evident, the root causes lie in deeper socio-economic dynamics that have eroded stewardship capacity—factors explored in the following section.

3.1.2. Socio-Economic Determinants of Degradation

The dissolution of collective farming after the Soviet era sharply eroded both the incentive and the capacity of land users to maintain shelterbelts. During the 1990s, these plantings became effectively *terra nullius*: they were excluded from the parcel-by-parcel privatization process and, unlike cropland, did not pass into private ownership [28,33,34]. Classified as agricultural land yet not treated as arable fields, shelterbelts slipped into an institutional vacuum, receiving neither supervision nor funding for many years [34].

Under the severe rural poverty of the 1990s, shelterbelts were viewed less as protective infrastructure and more as a short-term survival resource. Self-harvesting for fuelwood and ad hoc clearance for extra cropland were widely reported, as villagers struggled to secure both energy and sowing areas [35]. Enforcement was almost non-existent because no agency was tasked with monitoring or imposing sanctions for the destruction of protective plantings [34]. Thus, the core socio-economic drivers of decline in the 1990s were unclear property rights, the absence of a responsible management entity, rural hardship, and a general undervaluation of the economic services provided by shelterbelts.

Recovery of the farm sector in the 2000s altered the context but not the underlying incentives. Most land was now cultivated by tenants—either family farms or large agroholdings—who did not own the shelterbelts and therefore gained no direct financial return on maintenance investments [36]. Large enterprises often saw windbreaks as obstacles to machinery and, in the absence of local oversight, occasionally removed them illegally to consolidate fields [37].

Short-term gains from expanding cropland or harvesting timber outweighed the diffuse, long-term benefits of soil protection [38]. Because ecosystem services such as erosion control or moisture retention are not monetized at the farm level, farmers bear the full cost of planting and maintenance without receiving explicit revenue in return. As a result, in the absence of external incentives or regulatory requirements, many land users refrain from investing in shelterbelt restoration or maintenance, perceiving it as an uncompensated expense [39].

Demographic change has markedly worsened the situation. Since the early 1990s, rural Ukraine has undergone pronounced depopulation and ageing owing to rapid urbanization and large-scale labor migration abroad. Young adults left in search of employment, birth rates declined, and, by 2019, both the rural population and agricultural labor force had fallen sharply. The resulting emptiness of many villages, documented as a demographic crisis and exacerbated by wartime mobilization, strongly suggests that traditional shelterbelt

stewardship—planting, pruning, and repair—was likely reduced simply because there were too few people left to carry it out [40,41].

In recent years, against the backdrop of repeated attacks on the energy system and sharp fluctuations in energy prices, a significant share of households has reverted to solid fuels (firewood, coal, briquettes). Both humanitarian assessments and sectoral analyses report increased demand and use of such heating sources in rural and frontline areas [42–44]. This trend has, in turn, intensified pressure on nearby woody resources, including protective shelterbelts.

These processes have locked rural areas into a self-reinforcing downward spiral: poverty and out-migration accelerate the degradation of agroforestry systems, while the loss of shelterbelts further reduces yields, erodes farm incomes, and deteriorates living conditions, thereby intensifying the very socio-economic risks that caused the decline in the first place. These socio-economic pressures are further compounded by institutional and legal uncertainties that undermine long-term governance of agroforestry—issues examined in the following section.

3.1.3. Institutional and Legal Barriers

The legal standing of field shelterbelts has remained ambiguous ever since Ukraine gained independence in 1991, and that uncertainty lies at the heart of many subsequent governance failures. Under the Soviet system, windbreak projects were embedded in farm-level land-use plans: plantings on arable land were paid for by the Ministry of Agriculture, whereas anti-erosion belts in gullies, ravines, and along waterways were financed through forestry agencies. After the collapse of that system, the dual funding streams were never reconciled [45].

Land reform and the first ownership gap. When collective and state farms were re-registered as collective agricultural enterprises (KSPs), those new entities formally acquired titles to all farmlands, including protective plantings. The then-valid Land Code nonetheless classified shelterbelts—together with farm roads—as common-use land within the co-operative [46]. This separation of cropland from the trees that protected it created an administrative paradox: during the distribution of land shares, belts, as communal assets, were transferred to village councils rather than to individual shareholders [47].

Neither forest nor field. Article 22 of the current Land Code further muddled the water by defining shelterbelts as agricultural land while excluding them from the forest fund, thereby removing them from the remit of the State Forest Agency [48]. In theory, the 2001 Code (cl. 14) allowed such plantings to be conveyed to private owners or to the corporate successors of the old collectives, yet, in practice, belts were simply omitted from cadastral plans and left on the books of bankrupt farms or on paper as undefined state property [47,48]. As a result, parcels under shelterbelts were often never formed and thus were absent from the State Land Cadastre. Only the 2018 framework—Law No. 2498–VIII, (cl. 7)—created a pathway for communities to assume custodianship and to lease/register such belts, while Cabinet Resolution No. 650/2020 set mandatory maintenance rules [21,49].

No custodian, no norms. Jurisdictional responsibility was never assigned: the agrarian ministry supervised arable fields, the forestry ministry supervised the forest fund, and no one oversaw shelterbelts. For three decades, no government body was mandated to establish, safeguard, or service field windbreaks under market conditions. Nor did legislation contain rules for maintenance, thinning, replanting, or liability for destruction. Windbreaks could not be lawfully harvested—logging tickets apply only to the forest fund—yet they were not protected under forestry legislation either [21,45–47].

Investment paralysis. Uncertainty stifled any impulse to invest. A farmer wishing to plant a new belt had no secure title and risked shrinking the taxable cropland base. Lease

contracts for land shares rarely mentioned windbreaks; if a belt lay inside a rented plot, it was unclear who should manage it. Consequently, many belts were recorded de jure as “reserve” or communal land yet remained de facto ownerless [45,47].

Halting reform attempts. Meaningful intervention was delayed for two decades. Only in 2013 did the Cabinet of Ministers approve a Concept for the Development of Agro-Silvicultural Reclamation [50]. An action plan adopted in 2014 [51] proposed legislative amendments and compensation schemes for the managers of protective plantings, but, lacking earmarked funds, it was never executed.

A second effort was advanced in the 2018–2021 land-reform cycle by authorizing communities to register “ownerless” belts and take legal custody—an approach consistent with broader enabling-environment notes on improving land-tenure management for agroforestry [29,49]. Simultaneously, in 2020, the Cabinet issued national Rules for the Maintenance and Conservation of Protective Shelterbelts on Agricultural Land, which, for the first time, set standards for inventory, sanitary felling, replanting, and the prevention of unauthorized logging [21]. Since the beginning of Russia’s full-scale invasion in 2022, no new regulatory documents specifically addressing shelterbelts have been adopted, leaving Resolution No. 650/2020 [21] as the main legal framework in force.

By the early 2020s, Ukraine finally possessed a rudimentary legal framework for agroforestry that had been missing for three decades. Yet the architecture remains incomplete: shelterbelts are acknowledged as agricultural land, but a dedicated shelterbelt law is still absent, and the new by-laws merely lay a foundation for further reform [21,48–51]. These legal ambiguities and governance gaps have directly constrained financial investment in shelterbelt restoration, as examined in the subsequent analysis of funding landscapes.

3.1.4. Financing Landscapes and Support Programs

During the first two decades of independence, Ukraine provided virtually no dedicated financing for agroforestry. The Soviet network of centrally funded reclamation stations was dismantled, and no new funding streams emerged to support planting or maintenance. The cash-strapped state budgets of the 1990s and early 2000s included no specific line items for protective afforestation.

Although the problem began to receive policy recognition in the 2000s, funding remained marginal. The State Target Program, “Forests of Ukraine” (2010–2015), called for an expansion of shelterbelt areas [52], but the initiative failed: mass plantings were never financed, and field-level implementation mechanisms were lacking.

A significant shift occurred in 2017 with a Global Environment Facility (GEF) and FAO project aimed at restoring degraded steppe lands [27]. The project drafted by-laws for shelterbelt use and care, produced locally adapted management manuals, and proposed tenure-clarification and ecosystem-service payment schemes to incentivize conservation.

From the late 2010s, agroforestry slowly entered mainstream agricultural support. In 2020, the Ministry for Economic Development, Trade, and Agriculture classified the establishment of shelterbelts as a separate activity [21], which opened the possibility of addressing the previous policy gap and may allow their integration into the system of agricultural subsidies. In December 2021, the Cabinet of Ministers approved a Strategy for Preventing and Adapting to Climate Change in Agriculture, Forestry, Game, and Fisheries to 2030 [53]. As an integrated component of this program, agroforestry can make a notable contribution to climate-change adaptation. Implementation, however, stalled for lack of operational targets, and finance and was effectively frozen after the full-scale invasion in early 2022.

Nonetheless, the pre-war trajectory is positive: agroforestry is now embedded in national agricultural and climate strategies, supported by a fledgling regulatory base, pilot

projects, and eligibility for subsidies. Between 1991 and 2022, the sector moved from total neglect to initial program funding, though the gap between required and available investment remains vast: billions of hryvnias are needed, while only millions have been allocated. Even so, high-level recognition, newly adopted rules, and emerging pilot schemes constitute a window of opportunity for reversing decades of decline. Ultimately, the adequacy of financing will determine not only the speed of restoration but also the resilience of shelterbelts to emerging environmental pressures. These pressures—most notably those linked to climate change—form the focus of the following section.

3.1.5. Climate-Change Interactions

Climate change in Ukraine is expressed less through a rise in mean temperature and more as an upsurge in the frequency and severity of extreme events: heatwaves, droughts, floods, tornadoes, sudden thaws and frosts, debris flows, and windstorms. The growing amplitude and volatility of these phenomena demonstrate a destabilized climate system [54,55]. Recent decades have brought a distinct trend towards warmer and drier conditions, most evident in the southern and eastern steppe zones [56]. As agro-climatic belts shift northwards, their frontline has already advanced by about 200 km [57]: steppe conditions are encroaching on Cherkasy Oblast and approaching Vinnytsia, while the Polissya region is acquiring forest-steppe characteristics.

Forested ecosystems function as a principal self-regulating component in the biosphere and therefore play a decisive role in buffering or even preventing harmful climate fluctuations, influencing landscape processes as well as geophysical and biogeochemical cycles [58]. However, mounting observational evidence indicates that these stabilizing functions are being eroded under current climate stressors, with rising canopy mortality already documented across Europe. Satellite records show a sustained increase in canopy mortality across Europe since the 1980s, with unprecedented, temporally synchronized pulses following compound drought–heat events, as occurred in 2018 [59,60]. Emerging evidence also shows that drought stress interacts with biotic agents (insects, pathogens), amplifying mortality risk, and that predisposing stresses reduce tree resilience to subsequent windstorms and heat extremes [61,62]. However, on the other hand, the gaps that form are often colonized by volunteer saplings, shrubs, and other opportunistic vegetation, which can deliver valuable ecological benefits. Such spontaneous regrowth supports habitat continuity, enhances biodiversity by creating new niches, and can improve the structural and functional diversity of shelterbelts, thereby strengthening their capacity to buffer against climate variability and contribute to adaptive resilience [63].

In short, the evidence shows that climate change both intensifies shelterbelt degradation and erodes their protective capacity, while natural regeneration alone is insufficient to offset the losses, indicating that effective agroforestry adaptation requires explicit consideration of climate dynamics. Taken together, these biophysical, socio-economic, legal, financial, and climatic pressures highlight the systemic fragility of Ukraine’s shelterbelt system. Yet many of these challenges are not unique: comparable constraints have been documented in other transition and developed economies, whose diverse experiences provide valuable lessons for designing effective agroforestry policies and practices [59–62]. The following section situates Ukraine’s case within this broader global context.

3.2. Global Experience in Agroforestry Development

3.2.1. Overview of Global Trends and Regional Specificities

Bibliometric screening (Figures 1 and 2) shows a pronounced post-2020 surge in publications on digitally enabled agroforestry and a marked concentration of studies in

China, India, the United States, and EU Member States. These trends frame the comparative scope adopted below and motivate the transferal of lessons to transition economies.

Evidence across the analyzed sources indicates multiple advantages for farmers and rural territories. First, product diversification—fruit, nuts, fodder, timber, and other outputs—creates supplementary income streams and food sources, thereby improving household resilience to both economic and climatic shocks. Second, numerous empirical studies confirm that well-designed agroforestry systems can raise food security, enhance rural welfare, and lower poverty rates simultaneously. Third, trees function as a form of on-farm “insurance”: they buffer crops and soils from wind and heat and provide emergency fodder and household fuel, thus reinforcing the viability of smallholder operations [64].

Purely financial returns, however, may underperform those of intensive monoculture farming in the short term, limiting adoption. Meta-analysis for Europe and North America shows that, when ecosystem services are excluded from the balance sheet, gross margins from agroforestry tend to fall below those of tree-free farms. However, once favorable policy instruments—direct subsidies, PES, or carbon-credit revenues—are introduced, profitability improves markedly. Payback periods also depend on local biophysical factors (soil type, climate) and relative prices for both crop and woody components [65,66].

Social drivers and barriers are equally decisive. A survey of roughly 1500 European practitioners identified four barrier clusters that constrain agroforestry uptake [67]: first, technical barriers (limited knowledge of optimal tree–crop combinations and inadequate locally adapted guidelines); second, economic barriers (delayed cash flow until trees mature and the absence of mechanisms for early cost recovery); third, educational barriers (under-resourced extension services and low consumer awareness of agroforestry products); fourth and finally, policy and regulatory barriers (agricultural support schemes that overlook, or sometimes disincentivize, tree–crop integration).

However, potential risks and trade-offs warrant explicit consideration: tree–crop competition for light, water, and nutrients can depress yields near rows if species and spacing are poorly designed; inappropriate species choices can exacerbate pest and disease pressures or invasive behavior. Moreover, agroforestry typically increases management time requirements relative to monocrops, which can deter adoption where labor is scarce [39,64–67]. These risks underscore the need for site-specific design and strong extension services, as well as credible monitoring to detect unintended outcomes.

In sum, the acceleration and geographic concentration evidenced by Figures 1 and 2 justify prioritizing the United States, India, China, and the European Union as reference points for policy instruments relevant to Ukraine. The evidence points to the need for an integrated scaling strategy: farmer education and advisory services, demonstration of successful pilot cases, up-front financial incentives, and a supportive regulatory framework that recognizes agroforestry’s unique production logic and ecosystem value. How such strategies translate into practice becomes evident when examining institutional frameworks and policy instruments across different countries, many of which have integrated agroforestry into their agricultural and land-use agendas.

3.2.2. Institutional Frameworks and Policy Instruments

Over the past three decades, many countries have begun to weave agroforestry into their broader agricultural and land-use strategies. Consistent with the country distribution in Figure 2, these jurisdictions dominate the recent scholarship and policy experimentation. The United States and India were early movers: both issued national strategy papers on agroforestry in the early 2010s.

United States. A decade later, the pay-off is visible: the 2022 Census of Agriculture reports approximately 6% growth in the number of farms reporting agroforestry practices

versus 2017 [68]. U.S. policy frames agroforestry as a dual tool for climate-change mitigation/adaptation and for diversifying farm income while enhancing ecosystem services [69]. USDA conservation standards now list windbreaks/shelterbelts, hedgerows, and silvopasture among approved practices, and the Natural Resources Conservation Service (NRCS) has subsidized their establishment through successive Farm Bills [69]. Uptake remains modest, however, largely because guidance must be tailored to multiple agro-ecological zones and the financial case clearly communicated to producers [68,69].

India was the first country to adopt an independent National Agroforestry Policy (NAP) in 2014—widely hailed as a watershed and a model for others [70]. The NAP removed longstanding regulatory bottlenecks: rules governing the felling and transportation of on-farm trees were liberalized, a previous brake on expansion. Simultaneously, the government launched the Sub-Mission on Agroforestry with a budget of roughly USD 146 million, channeled through state governments.

Research and extension were upgraded as well: the National Agroforestry Centre was elevated to a fully fledged Central Agroforestry Research Institute (CAFRI) in close collaboration with the World Agroforestry Centre (ICRAF). Through training programs and demonstration plots, thousands of farmers—including many women—have adopted modern agro-silvicultural techniques. Official data showed that, from 2011 to 2021, tree cover on Indian farmland had expanded by about 0.49 million ha, and, by 2023, agroforestry occupied 8.65% of the national territory. The Indian pathway therefore positions agroforestry as a lever for combating land degradation, boosting ecosystem resilience, and underpinning food security [71].

China has no stand-alone agroforestry strategy, yet tree-based measures are embedded in large-scale ecological projects. The flagship example is the Sloping Land Conversion Program (SLCP), the world's largest payment-for-ecosystem-services scheme. Millions of smallholders receive in-kind and cash compensation for retiring erosion-prone sloping cropland and planting it to forest or perennial cover. Although SLCP spans tens of millions of hectares and had markedly reduced soil erosion, impact evaluations highlighted some limitations: centralized management, one-size-fits-all prescriptions, and weak community participation have produced mismatches between objectives and outcomes [72]. The Chinese case underscores the need for decentralization and local engagement to secure long-term success, even when political will and finance are abundant.

European Union. Institutional support in Europe emerged only from the 2000s [73], chiefly via the Common Agricultural Policy. The 2007–2013 programming period introduced Measure 222, the “establishment of agroforestry systems,” offering grants for on-farm tree planting; successor Measure 8.2 continued support in 2014–2020 [67]. Post hoc analysis revealed four limiting factors: low farmer awareness, limited technical capacity, competing afforestation grants (Measures 221/222, later 8.1) that paid farmers simply to convert farmland to forest for 15–25 years, and Common Agriculture Policy (CAP) Pillar I rules that penalized “excessive” tree cover on eligible hectares. Between 2005 and 2013, parcels with more than 50 trees ha^{−1} (later 100 trees ha^{−1}) could lose basic payments, prompting farmers to grub out millions of trees [67,74].

Reform began only recently. In 2018, the European Commission abolished the rigid tree-density cap, delegating a threshold setting to Member States, and the new CAP (2023–2027) introduces eco-schemes that reward sustainable practices—including agroforestry—without reducing baseline entitlements. CAP “greening” has also reclassified single trees, hedgerows, and windbreaks as valuable landscape features worthy of preservation and eligible for ecological focus-area credit [67].

Eastern Europe. The region historically maintained windbreak networks and orchard-pasture mosaics, but post-socialist transition left them unsupported. EU knowledge ex-

change and targeted initiatives—such as the EUKI Agroforestry project for newer Member States [75]—are now spurring a revival within a climate policy context.

In sum, the results of the study underscore that institutional design largely dictates agroforestry outcomes: where regulatory hurdles are removed, subsidies well-targeted, and research-extension systems effectively linked with farmers, adoption has accelerated, as in India and the United States. By contrast, insufficiently tailored programs—such as those historically seen in China and the EU—have yielded weaker results. Europe’s recent pivot from disincentives toward positive support highlights how governance reforms can unlock adoption at scale. Building on these institutional lessons, the next dimension concerns agroforestry’s role in addressing one of the most pressing global challenges: climate change.

3.2.3. Climate Adaptation and Mitigation Outcomes

Agroforestry is increasingly promoted as a dual-purpose instrument for climate-change mitigation and adaptation within agriculture. Integrating trees with crops or livestock sequesters carbon while hardening agro-ecosystems against extreme weather events [76]. Meta-analyses show substantial soil-carbon gains: in China, shelterbelts and tree-based plantations record the highest sequestration efficiencies among rural land-use options [77]. Trees capture carbon not only in aboveground biomass but also in deeper soil horizons, creating long-lived carbon sinks. Complex, multi-strata systems in south-eastern Brazil, for example, enhance nutrient cycling and soil-organic-carbon storage while moderating microclimate and lowering net greenhouse-gas emissions [78].

Voluntary carbon markets now remunerate these services. Farmers who implement verified reduction/removal activities can sell carbon credits to corporate and other voluntary buyers [79,80]. Platforms such as Agreea (Europe, soil-carbon from regenerative practices) and Rabobank’s ACORN (LMICs, smallholder agroforestry) provide MRV and market access; under ACORN, 80% of credit sale revenue flows to farmers [81–83].

Beyond carbon, agroforestry delivers multiple environmental co-benefits. Tree roots improve soil structure and fertility, curb wind and water erosion, and reduce surface runoff, thereby limiting nutrient and pesticide loading in water bodies [64]. Across Sub-Saharan Africa, evidence from Madagascar and East Africa shows that agroforestry increases carbon stocks and biodiversity while strengthening farm productivity and climate resilience, with documented livelihood co-benefits for smallholders [84–86].

Taken together, the literature indicates that agroforestry sequesters carbon, moderates microclimates, curbs erosion, and supports biodiversity, advancing multiple SDGs. Yet a persistent gap remains between ecological value and near-term farm income; even with emerging carbon programs, many producers face delayed or uncertain cash returns [77–80,86]. Closing this incentive gap—via robust PES designs, transparent carbon accounting, and accessible finance—remains critical for mainstreaming agroforestry.

In sum, while the ecological contributions of agroforestry to carbon sequestration, micro-climate regulation, soil protection, and biodiversity conservation are well established, these benefits rarely translate into immediate financial returns at the farm level. This persistent misalignment between ecological value and farmer income underscores the importance of exploring economic incentives and market mechanisms as the next dimension of analysis.

3.2.4. Economic Incentives and Market Mechanisms

The results of the study show that large-scale agroforestry uptake hinges on well-designed finance and incentive schemes. Aligned with the time profile in Figure 1, finance and incentive design has intensified in the most recent period, increasingly coupling support with carbon accounting and MRV capabilities. Trees generate benefits only grad-

ually: farmers pay the up-front costs of planting and early maintenance, whereas the returns—timber, fruit, fodder, improved soils—arrive years later and often in indirect form. Governments and development agencies therefore deploy instruments that offset start-up expenses and reward the delivery of ecosystem services.

Direct subsidies and grants. Under the EU's CAP, Measures 222 and 8.2 provided grants for on-farm tree establishment, covering seedlings, fencing, and annual compensation for 3–5 years to reflect transitional income loss [67]. Although uptake in 2007–2013 was limited, the concept has been retained: under the post-2023 CAP, Member States may channel eco-scheme (Art. 31) budgets to agroforestry practices; several approved CAP Strategic Plans already include dedicated eco-schemes for maintaining agroforestry alongside investment measures for establishment (e.g., Germany) [87,88]. India's 2014 Sub-Mission on Agroforestry likewise disbursed federal funds to states for free seedlings and cost sharing with smallholders, framing agroforestry as a lever in the national “doubling farmers' income” agenda [70].

In the United States, multiple federal programs embed monetary incentives. The Environmental Quality Incentives Program (EQIP) offers cost-share payments for riparian buffers and windbreaks, simultaneously curbing erosion and greenhouse-gas emissions while sustaining farm productivity [89]. Complementary mechanisms—e.g., the Conservation Reserve Program (CRP)—pay annual rents to farmers who retire acreage into woody cover, thus aligning production with ecological stewardship [90]. These contracts illustrate how carefully structured incentives can translate climate policy into field practice, even though challenges remain with regard to monitoring and evaluation.

Payments for ecosystem services. PES schemes compensate landholders for ecological outcomes rather than harvested products. China's SLCP is the world's largest example: farmers receive grain coupons and cash in return for afforesting erosion-prone slopes [72]. Despite billions of yuan invested and millions of households enrolled, evaluations reveal that insufficient or time-limited payments risk re-conversion to annual crops once subsidies lapse. Program success also hinges on equitable benefit sharing and local participation: where farmers feel like partners, long-term commitment to tree cover improves markedly [91,92]. The Latin American experience—e.g., Costa Rica's national PES and Argentina's native-forest PES—likewise highlights landholder engagement and secure tenure as prerequisites for both effectiveness and fairness [93,94].

Voluntary carbon markets. Schemes such as Agreena in Europe or Rabobank's ACORN in the Global South pay smallholders for verified carbon sequestration, forwarding up to 80% of credit revenue directly to farmers [81–83]. The rapid rise of corporate net-zero pledges is likely to expand demand for such credits, provided MRV remains robust.

Premium value chains. Market-based incentives can make agroforestry profitable without permanent subsidies. Niche markets for shade-grown coffee and cacao often pay price premiums linked to biodiversity-friendly practices and certification [95]. Studies from Costa Rica and Guatemala show that farms with moderate shade achieve the highest net present value across price scenarios [96]. In Colombia, recent research indicates that well-designed, diversified cocoa agroforestry systems can deliver competitive bean yields while providing additional ecosystem services [97].

Bioenergy integration. Coupling agroforestry with bioenergy technologies offers renewable energy without sacrificing food security [98,99]. In Ukraine, recent analyses indicate substantial bioenergy potential from agricultural residues and woody biomass, positioning bioenergy as a lever for post-conflict energy security and rural incomes [11]. Sequential on-farm biomass production supplies clean cooking fuel and surplus wood for small-scale power generation; modeling for rural settings demonstrates that farm-generated biomass can meet household energy needs and still produce excess electricity.

Co-benefits include soil-fertility gains via biochar (and, where applicable, nutrient recycling from residues/ash) and resilience to climate variability [99].

Institutional scaffolding and collective action. Financial tools work best when backed by supportive institutions. Collaborative platforms—linking farmers, researchers, NGOs, and authorities—often help overcome adoption barriers. In Madagascar, reviews highlight that secure tenure, accessible finance, and stable value chains are central to scaling agroforestry [85]. In Rwanda, co-operative membership, market orientation, and credit access strongly predict adoption [100]. Swedish evidence shows that network participation accelerates knowledge transfer and technical uptake [101]. In Bangladesh, frequent extension visits proved decisive for farmer engagement, underscoring the need for reliable advisory services [102]. EU thematic networks such as AFINET and AGFORWARD have likewise fostered cross-border learning and practitioner–researcher exchange [103,104]. Multilateral partners—including CIFOR–ICRAF, FAO, and the World Bank—have supported agroforestry pilots and capacity building in Indonesia and Nepal, embedding tree-based systems in rural-development agendas [105–107].

In sum, evidence across continents converges on a core lesson: combining direct subsidies, PES, carbon credits, market premiums, and institutional backing is critical in compensating for delayed financial returns and mobilizing farmer participation. Program success depends on fair resource distribution, genuine community involvement, and farmer access to knowledge, credit, and co-operative structures. Yet even where financial and institutional mechanisms are well aligned, their effectiveness increasingly hinges on robust evidence: credible data on biomass, carbon stocks, and ecosystem services. This dependency on accurate measurement and verification sets the stage for the next dimension: digital and AI-enabled approaches to agroforestry.

3.3. Digital and AI-Enabled Approaches to Agroforestry

Contemporary digital technologies are reshaping the analysis, planning, and monitoring of tree–crop systems, adding new precision to traditional agroforestry practice. Remote sensing became a cornerstone technology: satellite imagery and unmanned aerial vehicles (UAVs) equipped with multi-sensor payloads enable high-resolution mapping of on-farm trees and time-series tracking of their extent and condition [108].

Successful case studies illustrate the power of these tools. In arid Hotan (Xinjiang, China), multi-source remote sensing combined with deep learning was used to delineate agroforestry (walnut–intercrop) structure and quantify spatial planting patterns, informing layout planning [109]. In southern Ukraine, Landsat-8 imagery and indices such as NDVI, VTCI, and NDWI were applied to map moisture stress and to identify priority zones for shelterbelt establishment to mitigate wind erosion and moisture deficits [23]. Hyperspectral sensing adds further capability: by capturing detailed spectral signatures, it supports vegetation classification, disease detection, and crop/soil status assessment [110]. Machine-learning and deep-learning models—including Random Forest, XGBoost, and DNN architectures—paired with hyperspectral or unoccupied aircraft system (UAS) image data have proven effective for grading tree condition and monitoring stand health [111,112].

Artificial intelligence and deep-learning architectures—including multilayer perceptrons, long short-term memory networks, and convolutional neural networks—are employed to estimate aboveground biomass, especially in data-scarce settings [113]. Blending multi-source remote-sensing inputs with algorithms such as Random Forest or gradient-boosted trees markedly improves biomass-prediction accuracy [114]. UAV-borne LiDAR provides centimeter-scale 3-D structural metrics (e.g., canopy height and cover) and supports the mapping of AGB for carbon-stock accounting [115]. Digital MRV increasingly leverages satellite data to verify planting, survivorship, and biomass increments, helping to

cut transaction costs and increase transparency [116]. Within precision-agriculture frameworks, soil-moisture, temperature, and light sensors supply real-time data for targeted irrigation/fertilization that minimize tree–crop competition [117]. Big-data analytics and GIS helped to locate the most suitable hectares for agroforestry by overlaying climate, soil-degradation, and market-access layers. Machine-learning algorithms already generate agroforestry suitability maps across parts of Asia and Africa, guiding donors and governments toward sites where tree–crop integration will yield the greatest anti-desertification or productivity gains [118].

Crucially, digital tools complement—rather than replace—farmers’ local knowledge. Remote sensing validates field experience, distills best practice, and disseminates it through e-learning platforms. Robust statistical models enhance understanding of agroforestry’s ecological and economic payoffs, which is vital for climate-smart agriculture strategy design [119]. Additional gains are possible through blockchain integration within public–private partnerships: immutable ledgers can raise transparency, data accessibility, and accountability, thereby strengthening collaboration between state agencies and private actors [120].

First, very-high-resolution commercial imagery remains costly, creating affordability barriers for routine monitoring in many low- and middle-income countries; open-access missions (e.g., Landsat/Sentinel) mitigate but do not eliminate this constraint for agroforestry MRV [116,121]. UAVs are cost-effective for local surveys but cannot consistently cover large areas [122,123]. Second, space-borne sensors involve a trade-off between spatial detail and swath width, and cloud cover can obscure targets and degrade the textural metrics important for agroforestry mapping [122,124]. Third, sensor-hardware limits and atmospheric scattering reduce signal fidelity, complicating feature extraction and motivating super-resolution/denoising workflows [125]. Super-resolution techniques and adaptive algorithms are being tested to enhance low-quality imagery [126]. High-resolution scenes require significant processing power; moreover, sustaining mapping accuracy in heterogeneous tree–crop mosaics remains difficult [127,128]. Finally, many regions still lack the infrastructure and technical skills to integrate remote-sensing outputs into day-to-day farm management. Bridging this divide calls for capacity-building and user-friendly tools tailored to local contexts [129]. While the potential of high-resolution remote sensing for agroforestry is immense, overcoming these hurdles will require innovation in data-collection methods, processing technology, and cost-reduction strategies so that advanced analytics become accessible in resource-constrained settings.

4. Discussion

Cross-country evidence confirms that agroforestry can deliver substantial ecological and economic returns, though the potential therein depends on a favorable constellation of political, institutional, and socio-economic conditions. In India, the removal of legal barriers and direct financial incentives for tree planting were decisive [70]; in the United States, integration of agroforestry into farmer-support programs and a robust research-extension network underpinned progress [69]; in several EU Member States, rule changes that allowed trees and arable crops to coexist without loss of subsidies proved catalytic [67]. Collectively, these cases indicate that political will to treat agroforestry as a bona fide component of the farm sector—and to align regulations and incentives accordingly—is indispensable.

Although agro-silvicultural reclamation has appeared in Ukrainian policy papers since the early 1990s, systematic backing has never materialized. Institutional fragmentation, weak enforcement, and a disregard for scientific recommendations have led to the gradual degradation of existing belts and a near-absence of new plantings [15,28,46–48]. Ongoing hostilities further constrain action: fiscal resources are diverted to defense, and adminis-

trative focus is on keeping core agricultural functions afloat. Even a minimal package of policy and financial measures for agroforestry will therefore require external assistance and a post-war reordering of agricultural and climate priorities. Thus, Ukraine's trajectory is consistent with international patterns: without clear mandates, incentives, and enforcement, agroforestry remains marginal.

The results of the study also stress the importance of awareness building. Farmers adopt new practices more readily when nearby demonstration farms show profitable shelterbelts or alley orchards; conversely, EU measures in the 2000s underperformed largely because of poor outreach and competition from conventional subsidies [67]. While the Sloping Land Conversion Program in China generated ecological gains, its top-down design, limited participation, and inflexible prescriptions led to socio-economic distortions and jeopardized long-term outcomes [72]. In wartime Ukraine, where decision making is centralizing, similar risks loom and are compounded by traditional corruption vulnerabilities [130,131]. Overall, governance, outreach, and incentive design—not agronomic feasibility—emerge as the primary bottlenecks.

Agroforestry's promise to reconcile environmental gains with farm income is well documented, yet achieving that balance is challenging [64]. Local heterogeneity in household incomes, tenure, and decision-making power must be addressed [72,92,93]. Targeted policies—especially payment for ecosystem services—and institutional mechanisms that recognize and reward environmentally sound agroforestry are pivotal. Evidence from China, Costa Rica, and Mexico shows that well-designed PES with equitable benefit sharing and sustained participation deliver stronger environmental outcomes [72,91,92,94]. Reducing agroforestry to a “tree-planting fixes everything” slogan ignores institutional and economic constraints and the need for meaningful community participation in land-use decisions [92,93]. Accordingly, robust finance, clear tenure rules, credible monitoring, and inclusive governance are non-negotiable foundations for scaling agroforestry in Ukraine's post-war landscape [72,92,94]. This aligns with our focus on tenure clarity, targeted incentives, and transparent MRV as preconditions for scale.

Theoretical and practical significance. Beyond explaining outcomes, the findings inform policy sequencing and institutional design. In the Ukrainian context, conventional intervention pathways can be tailored to regional conditions. Ukraine's ecological diversity—from Polissya wetlands to the southern steppes—makes agroforestry a versatile tool for multiple policy objectives. In the north and west (forest-steppe and Polissya), tree-crop integration can help smallholders diversify output: fruit or nut strips between cereal fields raise land profitability and generate rural employment through on-farm processing of nuts, berries, and similar products. In the south and east, where wind erosion is severe, the revival and expansion of shelterbelts are particularly promising. International evidence from the United States, China, and elsewhere confirms the high efficacy of windbreaks for yield protection and soil conservation [68,69,71,72]. With drought-tolerant species and GIS-optimized spacing, a national revitalization program could curb dust storms, bolster drought resilience, and soften climate-change impacts. These regionally tailored pathways illustrate how general principles translate into Ukraine's diverse agro-climatic zones.

Although Russia's 2022 invasion has deferred many development initiatives, research continues even under fire. In left-bank Kherson Oblast, Sentinel-2 L2A images and NDVI/NBR indices were used to map burn scars, documenting the loss of 17.5% of the Oleshky forest—the world's largest planted woodland—and guiding future restoration [24]. Given the advanced age and degradation of Ukraine's shelterbelts, phased reconstruction is essential. Climate-smart windbreaks—mixing drought-hardy trees, shrubs, and fruit species—can provide protection, biodiversity, and marketable produce simultaneously. Modern silvicultural methods include the thinning and conversion of over-aged belts

into ventilated lattice structures that better withstand climatic stress while regaining agro-protective efficiency. Silvo-pastoral options in the Carpathians and Polissya—grazing livestock beneath fodder trees such as locust or poplar—could lift pasture productivity and yield ancillary outputs (timber, honey etc.), with the Eastern European experience showing benefits for farmers and the reintroduction of lost species [132,133].

To ensure successful adoption of international best practices, specific policy and institutional measures are required. First, consolidate currently scattered administrative responsibility for shelterbelts under a single accountable agency—India’s removal of redundant felling permits catalyzed on-farm tree planting [70]. Second, embed state aid for agroforestry within EU-aligned agri-environment and climate strategies, prioritizing erodible steppes and practices such as field shelterbelts and riparian buffers, with 5–7-year establishment compensation. Third, create clear rules for generating, registering, and trading high-quality carbon credits with transparent accounting and rigorous verification, hard-wiring agroforestry into climate and energy policy as a CO₂-removal track. Fourth, launch pilot farms and community projects, issuing verified credits to test mechanisms and build proof-of-concept. Finally, ensure investor confidence via trustworthy MRV, drawing on remote sensing, GIS, and soil analysis, and referencing USDA and leading voluntary-market methodologies.

Incentive package for farmers. If carbon prices remain low or volatile, smallholders will hesitate to invest in tree-based systems. A blended incentive mix is therefore recommended: direct grants for establishing shelterbelts and mixed plantings; tax holidays or transitional compensation while trees are non-productive; and subsidies for drip-irrigation kits, fencing, and other enabling infrastructure.

Role of research and education. Ukraine currently lacks specialized agroforestry centers, yet it possesses strong forestry institutes and agricultural universities. Inter-disciplinary teams—soil scientists, foresters, agronomists—should be assembled to generate location-specific data: optimal tree–crop combinations, payback periods, pest-management protocols in mixed stands, etc. Findings must be channeled to producers through a revitalized extension service. International links—membership in European networks such as AFINET or partnership with ICRAF—would unlock extensive knowledge bases and training resources.

Scaling will require blended finance. A favorable investment climate—clear “rules of the game”, a transparent carbon-credit market and government guarantees—will attract corporate funds. Ukraine should seek admission to World Bank facilities (e.g., Bio Carbon Fund), collaborate with voluntary-market platforms such as Agreena and Rabobank’s ACORN, and co-finance demonstration projects with EU instruments. If these pillars are put in place, agroforestry can move from pilot status to a mainstream pillar of the post-war climate, food-security, and rural-development agenda. However, destruction and institutional disarray have accelerated shelterbelt decline and exposed a technological gap in monitoring and management. Bridging this gap requires digital infrastructures that ensure transparency, scalability, and cost-effectiveness.

Policy recommendations—sequencing. Given differences in tenure systems, farm structures, state capacity, and climate, international models serve as design archetypes rather than plug-and-play solutions. Recommended measures are sequenced to Ukraine’s prerequisites (clear custodianship, minimal extension, constrained budgets) and to steppe/forest-steppe risks. Ambiguous property rights and lack of custodianship have paralyzed investment in shelterbelts; Land Law reform is essential in establishing ownership and management responsibility. Building on this foundation, cost-sharing subsidies, PES, and carbon-market mechanisms can transform shelterbelts into viable assets. To avoid compe-

tion with food-production supports, we propose a CAP-aligned Ecological Plan and a dedicated eco-scheme, “Agroforestry-UA”.

Within the pilot phase (2026–2028), the scheme would reimburse 70–80% of planting and maintenance costs and guarantee per-tree payments for 5 years in erosion-prone zones; an independent end-2028 evaluation would inform a 2029–2030 scale-up under the CAP-aligned Ecological Plan and the National Carbon Farming Fund, aligning short-term incentives with medium-term consolidation. A National Carbon Farming Fund—capitalized via EU ETS auction revenues, donor contributions, and domestic carbon-credit sales—would co-finance MRV, provide micro-loans for drip irrigation, and subsidize IT equipment, allowing short-term production priorities to align with long-term restoration. From 2031 onward, institutionalization would close monitoring-capacity and skills gaps via digital MRV, mandatory blockchain disclosure, and a nationwide network of demonstration farms.

Digital MRV and blockchain tools can reduce transaction costs and enhance transparency, while demonstration farms and capacity building address limited farmer awareness and skills. Public blockchain disclosure of planting data and biomass increments should be mandated for projects receiving state support; however, on-farm blockchain MRV is cost-prohibitive for smallholders in Ukraine, recommending centralized or donor-supported platforms that aggregate data and provide user-friendly interfaces. A network of 20–30 regional demonstration farms—“living laboratories” hosted by agricultural universities—should showcase drone scanners, IoT sensors, and mobile carbon-calculation apps and serve as an Agroforestry-AI hub. To assess the relative priority of reforms, Table 1 summarizes expected benefits, resource requirements, and implementation difficulty.

Table 1. Relative priority of agroforestry reforms in Ukraine by benefit, cost, and implementation difficulty.

Reform/Intervention	Expected Benefit	Cost/Resource Need	Implementation Difficulty
Institutional reforms			
Consolidate administrative responsibility (single agency)	High	Low	Medium
Farmer dialogue & inclusive governance	Medium	Low	Medium
PES schemes	Medium	Medium	Medium
Establish carbon-credit framework & MRV standards	High	Medium	High
Financial & incentive mechanisms			
Embed agroforestry in CAP-aligned strategies (priority zones)	High	Medium	Medium
Blended incentive mix (grants, tax holidays, subsidies)	High	Medium	Medium
Mobilize blended finance (WB, EU, private platforms)	High	High	High
Digital & monitoring tools			
Independent monitoring (satellite, GIS, digital tools)	High	Medium	Medium
Low-cost digital field-data tools & training	Medium	Low	Medium
National electronic agroforestry potential map	Medium	Medium	Medium
Repurpose drones & AI pipelines for agroforestry MRV	High	Medium	High
FAIR-compliant Ukrainian environmental data set	High	Medium	High
Digital MRV & carbon-market platform	High	Medium	High
Capacity & outreach			
Pilot farms & community projects (verified credits)	Medium	Low	Low
Agroforestry research & extension capacity	Medium	Medium	Medium
Agro-tech hubs & talent retention	High	High	High

Source: compiled by authors. Note: authorial heuristic synthesis based on the reviewed literature and the Ukrainian contextual analysis. Ratings are ordinal (relative) and intended for scoping only; they are not derived from an expert-elicitation survey or a cost–benefit analysis (CBA) and should be validated through stakeholder consultations and pilot evaluations (see Limitations).

Digital technologies as enabling infrastructure. Digital tools operationalize the above policy architecture through investment-grade MRV and inclusive scaling. Global experience shows that satellite constellations (Sentinel-2, Landsat-8) can locate remnant shelterbelts, monitor conditions, and rank fields where tree strips yield the greatest benefit; a national electronic agroforestry potential map would help planners target finance and farmers optimize placement, while open reporting enhances transparency for donors and private investors. The digital transition must remain inclusive: smallholders often lack capital, connectivity, or carbon-market literacy, so low-cost field-data tools, capacity building, and fair benefit sharing are needed, aligned with the Digital Ukraine agenda.

Wartime conditions have paradoxically created technological assets. Since 2022, Ukraine has developed fleets of long-range, high-precision drones and refined real-time image-analysis pipelines. Repurposed for agriculture, these systems can survey extensive territories at centimeter resolution and negligible marginal cost, overcoming cloud and revisit-time constraints. Battle-tested algorithms for object detection and change analysis can underpin an independent monitoring architecture that curbs corruption by verifying tree establishment, survival, and growth. An emergent talent pool—drone pilots, software developers, data scientists, and field technicians—could raise the technical ceiling, but post-war brain drain is a risk. Retention requires competitive conditions, agro-tech hubs, and sustained funding. Table 2 illustrates how conflict-refined technologies can be redirected to a civilian, climate-resilient agroforestry agenda.

Table 2. Challenges and potential digital technology pathways for agroforestry in Ukraine.

Challenge	Potential Technology Pathway (Authors' Synthesis)
High cost of airborne surveys and limited UAV coverage	The emergence of a low-cost, long-range drone market could enable deployment of co-operative UAV fleets scanning large fields at high resolution.
Cloud cover and insufficient satellite granularity	Fusion of satellite SAR with drone-borne RGB/IR imagery offers a possible route to generate weather-independent, higher-fidelity maps.
Heavy computational load	Distributed edge-AI servers, originally built for battlefield imagery, may be repurposed for on-board pre-processing, sharply reducing data-transfer volumes.
Lack of transparent MRV for carbon projects	Blockchain registries created to log war damage could be adapted as tamper-proof ledgers for shelterbelts and carbon data.
Shortage of soil-moisture sensors	Mass-produced, low-cost wireless probes—networks deployed for field monitoring during hostilities—could be redirected to agro-ecological sensing and UAV-linked relays.

Source: compiled by authors. Note: this table presents the authors' synthesis based on the literature reviewed and contextual analysis of Ukraine's national conditions. It does not imply one-to-one correspondence with individual sources.

A pivotal opportunity lies in assembling a “Ukrainian environmental data set”. On the one hand, such a repository would support post-war restoration; on the other, it would supply unique input for global research on how armed conflict perturbs climate- and ecosystem-related parameters. Deep-learning models need large, representative data sets, yet novel ecological “big data” are scarce. Ukraine offers a mosaic of abrupt anthropogenic impacts—fire-damaged shelterbelts, localized wildfires, heavy-metal deposition, soil compaction—within a compressed timeframe. Deploying drones and ground sensors across liberated areas would document vegetation change, soil properties, and carbon

fluxes at high resolution, including time-series of shelterbelt degradation/regrowth, high-frequency soil-carbon dynamics under mechanical and thermal disturbances, and biomass trajectories exposed to aerosols and wartime emissions. This would clarify recovery speeds after destructive events (reducing uncertainty in IPCC “land-shock” scenarios), train algorithms for abrupt shifts in albedo/burn-scar density/dust-storm frequency expected under future extremes, and improve carbon-credit calculations in risk zones. The data set could be curated under FAIR principles and aligned with the EU Carbon Removal Certification Scheme, enabling the export of Ukrainian credits and generating licensing revenue for reconstruction—a self-reinforcing “data → models → investment → restoration” cycle. Built upon this base, a platform ecosystem linking digital MRV services, farm-level initiatives, research centers, and carbon markets would lower transaction costs and enable large-scale farmer participation; integration with CMIP and Copernicus frameworks would quantify the climate and food-security costs of conflict and inform preventive diplomacy. Yet, despite advanced tools, national constraints—wartime infrastructure damage, uneven rural internet, and limited affordability—may slow adoption without targeted support.

These contributions are qualified by several limitations. The analysis relies predominantly on secondary sources: peer-reviewed literature, official statistics, international reports, and prior case studies. The absence of primary biophysical measurements introduces uncertainty in estimating shelterbelt degradation rates, MRV efficiency gains (EO + UAV/LiDAR + AI), and restoration potential. Ongoing hostilities restrict field access to southern and eastern oblasts, raising the risk of spatial sampling errors and precluding a fully representative map of current shelterbelt condition. In this context, references to “partial” or “complete” degradation are qualitative descriptors synthesized from secondary reports and expert evaluations, unlike standardized forest-health systems.

Second, the review of AI-based solutions builds on published work by other authors; an exhaustive head-to-head comparison of architectures and algorithms was beyond this paper’s social-institutional focus. Wartime disruption of research infrastructure further constrained access to high-impact outlets; some evidence from local, non-indexed journals may lack the visibility and scrutiny that support global generalizability. Finally, the comparative ratings in Table 1 reflect the authors’ heuristic judgment rather than a formal expert-elicitation process or cost-benefit analysis. They should therefore be treated as indicative and subject to validation in pilot implementations and stakeholder consultations.

Future research directions. Future work should close empirical gaps and test policy-technology interactions. Long-term field experiments on reconstructing degraded shelterbelts with drought-tolerant, fast-growing species are indispensable for refining sequestration rates and ecosystem-service recovery. Parallel socio-economic modeling should assess which instrument mixes—subsidies, PES, carbon credits—most effectively motivate different farm types while maintaining equity and avoiding digital exclusion. Validating MRV tool chains by benchmarking satellite, UAV, and multi-sensor accuracy across conflict-affected and undisturbed territories remains essential. Interdisciplinary research should integrate big-data/AI approaches with traditional knowledge and place-based practices. Finally, assembling an open, FAIR-compliant Ukrainian environmental data set would provide training material for global AI models in climate-risk assessment, landscape restoration, and ecosystem-service valuation.

5. Conclusions

International evidence leaves little doubt that agroforestry is technically feasible in Ukraine and capable of delivering substantial ecological, economic, and social returns once global lessons are adapted to local realities. The country must emulate proven successes—such as India’s decisive removal of bureaucratic barriers and Europe’s gradual integration

of tree–crop systems into mainstream agricultural policy—while avoiding pitfalls such as insufficient farmer consultation or conflicting subsidies. Properly framed, agroforestry represents a clear win–win, enhancing food and energy security, rehabilitating war-scarred landscapes, and positioning Ukraine within global climate–finance regimes.

The evidence assembled in this study confirms that agroforestry remains an under-valued strategic asset in Ukraine’s agri-food sector. Over three decades of institutional turbulence, shelterbelts have drifted from vital ecological infrastructure to an effectively ownerless asset: clear property rights were never established, reliable funding never materialized, and no responsible manager emerged. Without timely reconstruction, continuing belt degradation will amplify erosion, moisture loss, and crop vulnerability to extreme weather—especially across the steppe zone.

Paradoxically, wartime conditions have opened a technological window: Ukraine now possesses a rare concentration of drone pilots, multi-sensor analytics specialists, and blockchain engineers. Redirecting these skills from defense to ecology could reduce transaction costs in agroforestry projects and contribute to the creation of a unique environmental data set documenting ecosystem degradation and recovery under extreme conditions. Such a resource would strengthen climate models and potentially generate new financing opportunities for restoration.

Taken together, the results demonstrate that AI-driven agroforestry, when supported by coherent legal, financial, and educational instruments, can help transform Ukraine’s degrading landscapes from risk liabilities into climate-resilient assets. While the Ukrainian case is shaped by specific historical and wartime circumstances, some of the digital approaches—such as low-cost UAV monitoring, multi-sensor data fusion, and blockchain-based MRV—may hold relevance for other countries facing infrastructure constraints or post-conflict recovery needs.

While international exemplars informed our design choices, material differences in land tenure and custodianship, production structures, administrative capacity, and biophysical conditions limit direct policy transplantation to Ukraine. The comparative cases are therefore used as design archetypes and sequencing templates rather than ready-made solutions, underscoring the need for locally adapted pilots and phased implementation strategies. At the same time, the study is subject to limitations related to reliance on secondary sources and restricted field access during wartime. Future research should therefore prioritize long-term field experiments, validation of digital MRV toolchains, and the socioeconomic modeling of farmer adoption pathways. Addressing these gaps will enhance the robustness and sustainability of agroforestry policy design in Ukraine and inform broader discussions on the role of digital tools in sustainable land-use strategies.

Author Contributions: Conceptualization, S.P., O.P. and P.P.; methodology, S.P., O.P. and P.P.; software, S.P.; investigation, S.P., O.P. and L.M.; data curation and analysis of the results, S.P., O.P. and L.M.; validation, P.P. and S.P.; formal analysis, O.P.; writing—original draft preparation, O.P., S.P., P.P. and L.M.; writing—review and editing O.P., S.P., P.P. and K.S.; project administration, O.P., S.P. and P.P.; supervision, P.P. and O.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable for studies not involving humans or animals.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: Authors declare that they do not have any competing financial, professional, or personal interests from other parties.

References

1. Moldavan, L.; Pimenowa, O.; Prus, P.; Pimenow, S. Pollution Problems in the Economic Agricultural Sector: Evaluating the Impact on Natural Resources and Solutions for Improvement. *Sustainability* **2024**, *16*, 11294. [CrossRef]
2. Food and Agriculture Organization of the United Nations. *Overview of Agroforestry*; FAO: Rome, Italy, 2025. Available online: <https://www.fao.org/agroforestry/about-agroforestry/overview/en/> (accessed on 18 June 2025).
3. Ghimire, M.; Dahal, D.; Giri, S.; Khanal, A.; Bhatt, D. Agroforestry systems in Nepal: Enhancing food security and rural livelihoods—a comprehensive review. *Food Energy Secur.* **2024**, *13*, e524. [CrossRef]
4. Quandt, A.; Neufeldt, H.; Gorman, K. Climate change adaptation through agroforestry: Opportunities and gaps. *Curr. Opin. Environ. Sustain.* **2023**, *60*, 101244. [CrossRef]
5. Food and Agriculture Organization of the United Nations. *Committee on Agriculture: Silvopastoral Systems as a Major Vehicle for Empowering Small Scale Farmers* (COAG/2024/3); FAO: Rome, Italy, 2024. Available online: <https://openknowledge.fao.org/server/api/core/bitstreams/f7fd8fd9-0384-4446-9ea2-06ac6494fe2f/content> (accessed on 16 June 2025).
6. Fuentes-Peñailillo, F.; Gutter, K.; Vega, R.; Silva, G.C. Transformative Technologies in Digital Agriculture: Leveraging Internet of Things, Remote Sensing, and Artificial Intelligence for Smart Crop Management. *J. Sens. Actuator Netw.* **2024**, *13*, 39. [CrossRef]
7. Pal, A.; Dubey, S.K.; Goel, S.; Kalita, P.K. Portable Sensors in Precision Agriculture: Assessing Advances and Challenges in Soil Nutrient Determination. *TrAC Trends Anal. Chem.* **2024**, *180*, 117981. [CrossRef]
8. Karunathilake, E.M.B.M.; Le, A.T.; Heo, S.; Chung, Y.S.; Mansoor, S. The Path to Smart Farming: Innovations and Opportunities in Precision Agriculture. *Agriculture* **2023**, *13*, 1593. [CrossRef]
9. Miller, T.; Mikiciuk, G.; Durlík, I.; Mikiciuk, M.; Łobodzińska, A.; Śnieg, M. The IoT and AI in Agriculture: The Time Is Now—A Systematic Review of Smart Sensing Technologies. *Sensors* **2025**, *25*, 3583. [CrossRef]
10. Tan, H.; Wang, L.; Lu, N.; Kou, W.; Wang, H.; Xu, W. Improved Estimation of Aboveground Biomass in Rubber Plantations Using Deep Learning on UAV Multispectral Imagery. *Drones* **2025**, *9*, 32. [CrossRef]
11. Pimenow, S.; Pimenowa, O.; Moldavan, L.; Udova, L.; Wasilewski, M.; Wasilewska, N. Transforming Agriculture into Energy: Unlocking Ukraine’s Bioenergy Potential for Sustainable Post-Conflict Recovery. *Energies* **2025**, *18*, 1212. [CrossRef]
12. Ocaña-Zuñiga, C.; Quiñones-Huatangari, L.; Barboza, E.; Peña, N.C.; Zamora, S.H.; Ojeda, J.M.P. Coffee Rust Severity Analysis in Agroforestry Systems Using Deep Learning in Peruvian Tropical Ecosystems. *Agriculture* **2025**, *15*, 39. [CrossRef]
13. Agyekumhene, C.; de Vries, J.R.; van Paassen, A.; Macnaghten, P.; Schut, M.; Bregt, A. Digital platforms for smallholder credit access: The mediation of trust for cooperation in maize value chain financing. *NJAS Wagening. J. Life Sci.* **2018**, *86–87*, 77–88. [CrossRef]
14. Cravero, A.; Bustamante, A.; Negrier, M.; Galeas, P. Agricultural Big Data Architectures in the Context of Climate Change: A Systematic Literature Review. *Sustainability* **2022**, *14*, 7855. [CrossRef]
15. Furdychko, O.I.; Drobot, O.I.; Dem’yaniuk, O.S.; Tkach, Y.D.; Bunas, A.A. (Eds.) *Ekologiya Ahrosfery: Pidruchnyk [Ecology of the Agrosphere: Textbook]*; DIA: Kyiv, Ukraine, 2022. Available online: https://www.agroeco.org.ua/wp-content/uploads/Publications/ecology_agrosphere.pdf (accessed on 28 August 2025).
16. Natchev, V.; Harnessing AI to Empower Smallholder Farmers: Bridging the Digital Divide for Sustainable Growth. Harvard Advanced Leadership Initiative Social Impact Review. 2024. Available online: <https://www.sir.advancedleadership.harvard.edu/articles/harnessing-ai-empower-smallholder-farmers-bridging-digital-divide-sustainable-growth> (accessed on 13 June 2025).
17. World Bank. *Agriculture, Forestry, and Fishing, Value Added (% of GDP)—Ukraine [Data Set]*; World Bank: Washington, DC, USA, 2024. Available online: <https://data.worldbank.org/indicator/NV.AGR.TOTL.ZS?locations=UA> (accessed on 25 August 2025).
18. World Bank. *Ukraine: Repairing Essential Logistics Infrastructure and Network Connectivity (RELINC) Project—Ukraine’s Transport and Logistics System*; World Bank: Washington, DC, USA, 2025. Available online: <https://documents1.worldbank.org/curated/en/099061725033525342/pdf/P502442-346a4fd3-882f-46ca-95c9-ce90c0a71619.pdf> (accessed on 28 August 2025).
19. Food and Agriculture Organization of the United Nations (FAO). *Agroforestry for Landscape Restoration: Exploring the Potential of Agroforestry to Enhance the Sustainability and Resilience of Degraded Landscapes*; FAO: Rome, Italy, 2017. Available online: <https://openknowledge.fao.org/server/api/core/bitstreams/8cd17c6f-051b-4105-866b-dcd344d4ba78/content> (accessed on 25 August 2025).
20. United States Department of Agriculture, Natural Resources Conservation Service (USDA NRCS). *Conservation Practice Standard 380: Windbreak-Shelterbelt Establishment and Renovation*; USDA NRCS: Washington, DC, USA, 2021. Available online: https://www.nrcs.usda.gov/sites/default/files/2022-10/Windbreak-Shelterbelt_Establishment_380_NHCP_CPS_2021.pdf (accessed on 20 August 2025).
21. Cabinet of Ministers of Ukraine. Regulation on the Maintenance and Preservation of Protective Forest Belts Located on Agricultural Lands (Resolution No. 650). 2020. Available online: <https://zakon.rada.gov.ua/laws/show/650-2020-%D0%BF#Text> (accessed on 19 June 2025).

22. Matsala, M.; Odruzhenko, A.; Sydorenko, S.; Sydorenko, S. War threatens 18% of protective plantations in eastern agroforestry region of Ukraine. *For. Ecol. Manag.* **2025**, *578*, 122361. [\[CrossRef\]](#)
23. Danylenko, I.; Bohaienko, V.; Liutnytskyi, S.; Mykhaylov, Y. Determination of Optimal Locations of Shelterbelts in Southern Ukraine Using Remote Sensing Data. *J. Indian. Soc. Remote Sens.* **2025**, *53*, 1495–1505. [\[CrossRef\]](#)
24. Breus, D.; Nikonchuk, N.; Pismennyi, O. Influence of War on the Forest Plantations of the Left Bank Kherson Region. *Eur. J. For. Eng.* **2024**, *10*, 123–132. [\[CrossRef\]](#)
25. Maliuha, V.; Sovakov, O.; Dudarets, S. The current state of windbreaks in the Left Bank Forest-Steppe of Ukraine. *Ukr. J. For. Wood Sci.* **2023**, *14*, 53–66. [\[CrossRef\]](#)
26. Jose, S. Agroforestry for ecosystem services and environmental benefits. *Agroforest Syst.* **2009**, *76*, 1–10. [\[CrossRef\]](#)
27. Food and Agriculture Organization of the United Nations. *Supporting the Restoration of Degraded Forest Steppe and Steppe Zones in Ukraine Through Integrated Natural Resources Management (Project GCP/UKR/004/GFF)*; FAO: Rome, Italy, 2025. Available online: <https://www.fao.org/partnerships/resource-partners/results/detail/supporting-the-restoration-of-degraded-forest-steppe-and-steppe-zones-in-ukraine-through-integrated-natural-resources-management-gcp-ukr-004-gff/en/> (accessed on 18 June 2025).
28. Tkachuk, O.; Viter, N.; Pankova, S.; Titarenko, O.; Yakovets, L. The current environmental state of the field protective forest belts of the forest-steppe of Ukraine. *Int. J. Ecosyst. Ecol. Sci.* **2023**, *13*, 1–8. [\[CrossRef\]](#)
29. United Nations Environment Programme (UNEP). *Climate Oriented Agroforestry for Shelterbelts: Estimating Biomass Through AI and Remote Sensing*; UNEP Tech Action: Copenhagen, Denmark, 2021. Available online: <https://tech-action.unepccc.org/wp-content/uploads/sites/2/2021/12/agroforestry.pdf> (accessed on 18 June 2025).
30. European Agroforestry Federation (EURAF). Ukraine. Available online: <https://euraf.isa.utl.pt/countries/ukraine> (accessed on 18 June 2025).
31. Bioenergy Association of Ukraine. *Analysis of Additional Sources of Wood Fuel in Ukraine (Position Paper No. 15)*; Bioenergy Association of Ukraine: Kyiv, Ukraine, 2016. Available online: <https://uabio.org/wp-content/uploads/2016/04/position-paper-uabio-15-en.pdf> (accessed on 18 June 2025).
32. Pereira, P.; Bašić, F.; Bogunovic, I.; Barcelo, D. Russian-Ukrainian war impacts the total environment. *Sci. Total Environ.* **2022**, *837*, 155865. [\[CrossRef\]](#)
33. Ukraine. Ukaz of the President of Ukraine No. 720/95 “On the Procedure for Allocation of Land Shares Transferred to Collective Ownership of Agricultural Enterprises and Organizations”. *Zakon.rada.gov.ua* Database. 1995. Available online: <https://zakon.rada.gov.ua/go/720/95#Text> (accessed on 27 June 2025).
34. Kovalenko, A.; Sakal, O.; Tretiak, N.; Skolskyi, I.; Shtohryn, H.; Tretiak, R. Field shelterbelts: Current state, land use issues and perspective in Ukraine. *Sci. Papers. Ser. E. Land Reclam. Earth Obs. Surv. Environ. Eng.* **2021**, *10*, 229–240.
35. Popov, A.; Tymoshevskiy, V.; Poliakh, V. Costs, Benefits and Obstacles to the Adoption and Retention of Shelterbelts: Regional Perception and Mind Map Analyses for Ukraine. *Geomat. Environ. Eng.* **2022**, *16*, 157–176. [\[CrossRef\]](#)
36. Moldavan, L.; Pimenova, O. “Holdingization” of the agricultural sector of Ukraine: Consequences and ways of their prevention. *Manag. Theory Stud. Rural. Bus. Infrastruct.* **2021**, *43*, 217–224. [\[CrossRef\]](#)
37. Hladun, H.B. Suchasnyi stan lisovykh melioratsii v agrolandshaftakh rivnynnoi chastyny Ukrainy [The current state of forest melioration in agro-landscapes of the flat part of Ukraine]. *Agroekologichnyi Zhurnal* **2004**, *1*, 66–71.
38. Moldavan, L.; Pimenowa, O.; Wasilewski, M.; Wasilewska, N. Crop rotation management in the context of sustainable development of agriculture in Ukraine. *Agriculture* **2024**, *14*, 934. [\[CrossRef\]](#)
39. Tranchina, M.; Reubens, B.; Frey, M.; Mele, M.; Mantino, A. What challenges impede the adoption of agroforestry practices? A global perspective through a systematic literature review. *Agrofor. Syst.* **2024**, *98*, 1817–1837. [\[CrossRef\]](#)
40. Rogoza, J. *Ukraine in the Face of A Demographic Catastrophe*; OSW Commentary; Ośrodek Studiów Wschodnich: Warszawa, Poland, 2023. Available online: <https://www.osw.waw.pl/en/publikacje/osw-commentary/2023-07-11/ukraine-face-a-demographic-catastrophe> (accessed on 18 June 2025).
41. Wengle, S.; Dankevych, V.; Mamonova, N. *Farming the Black Earth: The History and Politics of Ukraine’s Agricultural Land Markets Before, During and After the War*; Food and Agriculture Organization of the United Nations: Rome, Italy, 2024. Available online: <https://openknowledge.fao.org/server/api/core/bitstreams/96184d0f-e1c3-4c40-9a9e-084e4c25f4a8/content> (accessed on 27 July 2025).
42. United Nations Economic Commission for Europe; Food and Agriculture Organization of the United Nations. *Forest Products Annual Market Review 2022–2023 (UNECE/FAO Forest Products Annual Market Review)*; UNECE/FAO: Geneva, Switzerland, 2023. Available online: https://unece.org/sites/default/files/2023-11/FPAMR23_WEB.pdf (accessed on 27 July 2025).
43. Shelter Cluster Ukraine. *Winterization 2024–2025 Lessons Learned*; Shelter Cluster: Kyiv, Ukraine, 2025. Available online: https://s3.eu-north-1.amazonaws.com/cdn.sheltercluster.org/public/docs/Winterization%202024-2025%20Lessons%20Learned%20Final%2026_06_2025_0.pdf (accessed on 27 July 2025).

44. World Health Organization. *Ukraine: 2023–2024 Winter Risk Assessment*; WHO: Geneva, Switzerland, 2023. Available online: https://www.who.int/docs/librariesprovider2/default-document-library/risk-assessment-winter-in-ukraine_fin.pdf (accessed on 26 August 2025).
45. World Bank. *Ukraine Country Forest Note: Growing Green and Sustainable Opportunities (Report No. 149186-UA)*; World Bank: Washington, DC, USA, 2020. Available online: <https://documents1.worldbank.org/curated/en/938941593413817490/pdf/Ukraine-Country-Forest-Note.pdf> (accessed on 27 June 2025).
46. Verkhovna Rada of Ukraine. Land Code of Ukraine (Law No. 561-XII). 1990. Available online: https://www.wto.org/english/thewto_e/acc_e/ukr_e/wtaccukr88_leg_1.pdf (accessed on 19 June 2025).
47. Kulinich, P.F. Pravovyi rezhym zemel', peredanykh sil's'kohospodars'kym pidpriemstvam u kolektyvnu vlasnist' [Legal regime of lands transferred to agricultural enterprises into collective ownership]. *Pidpriemstvo Hospod. Pravo* **2005**, *10*, 29–32.
48. Verkhovna Rada of Ukraine. Land Code of Ukraine, Article 22. 2001. Available online: https://kodeksy.com.ua/zemel_nij_kodeks_ukraini/statja-22.htm (accessed on 18 June 2025).
49. Verkhovna Rada of Ukraine. On Amendments to Certain Legislative Acts of Ukraine Concerning Resolution of Collective Land Ownership Issues, Improvement of Land-Use Rules in Agricultural Land Areas, Prevention of Raiding, and Encouragement of Irrigation in Ukraine (Law No. 2498-VIII). 2018. Available online: <https://zakon.rada.gov.ua/laws/main/2498-19#Text> (accessed on 26 August 2025).
50. Cabinet of Ministers of Ukraine. Concept for the Development of Agroforestry in Ukraine (Decree No. 725-r). 2013. Available online: <https://zakon.rada.gov.ua/laws/show/725-2013-p#Text> (accessed on 26 August 2025).
51. Cabinet of Ministers of Ukraine. Action Plan for the Implementation of the Concept for the Development of Agroforestry in Ukraine (Order No. 582-r). 2014. Available online: <https://zakon.rada.gov.ua/laws/show/582-2014-p#Text> (accessed on 26 August 2025).
52. Cabinet of Ministers of Ukraine. On approval of the State Targeted program “Forests of Ukraine” for 2010–2015 (Resolution No. 977–2009 p). 2009. Available online: <https://zakon.rada.gov.ua/laws/show/977-2009-%D0%BF> (accessed on 19 June 2025).
53. Cabinet of Ministers of Ukraine. Strategy for Environmental Safety and Adaptation to Climate Change Until 2030 (Resolution No. 1363–2021 p). 2021. Available online: <https://zakon.rada.gov.ua/laws/show/1363-2021-p#Text> (accessed on 19 June 2025).
54. Semenova, I.; Vicente-Serrano, S.M. Long-term variability and trends of meteorological droughts in Ukraine. *Int. J. Climatol.* **2024**, *44*, 1849–1866. [CrossRef]
55. Capua, G.D.; Rahmstorf, S. Extreme weather in a changing climate. *Environ. Res. Lett.* **2023**, *18*, 102001. [CrossRef]
56. European Agroforestry Federation (EURAF). Agroforestry in Ukraine. 20 January 2023. Available online: <https://euraf.net/2023/01/20/ukraine/> (accessed on 18 June 2025).
57. Krysanov, D.; Dragan, O.; Tkachenko, K. The agricultural sector of the economy of Ukraine in the minds of increasing turbulence. *AIC Econ. Manag.* **2022**, *2*, 47–66. [CrossRef]
58. Gregor, K.; Reyer, C.P.O.; Nagel, T.A.; Mäkelä, A.; Krause, A.; Knoke, T.; Rammig, A. Reconciling the EU forest, biodiversity, and climate strategies. *Glob. Change Biol.* **2024**, *30*, e17431. [CrossRef]
59. Senf, C.; Pflugmacher, D.; Zhiqiang, Y.; Sebald, J.; Knorn, J.; Neumann, M.; Hostert, P.; Seidl, R. Canopy mortality has doubled in Europe's temperate forests over the last three decades. *Nat. Commun.* **2018**, *9*, 4978. [CrossRef] [PubMed]
60. Senf, C.; Seidl, R. Persistent impacts of the 2018 drought on forest disturbance regimes in Europe. *Biogeosciences* **2021**, *18*, 5223–5230. [CrossRef]
61. Seidl, R.; Thom, D.; Kautz, M.; Martin-Benito, D.; Peltoniemi, M.; Vacchiano, G.; Wild, J.; Ascoli, D.; Petr, M.; Honkaniemi, J.; et al. Forest disturbances under climate change. *Nat. Clim. Change* **2017**, *7*, 395–402. [CrossRef] [PubMed]
62. Allen, C.; Macalady, A.K.; Chenchouni, H.; Bachelet, D.; McDowell, N.; Vennetier, M.; Kitzberger, T.; Rigling, A.; Breshears, D.D.; Hogg, E.; et al. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *For. Ecol. Manag.* **2010**, *259*, 660–684. [CrossRef]
63. Enescu, C.M.; Dinca, L.; Ilie, L.; Mihalache, M.; Murariu, G.; Constandache, C. Agricultural Benefits of Shelterbelts and Windbreaks: A Bibliometric Analysis. *Agriculture* **2025**, *15*, 1204. [CrossRef]
64. Castle, S.E.; Miller, D.C.; Merten, N.; Ordonez, P.J.; Baylis, K. Evidence for the impacts of agroforestry on ecosystem services and human well-being in high-income countries: A systematic map. *Environ. Evid.* **2022**, *11*, 10. [CrossRef]
65. Torralba, M.; Fagerholm, N.; Burgess, P.J.; Moreno, G.; Plieninger, T. Do European agroforestry systems enhance biodiversity and ecosystem services? A meta-analysis. *Agric. Ecosyst. Environ.* **2016**, *230*, 150–161. [CrossRef]
66. Thiesmeier, A.; Zander, P. Can agroforestry compete? A scoping review of the economic performance of agroforestry practices in Europe and North America. *For. Policy Econ.* **2023**, *150*, 102939. [CrossRef]
67. Mosquera-Losada, M.R.; Santos, M.G.S.; Gonçalves, B.; Ferreira-Domínguez, N.; Castro, M.; Rigueiro-Rodríguez, A.; González-Hernández, M.P.; Fernández-Lorenzo, J.L.; Romero-Franco, R.; Aldrey-Vázquez, J.A.; et al. Policy challenges for agroforestry implementation in Europe. *Front. For. Glob. Change* **2023**, *6*, 1127601. [CrossRef]

68. Kellerman, T.; Feibel, S.; Smith, M.M.; Bentrup, G.; Batcheler, M.; Macfarland, K. Agroforestry across the United States: Results of the 2022 Census of Agriculture. *Agrofor. Syst.* **2025**, *99*, 34. [CrossRef]
69. Schoeneberger, M.M.; Bentrup, G.; Patel-Weynand, T. (Eds.) *Agroforestry: Enhancing Resiliency in U.S. Agricultural Landscapes under Changing Conditions (Gen. Tech. Report WO-96, 228 p.)*; U.S. Department of Agriculture, Forest Service: Washington, DC, USA, 2017. [CrossRef]
70. Rizvi, J.; Dhyani, S.K.; Arunachalam, A.; Rouge, J.C.; Singh, A. *The Success of A National Agroforestry Policy in India has Become A Model for Other Countries (CIFOR ICRAF Brief No. 9240)*; Center for International Forestry Research—World Agroforestry (CIFOR ICRAF): Bogor, Indonesia, 2024. [CrossRef]
71. Singh, K.; Dhyani, S.; Mishra, N.; Baudh, K.; Byun, C.; Agrawala, M. Land degradation and development in India: Status quo, challenges and opportunities. *Land Degrad. Dev.* **2024**, *35*, 2675–2683. [CrossRef]
72. He, J.; Sikor, T. Notions of justice in payments for ecosystem services: Insights from China's Sloping Land Conversion Program in Yunnan Province. *Land Use Policy* **2015**, *43*, 207–216. [CrossRef]
73. Pimenova, O.; Fylyuk, G. State support of agriculture: The analysis of an experience of Germany. *J. Financ. Manag. Acc.* **2014**, *2*, 19–30.
74. Santiago-Freijanes, J.J.; Rigueiro-Rodríguez, A.; Aldrey, J.A.; Moreno, G.; den Herder, M.; Burgess, P.; Mosquera-Losada, M.R. Understanding Agroforestry Practices in Europe Through Landscape Features Policy Promotion. *Agroforest. Syst.* **2018**, *92*, 1105–1115. [CrossRef]
75. Vaatz, A. Reviving Agroforestry: Unlocking Sustainable Farming Potential in the Baltics. EUKI. 2024. Available online: <https://www.euki.de/en/news/reviving-agroforestry-unlocking-sustainable-farming-potential-in-the-baltics/> (accessed on 19 June 2025).
76. Sileshi, G.W.; Dagar, J.C.; Nath, A.J.; Kuntashula, E. Agroforestry as a climate-smart agriculture: Strategic interventions, current practices and policies. In *Agroforestry for Sustainable Intensification of Agriculture in Asia and Africa*; Dagar, J.C., Gupta, S.R., Sileshi, G.W., Eds.; Springer: Singapore, 2023; pp. 589–640. [CrossRef]
77. Hübner, R.; Kühnel, A.; Lu, J.; Dettmann, H.; Wang, W.; Wiesmeier, M. Soil carbon sequestration by agroforestry systems in China: A meta-analysis. *Agric. Ecosyst. Environ.* **2021**, *315*, 107437. [CrossRef]
78. Steinfeld, J.P.; Bianchi, F.J.; Luiz Locatelli, J.; Rizzo, R.; Eduarda Bispo De Resende, M.; Ramos Ballester, M.V.; Cerri, C.E.P.; Bernardi, A.C.C.; Creamer, R.E. Increasing complexity of agroforestry systems benefits nutrient cycling and mineral-associated organic carbon storage, in south-eastern Brazil. *Geoderma* **2023**, *440*, 116726. [CrossRef]
79. U.S. Department of Agriculture. *A General Assessment of the Role of Agriculture and Forestry in U.S. Carbon Markets (Report to Congress)*; USDA: Washington, DC, USA, 2023. Available online: <https://www.usda.gov/sites/default/files/documents/USDA-General-Assessment-of-the-Role-of-Agriculture-and-Forestry-in-US-Carbon-Markets.pdf> (accessed on 20 June 2025).
80. Ecosystem Marketplace. *State of the Voluntary Carbon Markets Report 2023*; Forest Trends: Washington, DC, USA, 2023. Available online: <https://www.ecosystemmarketplace.com/publications/state-of-the-voluntary-carbon-market-report-2023/> (accessed on 20 June 2025).
81. Birkebaek, J. Ag Tech Firm Agreea Experiences Growth in Farmer Participation. Reuters. 2023. Available online: <https://www.reuters.com/sustainability/ag-tech-firm-agreena-experiences-growth-farmer-participation-2023-06-14/> (accessed on 20 June 2025).
82. Agreea. *How the AgreeaCarbon Programme Works: Rewarding Farmers for Making Meaningful Changes with Maximum Impact*; Agreea: Copenhagen, Denmark, 2024. Available online: <https://agreea.com/news/agreenacarbon-programme-how-to/> (accessed on 20 June 2025).
83. Agri-Climate Outcomes & Revenue (Acorn). *Planting A Better Future: Empower Smallholder Farmers*; Rabobank: Utrecht, The Netherlands, 2024. Available online: <https://acorn.rabobank.com/en/> (accessed on 21 June 2025).
84. Bogale, G.A.; Bekele, S.E. Sustainability of Agroforestry Practices and their Resilience to Climate Change Adaptation and Mitigation in Sub-Saharan Africa: A Review. *Ekológia* **2023**, *42*, 179–192. [CrossRef]
85. Andriatsitohaina, R.N.N.; Laby, P.; Llopis, J.C.; Martin, D.A. Agroforestry in Madagascar: Past, present, and future. *Agrofor. Syst.* **2024**, *98*, 1659–1680. [CrossRef]
86. Muthuri, C.W.; Kuyah, S.; Njenga, M.; Kuria, A.; Öborn, I.; Van Noordwijk, M. Agroforestry's contribution to livelihoods and carbon sequestration in East Africa: A systematic review. *Trees For. People* **2023**, *14*, 100432. [CrossRef]
87. European Union. Regulation (EU) 2021/2115 of the European Parliament and of the Council of 2 December 2021 establishing rules on support for strategic plans. *Off. J. Eur. Union* **2021**, *L 435*, 1–186.
88. European Commission. *Approved 28 CAP Strategic Plans (2023–2027): Summary Overview for 27 Member States—Facts and Figures*; Publications Office of the European Union: Luxembourg, 2023. Available online: <https://agriculture.ec.europa.eu/system/files/2023-06/approved-28-cap-strategic-plans-2023-27.pdf> (accessed on 27 August 2025).
89. Canales, E.; Bergtold, J.S.; Williams, J.R. Conservation intensification under risk: An assessment of adoption, additionally, and farmer preferences. *Am. J. Agric. Econ.* **2023**, *106*, 45–75. [CrossRef]

90. Secchi, S. The role of conservation in United States' agricultural policy from the Dust Bowl to today: A critical assessment. *Ambio* **2023**, *53*, 421–434. [CrossRef] [PubMed]
91. Charoud, H.; Costedoat, S.; Izquierdo-Tort, S.; Moros, L.; Villamayor-Tomás, S.; Castillo-Santiago, M.Á.; Wunder, S.; Corbera, E. Sustained participation in a Payments for Ecosystem Services program reduces deforestation in a Mexican agricultural frontier. *Sci. Rep.* **2023**, *13*, 22314. [CrossRef]
92. Pascual, U.; Phelps, J.; Garmendia, E.; Brown, K.; Corbera, E.; Martin, A.; Gomez-Baggethun, E.; Muradian, R. Social equity matters in payments for ecosystem services. *BioScience* **2014**, *64*, 1027–1036. [CrossRef]
93. Nuñez Godoy, C.C.; Pienaar, E.F. Motivations for, and barriers to, landowner participation in Argentina's payments for ecosystem services program. *Conserv. Sci. Pract.* **2023**, *5*, e12991. [CrossRef]
94. Robalino, J.; Pfaff, A.; Sandoval, C.; Sanchez-Azofeifa, G.A. Can we increase the impacts from payments for ecosystem services? Impact rose over time in Costa Rica, yet spatial variation indicates more potential. *For. Policy Econ.* **2021**, *132*, 102577. [CrossRef]
95. Hernandez-Aguilera, J.N.; Conrad, J.M.; Gómez, M.I.; Rodewald, A.D. The Economics and Ecology of Shade-grown Coffee: A Model to Incentivize Shade and Bird Conservation. *Ecol. Econ.* **2019**, *159*, 110–121. [CrossRef]
96. Lalani, B.; Lanza, G.; Leiva, B.; Mercado, L.; Haggard, J. Shade versus intensification: Trade-off or synergy for profitability in coffee agroforestry systems? *Agric. Syst.* **2023**, *214*, 103814. [CrossRef]
97. Hernández-Núñez, H.E.; Suárez, J.C.; Andrade, H.J.; Acosta, J.R.S.; Gutiérrez-Montes, I.; Núñez, R.D.; Casanoves, F.; Gutiérrez, G.A.; Gutiérrez, D.R. Interactions between climate, shade canopy characteristics and cocoa production in Colombia. *Front. Sustain. Food Syst.* **2024**, *8*, 1295992. [CrossRef]
98. Bojović, M.; Mrkonjić, Z.; Vukelić, I. Agroforestry systems and forest resources as a potential for sustainable energy development in the Western Balkan region. *Energy Sustain. Soc.* **2024**, *14*, 68. [CrossRef]
99. García-López, N.; Bargués-Tobella, A.; Goodman, R.C.; Uwingabire, S.; Sundberg, C.; Boman, C.; Nyberg, G. An integrated agroforestry-bioenergy system for enhanced energy and food security in rural sub-Saharan Africa. *Ambio* **2024**, *53*, 1492–1504. [CrossRef] [PubMed]
100. Ngango, J.; Musabanganji, E.; Maniriho, A.; Nkikabahizi, F.; Mukamuhire, A. Examining the adoption of agroforestry in Southern Rwanda: A double hurdle approach. *For. Sci. Technol.* **2023**, *19*, 260–267. [CrossRef]
101. Leduc, G.; Hansson, H. Behavioural factors for farmers' adoption of agroforestry practices in Sweden. *Sustain. Prod. Consum.* **2024**, *47*, 178–189. [CrossRef]
102. Ali, M.M.; Ahmad, B.; Sarmin, I.J.; Bari, M.S.; Pal, A.C.; Rahman, M.L. An assessment of agroforestry as a climate-smart practice: Evidences from farmers of northwestern region of Bangladesh. *Agrosyst. Geosci. Environ.* **2024**, *7*, e20501. [CrossRef]
103. European Forest Institute. *AGFORWARD—Agroforestry that Will Advance Rural Development [Project Description]*; European Forest Institute: Joensuu, Finland, 2025. Available online: <https://efi.int/projects/agforward-agroforestry-will-advance-rural-development> (accessed on 27 August 2025).
104. European Commission. *Agroforestry Innovation Networks (AFINET)* (Grant No. 727872). 2016. Available online: <https://cordis.europa.eu/project/id/727872> (accessed on 27 August 2025).
105. Finlayson, R.; Paramita, E. *Infographic: Agroforestry and Forestry in Sulawesi (AgFor)—Project Achievements*; Southeast Asia Regional Office, World Agroforestry Centre (ICRAF): Bogor, Indonesia, 2016. Available online: <https://www.cifor-icraf.org/publications/sea/Publications/files/brochure/BR0031-15.pdf> (accessed on 27 August 2025).
106. Food and Agriculture Organization of the United Nations. *Farmer Field Schools on Forestry. Global Farmer Field School Platform*. Available online: <https://www.fao.org/farmer-field-schools/ffs-overview/forestry/en/> (accessed on 28 August 2025).
107. World Bank. *Implementation Status & Results Report: Forests for Prosperity Project (P170798)*; World Bank: Washington, DC, USA, 2025. Available online: <https://documents1.worldbank.org/curated/en/099062024020027199/pdf/P170798-18942555-5ccd-4b4b-ae32-9e75b0f97b30.pdf> (accessed on 28 August 2025).
108. Pimenow, S.; Pimenowa, O.; Prus, P.; Niklas, A. The Impact of Artificial Intelligence on the Sustainability of Regional Ecosystems: Current Challenges and Future Prospects. *Sustainability* **2025**, *17*, 4795. [CrossRef]
109. Kou, W.; Shen, Z.; Zhang, Y.; Wang, H.; Ji, P.; Huang, L.; Zhang, C.; Ma, Y. Spatio-temporal analysis of agroforestry systems in hotan using multi-source remote sensing and deep learning. *Smart Agric. Technol.* **2024**, *9*, 100641. [CrossRef]
110. Stamford, J.; Aciksoz, S.B.; Lawson, T. Remote Sensing Techniques: Hyperspectral Imaging and Data Analysis. *Methods Mol. Biol.* **2024**, *2790*, 373–390. [CrossRef]
111. Navrozidis, I.; Lagopodi, A.; Alexandridis, T.K.; Bochtis, D.; Pantazi, X.E. Application of Machine Learning for Disease Detection Tasks in Olive Trees Using Hyperspectral Data. *Remote Sens.* **2023**, *15*, 5683. [CrossRef]
112. Turkulainen, E.; Honkavaara, E.; Näsi, R.; Koivumäki, N.; Östersund, M.; Pelto-Arvo, M.; Lyytikäinen-Saarenmaa, P.; Juntila, S.; Pölönen, I.; Karila, K.; et al. Comparison of Deep Neural Networks in the Classification of Bark Beetle-Induced Spruce Damage Using UAS Images. *Remote Sens.* **2023**, *15*, 4928. [CrossRef]
113. Noa-Yarasca, E.; Osorio Leyton, J.M.; Angerer, J.P. Deep Learning Model Effectiveness in Forecasting Limited-Size Aboveground Vegetation Biomass Time Series: Kenyan Grasslands Case Study. *Agronomy* **2024**, *14*, 349. [CrossRef]

114. Yan, X.; Li, J.; Smith, A.R.; Yang, D.; Ma, T.; Su, Y.; Shao, J. Evaluation of machine learning methods and multi-source remote sensing data combinations to construct forest aboveground biomass models. *Int. J. Digit. Earth* **2023**, *16*, 4471–4491. [CrossRef]
115. Wang, G.; Li, Y.; Feng, J.; Qiu, L.; Tang, F.; Yan, P.; Huang, C.; Li, S.; He, G. Mapping the Spatial Distribution of Aboveground Biomass in China's Subtropical Forests Based on UAV LiDAR Data. *Forests* **2023**, *14*, 1560. [CrossRef]
116. World Bank. *Digital Monitoring, Reporting, and Verification Systems and Their Application in Future Carbon Markets*; World Bank: Washington, DC, USA, 2022. Available online: <https://documents1.worldbank.org/curated/en/099605006272210909/pdf/IDU0ca02ce8009a2404bb70bb6d0233b54ffad5e.pdf> (accessed on 27 August 2025).
117. Soussi, A.; Fossa, M.; Zero, E.; Trincherio, D.; Sacile, R. Smart Sensors and Smart Data for Precision Agriculture: A Review. *Sensors* **2024**, *24*, 2647. [CrossRef] [PubMed]
118. Singh, R.K.; Behera, M.D.; Das, P.; Rizvi, J.; Dhyani, S.K.; Biradar, Ç.M. Agroforestry Suitability for Planning Site-Specific Interventions Using Machine Learning Approaches. *Sustainability* **2022**, *14*, 5189. [CrossRef]
119. Golicz, K.; Piepho, H.-P.; Minarsch, E.-M.L.; Niether, W.; Große-Stoltenberg, A.; Oldeland, J.; Breuer, L.; Gattinger, A.; Jacobs, S. Highlighting the potential of multilevel statistical models for analysis of individual agroforestry systems. *Agrofor. Syst.* **2023**, *97*, 1481–1489. [CrossRef]
120. Tafuro, A.; Costa, A.; Dammacco, G. A Conceptual Study on the Role of Blockchain in Sustainable Development of Public-Private Partnership. *Adm. Sci.* **2023**, *13*, 175. [CrossRef]
121. Nakalembe, C.; Becker-Reshef, I.; Bonifacio, R.; Hu, G.; Humber, M.L.; Justice, C.J.; Keniston, J.; Mwangi, K.; Rembold, F.; Shukla, S.; et al. A review of satellite-based global agricultural monitoring systems available for Africa. *Glob. Food Secur.* **2021**, *29*, 100543. [CrossRef]
122. Wasehun, E.T.; Hashemi Beni, L.; Di Vittorio, C.A. UAV and satellite remote sensing for inland water quality assessments: A literature review. *Environ. Monit. Assess.* **2024**, *196*, 277. [CrossRef]
123. Niu, X.; Chen, B.; Sun, W.; Feng, T.; Yang, X.; Liu, Y.; Liu, W.; Fu, B. Estimation of Coastal Wetland Vegetation Aboveground Biomass by Integrating UAV and Satellite Remote Sensing Data. *Remote Sens.* **2024**, *16*, 2760. [CrossRef]
124. Han, H.; Feng, Z.; Du, W.; Guo, S.; Wang, P.; Xu, T. Remote sensing image classification based on multi-spectral cross-sensor super-resolution combined with texture features: A case study in the Liaohe planting area. *IEEE Access* **2024**, *12*, 16830–16843. [CrossRef]
125. Wang, L.; Zhang, H.; Zeng, H.; Li, X.; Gao, H.; Yu, Q. A CBAM-GAN-based method for super-resolution reconstruction of remote sensing image. *IET Image Process.* **2023**, *18*, 548–560. [CrossRef]
126. Wang, P.; Bayram, B.; Sertel, E. A comprehensive review on deep learning based remote sensing image super-resolution methods. *Earth-Sci. Rev.* **2022**, *232*, 104110. [CrossRef]
127. Escobar-López, A.; Castillo-Santiago, M.Á.; Mas, J.F.; Hernández-Stefanoni, J.L.; López-Martínez, J.O. Identification of coffee agroforestry systems using remote sensing data: A review of methods and sensor data. *Geocarto Int.* **2024**, *39*, 2297555. [CrossRef]
128. Du, B.; Shan, L.; Shao, X.; Zhang, D.; Wang, X.; Wu, J. Transform Dual-Branch Attention Net: Efficient Semantic Segmentation of Ultra-High-Resolution Remote Sensing Images. *Remote Sens.* **2025**, *17*, 540. [CrossRef]
129. Kouadio, L.; Roni, M.Z.K.; Amine, I.D.I.; El Jarroudi, M.; Junk, J.; Mokhtari, N.; Mokrini, F.; Laasli, S.-E.; Lahlali, R.; Belabess, Z. A Review on UAV-Based Applications for Plant Disease Detection and Monitoring. *Remote Sens.* **2023**, *15*, 4273. [CrossRef]
130. Cifuentes-Faura, J. Corruption in Ukraine during the Ukrainian–Russian war: A decalogue of policies to combat it. *J. Public Aff.* **2024**, *24*, e2905. [CrossRef]
131. Pimenow, S.; Pimenowa, O.; Prus, P. The impact of business model sustainability on the financial performance of Ukraine's leading companies before the military conflict. *Sustainability* **2024**, *16*, 10008. [CrossRef]
132. Hartel, T.; Dorresteyn, I.; Klein, C.; Máthé, O.; Moga, C.I.; Öllerer, K.; Roellig, M.; von Wehrden, H.; Fischer, J. Wood-pastures in a traditional rural region of Eastern Europe: Characteristics, management and status. *Biol. Conserv.* **2013**, *166*, 267–275. [CrossRef]
133. Plieninger, T.; Hartel, T.; Martín-López, B.; Beaufoy, G.; Bergmeier, E.; Kirby, K.; Montero, M.J.; Moreno, G.; Oteros-Rozas, E.; van Uytvanck, J. Wood-pastures of Europe: Geographic coverage, social–ecological values, conservation management, and policy implications. *Biol. Conserv.* **2015**, *190*, 70–79. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.