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Woody encroachment on agricultural land – environmental drivers and carbon stock assessment: A case of Lithuania

Edita Abalikštienė[1*], Vilma Šalkauskienė[1]

[1] Faculty of Environmental Engineering, Lietuvos Inzinerijos Kolegija, Higher Education Institution, Tvirtovės Al. 35, Kaunas, LT-50154, Lithuania
* Corresponding author's e-mail: edita.abalikstiene@lik.tech

ABSTRACT

This study investigates woody encroachment on agricultural land and evaluates its biomass accumulation and carbon sequestration potential. By integrating spatial data analysis with field-based measurements, areas of naturally afforested agricultural land were identified and assessed for the period 2016–2025. The results show that over ten years, 59,797 ha of agricultural land became naturally overgrown with woody vegetation, primarily on light-textured soils (42.6%) and in undulating terrain (65.5%). Field surveys were conducted in 80 naturally afforested plots, where tree height, diameter at breast height, stand density, and species composition were recorded. Based on these measurements, biomass accumulation and carbon content were estimated. The findings indicate that after approximately a decade of natural succession, the studied areas accumulated on average 36.0 t ha^{-1} of biomass, containing 18.0 t ha^{-1} of carbon, equivalent to 66.1 t CO_2 ha^{-1}. When extrapolated to the total area of 59,797 ha, this corresponds to approximately 2.15 million tonnes of biomass, 1.08 million tonnes of carbon, and 3.95 million tonnes of CO_2 stored in naturally afforested land. These results demonstrate that woody encroachment on abandoned agricultural land serves as a significant natural carbon sink, accumulating on average 66 t CO_2 ha^{-1} over a decade – several times higher than in unmanaged or extensively managed grasslands.

Keywords: woody encroachment, agricultural land, biomass estimation, carbon sequestration, land-use change, spatial analysis.

INTRODUCTION

Woody encroachment on agricultural land is currently one of the main processes shaping landscape change in Lithuania. This process alters ecosystem structure, modifies plant communities, and affects local biodiversity (Ghafari et al., 2020; Biczkowski et al., 2024; Juknelienė et al., 2024; Karásek et al., 2022).

Similar patterns are observed across Europe, where the decline in agricultural intensity and shifts in land use promote natural vegetation succession in rural areas (Navarro et al., 2012; Davison et al., 2021). In Central and Eastern Europe, this trend is most pronounced in remote agricultural regions characterized by depopulation, low soil fertility, and limited economic profitability (Mason et al., 2024; Banach et al., 2017; Pawłat-Zawrzykraj et al., 2019; Noszczyk, 2018).

In Lithuania, natural regeneration has been occurring for several decades, as abandoned fields gradually become overgrown with shrubs and young trees (Ivavičiūtė, 2018; Mozgeris et al., 2021; Tiškutė-Memgaudienė, 2021; Sujetovienė et al., 2022; Ivavičiūtė, 2023; Kryszk et al., 2024). The rate and direction of these changes depend on soil characteristics, terrain, proximity to mature forests, and local climatic conditions (Chappell, 2019; Petrokas et al., 2025; Segura et al., 2021; Šepeteinė et al., 2014).

Woody encroachment has also received increasing attention for its contribution to climate change mitigation (Thibault et al., 2022). Naturally regenerated forests store considerably more carbon than unmanaged grasslands—about 4–5 t C ha^{-1} yr^{-1} compared with 0.8–1.2 t C ha^{-1} yr^{-1} in wet grasslands (IPCC, 2014; Fisher et al., 2014; Wellock et al., 2014; Nabuurs et al., 2016; Psistaki et al., 2024). Over ten years, this difference can result in up to eight times greater CO_2 accumulation in naturally regenerated forests. Because of this, woody encroachment, often called natural regeneration, is now viewed as a practical and low-cost approach to large-scale carbon capture (Kilpeläinen et al., 2022; Lal, 2020).

This study employed spatial data analysis, records of woody encroachment, and field measurements to assess woody encroachment on agricultural land in Lithuania. The research integrates land-use change datasets with geospatial information and empirical field surveys to evaluate tree biomass and carbon accumulation within naturally afforested areas.

Research aim: To assess the extent, environmental drivers, and carbon stock of woody encroachment on agricultural land in Lithuania.

Research objectives: (1) To evaluate the extent and spatial patterns of woody encroachment on agricultural land during 2016–2025 and identify the main environmental drivers influencing this process using spatial datasets; (2) Based on field measurements, to estimate biomass accumulation and carbon stock within newly established woody vegetation and compare it with extensively managed grasslands.

The study provides a comprehensive assessment of woody encroachment on agricultural land, highlighting its significance for land-use management and climate change mitigation strategies.

MATERIALS AND METHODS

This study combined spatial analysis and field-based measurements to assess woody encroachment on agricultural land in Lithuania (Figure 1).

The research was conducted in two main stages: (1) Assessment of land-use change and analysis of environmental factors; (2) Field-based estimation of biomass and carbon content.

1. Land-use change was determined using the Cadastral Data of the Republic of Lithuania for the years 2016 and 2025. These datasets made it possible to identify agricultural areas naturally overgrown by woody vegetation. The spatial analysis was conducted integrating the following geospatial layers: Digital orthophoto maps; Lithuanian Forest Cadastre data; Soil spatial datasets by soil type and granulometric composition; Topographic and relief data; Abandoned land dataset; Drainage and waterlogging condition dataset; Special land-use condition dataset. Distances between newly established woody vegetation patches and existing forests were calculated to assess seed dispersal proximity, while expansion direction was used to evaluate the potential influence of prevailing wind patterns on natural regeneration.
2. Field data were collected in 80 naturally overgrown sites, representing various stages of woody encroachment on agricultural land. Sample plots of 10 × 10 m were established in areas where spontaneous woody vegetation had reached a visually stable structure and measurable tree dimensions. The selection of plots was based on preliminary field surveys and dendrometric indicators such as tree height, diameter at breast height (DBH), and stand density, ensuring that only sites with well-developed spontaneous growth were included.

Within each plot, all trees exceeding 2 m in height were measured, while shrubs and undergrowth were recorded separately to assess vertical stand structure. For each tree, species identification was performed through field-based dendrological assessment using diagnostic morphological traits, primarily bark characteristics and leaf morphology, DBH (cm) and total height (m) were measured using a dendrometric caliper and a laser hypsometer or clinometer. The number of individuals per species was counted to calculate stand density (trees per hectare) and species composition.

All investigated sites were confirmed to be at least ten years old, based on field observations of trunk dimensions, bark texture, and growth form, indicating a stage of stable spontaneous regeneration and sufficient biomass accumulation for reliable carbon stock estimation.

In each sample plot, the following biometric parameters were measured: tree density (trees per ha) and mean diameter at breast height (DBH, cm). Only trees exceeding 2 m in height were measured to ensure inclusion of well-established spontaneous woody vegetation.

Above-ground biomass (AGB, kg tree^{-1}) was estimated from DBH using species-group–specific allometric equations developed by Jenkins et al. (2003), which directly relate stem diameter to dry biomass without requiring explicit height or form-factor parameters:

$$AGB = \exp\left(b_0 + b_1 \ln(DBH)\right) \tag{1}$$

where: b_0 and b_1 are regression coefficients corresponding to each forest-type group (pine, spruce, birch, alder/aspen, and mixed hardwoods). The relative proportions of these groups in the studied sites were: pine – 35%, spruce – 21%, birch – 22%, black alder – 7%, and other deciduous species – 15%.

Below-ground biomass (BGB) was calculated as a proportion of above-ground biomass according to Jenkins et al. (2003):

$$BGB = AGB \times \exp\,(-1.6911 + 0.816/DBH) \quad (2)$$

Total tree biomass was derived as the sum of above- and below-ground components:

$$B_{Total} = AGB + BGB \quad (3)$$

It was assumed that 50% of dry biomass consists of carbon (IPCC, 2006):

$$C = 0.5 \times B_{Total} \quad (4)$$

Carbon content was converted to CO_2 equivalent using the molecular weight ratio of 44/12 = 3.67:

$$CO_{2eq} = C \times 3.67 \quad (5)$$

Per-hectare values were obtained by scaling tree-level estimates by the mean stand density (1.500 trees ha^{-1}), and total landscape-level carbon accumulation was extrapolated using the total area of spontaneously afforested land (59,797 ha).

The ecological significance of spontaneous woodland and shrub expansion was assessed by comparing the obtained results with literature-based reference values. According to IPCC (2014), unmanaged grasslands typically accumulate 0.8–1.2 t C ha^{-1} yr^{-1}, while self-seeded young woodlands can reach 4–5 t C ha^{-1} yr^{-1} or more. This comparison enables the evaluation of the relative climate-mitigation potential of spontaneous woodland and shrub expansion in Lithuania's post-agricultural landscapes.

RESULTS AND DISCUSSION

Drivers and implications of woody encroachment on agricultural land

Woody encroachment on agricultural land refers to the establishment of trees and shrubs without direct human planting or management. Such processes usually occur on parcels that were previously used for farming and have since remained uncultivated. Land that is abandoned or managed with low intensity is especially prone to natural regeneration of woody vegetation (Fayet et al., 2022).

The development of these areas depends on a combination of ecological factors – uch as slope, soil type, and terrain – and on social, demographic, economic, and institutional conditions. These processes are happening for a few reasons: villages are losing people, society is getting older, many farms are not economically viable, and

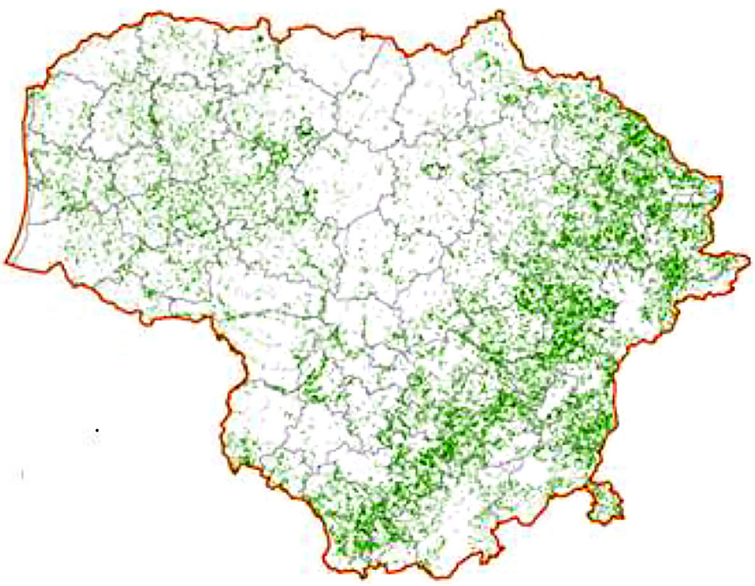

Figure 1. Woody encroachment on agricultural land

changes in agricultural policy support and land ownership after the collapse of collective farms have reinforced these trends (Castillo et al., 2021).

In Lithuania, naturally regenerated woody vegetation most often develops on abandoned agricultural land, especially on plots bordering existing forests (Šalkauskienė et al., 2019). The most favourable conditions occur in the eastern and southeastern parts of the country, particularly on the leeward sides of prevailing winds and along the edges of mature forest stands (Tumelienė et al., 2022).

The woody encroachment on farmland results from both ecological and socio-economic drivers. Although it can improve environmental quality, it may also complicate land management (Oszako et al., 2023). The abandonment of farmland remains one of the main drivers of woody encroachment. In Lithuania, it is linked to low farm income, rural depopulation, and changes in land ownership. Once farming stops, trees and shrubs establish naturally (Juknelienė et al., 2025).

Soil fertility is another factor that affects this process. Land with poorer soils is less suitable for intensive farming and tends to become naturally overgrown by woody vegetation more easily.

In recent years, naturally regenerated forests have received growing attention for their role in mitigating climate change. Such forests store much more carbon than unmanaged grasslands. Across Europe, wet grasslands capture about 0.8–1.2 tonnes of carbon per hectare each year, while young, naturally regenerated forests store around 4–5 tonnes (Hu et al., 2023; Nabuurs et al., 2018; IPCC, 2014). Over ten years, this creates a significant difference and shows that allowing forests to regrow naturally can be an effective and low-cost way to reduce carbon dioxide in the atmosphere (Schmitz et al., 2023; Lal, 2021).

As woody vegetation continues to expand naturally, both biodiversity and carbon storage increase. In Lithuania, these land-use trends have also been supported by EU Rural Development Programme measures and funding (Kryszk et al., 2024). However, while this process benefits nature, it can also have downsides – open habitats disappear, farm productivity decreases, and the landscape structure changes. That's why it is important to find a balance between environmental protection, agricultural use, and social needs (Jasinavičiūtė et al., 2022).

To make informed decisions and manage land sustainably, it is necessary to monitor how land cover is changing. This requires the integration of spatial data, regular field observations, and carbon stock assessments to determine how much naturally regenerated woody vegetation contributes to Lithuania's and the EU's climate goals. Sustainable land management depends on continuous monitoring and well-coordinated actions.

Woody encroachment on agricultural land

Forests currently cover more than one-third of Lithuania's territory (approximately 2.2 million hectares). Using agricultural land census and cadastral data, the analysis assessed spontaneously afforested areas within agricultural land, revealing their long-term dynamics and shifting share within the national land-use structure. Between 2016 and 2025, the total area of woody vegetation on agricultural land increased by 59,797 ha, from 158,559 ha to 218,356 ha, corresponding to about 0.9% of the country's territory. The analysis of cadastral data revealed marked regional differences in the intensity and direction of these changes.

The most extensive woody encroachment occurred in the eastern and southeastern regions, notably in Molėtai, Utena, Zarasai, Anykščiai, and Lazdijai municipalities, where the proportion of overgrown agricultural land increased by 2.0–2.6%. These territories are characterized by light-textured soils, rolling terrain, and high forest connectivity, all of which favour natural regeneration. Moderate expansion, typically 0.6–1.5%, was recorded in the central and southern regions, such as Elektrėnai, Širvintos, and Rokiškis, while minimal or even negative change was observed in Pasvalys (–162 ha) and Klaipėda (–136 ha), reflecting urban development and intensive land use.

A comparison with land productivity indicators shows that low- to medium-productivity municipalities (35–42 points) experienced the largest increase in woody cover, whereas high-productivity areas (above 50 points) remained stable or slightly declined. This confirms that marginal farmland is most vulnerable to natural succession once active cultivation ceases.

Municipalities with a higher proportion of forested land (over 40%) experienced faster woody encroachment, underscoring the importance of proximity to seed sources and edge effects in promoting spontaneous afforestation. In contrast, areas dominated by heavy clay or peat soils were less favourable for natural regeneration due to poor drainage and soil compaction.

Overall, the results demonstrate that woody encroachment in Lithuania is a spatially heterogeneous yet persistent process, strongly influenced by environmental conditions, land-use intensity, and demographic factors. When viewed together with broader socio-ecological patterns, it becomes evident that woody encroachment depends on regional land-use history, demographic change, agricultural policy measures, and institutional settings. Because of this diversity, both environmental and human drivers must be considered when assessing landscape development and planning future land use.

Although soils with lower agricultural potential are generally more susceptible to abandonment and natural regeneration, land productivity alone does not determine expansion outcomes. The analysis illustrates the interplay between land quality and a range of ecological, social, economic, and institutional factors shaping land-use change in Lithuania. Understanding these multifaceted interactions is essential for developing targeted, evidence-based land management and climate mitigation strategies.

According to cadastral records, 24,271 parcels of naturally regenerated woody vegetation were registered nationwide, and these self-overgrown areas are presented in Figure 2.

The average parcel size was 0.63 ha, while the largest identified parcel reached 21 ha, indicating substantial variability in parcel size and the extent of woody vegetation establishment. To further analyse spatial trends, a representative sample of parcels was selected for detailed geostatistical evaluation, incorporating environmental layers such as soil type, topography, and proximity to existing forests.

Analysis of parcel distribution by soil type revealed that woody encroachment predominantly occurred on light-textured soils (sandy – 24.3%; sandy loam – 18.3%; light loam – 19.2%; medium loam – 17.6%), while peat (14.5%) and clay soils (6.1%) were less conducive to spontaneous afforestation. These findings indicate that lighter soils are more susceptible to the natural regeneration of woody vegetation, whereas heavier soils inhibit such processes.

Topographical patterns reinforced this trend. More than half of the analysed parcels (51.4%) were located on undulating terrain, with the remainder distributed across flat (34.5%) and sloped (14.1%) areas. Microrelief variation supports natural regeneration by creating small sheltered microsites that favour seed germination and early growth.

The proximity analysis showed that woody encroachment was most intensive on parcels located within about 100 meters of existing forest edges, highlighting the decisive influence of nearby seed sources on regeneration processes. Wind direction did not show any clear relationship with the rate of woody encroachment, indicating that most seeds spread locally from adjacent forests rather than being carried over long distances.

The results of this study confirm earlier research showing that woody encroachment is driven by soil type, terrain morphology, and proximity to existing forest stands (Jõgiste et al., 2015; Fayet et al., 2022; Juknelienė et al., 2024; Blaud et al., 2023). Sandy and loamy sand soils provide favourable conditions for the establishment of woody vegetation, whereas loam and clay soils limit this process due to higher moisture content and reduced aeration (Gxasheka et al., 2023). Areas with greater slope inclination exhibit faster woody vegetation expansion. The most intensive encroachment occurs in areas where agricultural activities have not been carried out and which are directly adjacent to existing forests (Pedersen et al., 2025). The findings of this study further show that light soils, undulating terrain, and locations adjacent to forest stands represent the most favourable conditions for spontaneous woodland development on agricultural land.

Carbon sequestration potential of spontaneously afforested areas

To evaluate the climate-mitigation potential of woody encroachment on former agricultural land, a field-based biomass survey was conducted across 80 naturally regenerated sites

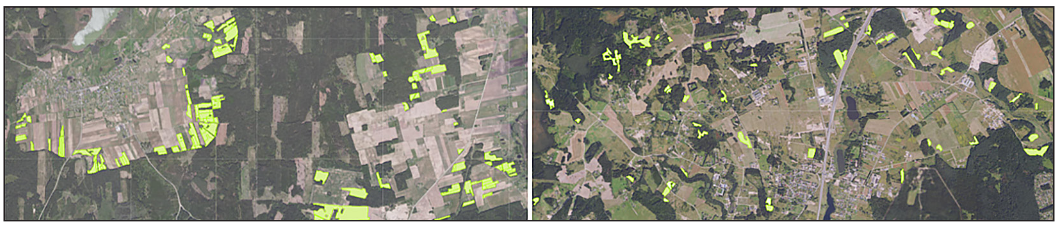

Figure 2. Naturally regenerated areas

in Lithuania. The selected plots represented a variety of soil types, moisture regimes, and land-use legacies, ensuring that the sampling captured the diversity of natural regeneration conditions. Only areas where succession had continued for at least ten years were included, ensuring that the recorded vegetation reflected established young stands rather than temporary shrub communities.

The average tree height was 8.8 m, ranging from 6–7 m in conifers (mainly *Pinus sylvestris* and *Picea abies*) to 13–15 m in fast-growing deciduous species such as grey alder (*Alnus incana*), black alder (*Alnus glutinosa*), and aspen (*Populus tremula*). The mean DBH was 8.9 cm, with the majority of stems ranging between 6 and 12 cm, reflecting typical stand structure at the early pole-wood stage of natural succession.

Tree density varied from 1.200 to 2.200 individuals ha^{-1}, with an average of 1.500 trees ha^{-1}, indicating vigorous natural regeneration and high site occupancy. In most sites, species composition reflected local environmental conditions: pine and birch dominated on light sandy soils, whereas black alder and aspen were more frequent in moist or periodically waterlogged depressions. Shrub species such as willow (*Salix* spp.), rowan (*Sorbus aucuparia*), and hazel (*Corylus avellana*) often formed a dense lower layer, contributing to ground shading and organic matter accumulation.

Above-ground biomass (AGB) was estimated from DBH using species-group–specific allometric equations developed by Jenkins et al. (2003) for temperate forests. The overall species composition of the sample plots comprised approximately pine (35%), spruce (21%), birch (22%), black alder (7%), and other deciduous species (15%) (Table 1).

Each tree contained on average 24.0 kg of dry biomass, corresponding to 12.0 kg of carbon and 44.1 kg of CO_2. When extrapolated to a mean stand density of 1.500 trees ha^{-1}, this represents 36.0 t biomass ha^{-1}, 18.0 t C ha^{-1}, and 66.1 t CO_2 ha^{-1} (Table 1). When scaled to the total area of 59,797 ha of naturally afforested land, the accumulated stock equals approximately 2.15 million tonnes of biomass, 1.08 million tonnes of carbon, and 3.95 million tonnes of CO_2 stored over a ten-year period.

Across all plots, the mean above-ground biomass accumulation reached approximately 36 t ha^{-1}, corresponding to about 18 t C ha^{-1} or 66 t CO_2 ha^{-1}. These values are consistent with findings from comparable naturally regenerated stands in Northern and Central Europe, confirming that spontaneous regeneration on abandoned farmland represents a significant short-term carbon sink.

Carbon sequestration rates differ according to land-cover type. IPCC (2014) reports that unmanaged grasslands typically accumulate about 10 t C ha^{-1} over ten years (≈ 36.7 t CO_2 eq), while naturally regenerated forests in Europe may reach approximately 45 t C ha^{-1} over similar periods (≈ 165 t CO_2 eq). The 18.0 t C ha^{-1} (≈ 66 t CO_2 eq) observed in this study therefore fits well within the lower range of carbon stocks expected in young spontaneous woodlands. This suggests that natural regeneration processes on abandoned farmland are functioning effectively under the prevailing soil and climatic conditions.

Early-successional forests sequester carbon more rapidly than herbaceous vegetation, with above-ground accumulation commonly reaching 1.5–3.0 t C ha^{-1} yr^{-1} (Chazdon et al., 2016; Bai et al., 2022). Over longer timescales, spontaneous forests on former cropland develop 70–120 t C ha^{-1} of above-ground biomass carbon (Pugh et al., 2019; Nabuurs et al., 2016), demonstrating a markedly higher long-term storage potential compared to grassland systems.

Below-ground carbon stocks exhibit a similar trend. Meta-analyses show that agricultural abandonment and subsequent natural succession typically increase soil organic carbon by 20–40% within the first decades, largely due to increased litter inputs and the cessation of soil disturbance (Xu, 2023; Lu et al., 2023). Collectively, these findings confirm the substantial contribution of spontaneous afforestation to ecosystem-level carbon accumulation (Varnagirytė-Kabašinskienė et al., 2021). These trends are consistent with conditions in Lithuania, where spontaneous regeneration predominantly takes place on light-textured soils previously depleted by cultivation.

The results show that woody encroachment on abandoned agricultural land acts as a natural sink of carbon dioxide, accumulating significantly more CO_2 per hectare than extensively managed grasslands. Future studies should integrate climate projections, socio-economic trends, and land-use policy scenarios to evaluate the extent to which natural regeneration of woody vegetation can offset the loss of productive agricultural areas.

Table 1. Mean stand parameters and carbon accumulation in spontaneous forests

Parameter	Mean ± SD	Description / Note
Tree height, m	8.8 ± 2.9	Average height of dominant trees
Diameter at breast height (DBH), cm	8.9 ± 1.8	Mean stem diameter
Stand density, trees/ha	1.500 ± 320	Number of trees per hectare
Above-ground biomass per tree kg/tree	20.0 ± 2	Estimated from dendrometric volume and wood density
Below-ground biomass per tree, kg/tree	4.0 ± 0.4	Estimated as 20% of above-ground biomass
Total biomass per tree, kg/tree	24.0 ± 2.4	Combined above- and below-ground biomass
Carbon per tree, kg/tree	12.0 ± 1.2	50% of dry biomass
CO_2 equivalent per tree, kg/tree	44.1 ± 4.4	3.67 × carbon content
Total biomass per hectare, t/ha	36.0 ± 3.6	24.0 kg × 1.500 trees ha^{-1} / 1.000
Carbon stock per hectare, t C / ha	18.0 ± 1.8	12.0 kg × 1.500 trees ha^{-1} / 1.000
CO_2 equivalent per hectare, t CO_2 eq/ha	66.1 ± 6.6	44.1 kg × 1.500 trees ha^{-1} / 1.000
Estimated total (59,797 ha)	2.15 Mt biomass / 1.08 Mt C / 3.95 Mt CO_2 eq	Ten-year accumulation across all naturally afforested land in Lithuania

Note: Biomass estimates are subject to approximately ±10% uncertainty due to species-specific variability in allometric equations.

CONCLUSIONS

This study assessed the woody encroachment on agricultural land in Lithuania between 2016 and 2025, integrating spatial analysis, field measurements, and carbon sequestration assessment to provide a comprehensive understanding of this land-use transition. During the study period, the area of naturally afforested agricultural land increased by 59,797 ha, with the most extensive expansion occurring on light-textured soils (e.g., sandy and sandy loam) and in undulating terrain. Spatial analysis revealed that overgrowth was most intensive within approximately 100 m of existing forest edges, highlighting the strong influence of seed-source proximity on natural regeneration patterns.

Field-based results indicated that spontaneously established woody vegetation stores on average 18.0 t C ha^{-1}, equivalent to 66.1 t CO_2 ha^{-1} over a ten-year period. When extrapolated to the total area of 59,797 ha, this corresponds to approximately 2.15 million tonnes of biomass, 1.08 million tonnes of carbon, and 3.95 million tonnes of CO_2 equivalent. These values substantially exceed the carbon sequestration potential of unmanaged grasslands, emphasizing the effectiveness of woody encroachment as a nature-based solution for climate-change mitigation.

Naturally regenerated forests can absorb nearly twice as much carbon as grasslands, but the loss of agricultural land to woody vegetation should be assessed from multiple perspectives, not only in terms of carbon balance. The findings highlight the importance of integrating woody encroachment processes into land-use planning, national carbon accounting under the EU LULUCF Regulation, and broader climate-mitigation and biodiversity-restoration strategies in Lithuania and other temperate regions.

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