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# Application of the Nature Frame concept to ensure the sustainability of agroecosystems and manage Soil Organic Carbon content in agricultural soils

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**Context:** This conceptual study explores the role and application of landscape polarisation principles in addressing applied issues of agriculture and soil health maintenance. The Nature Frame concept reflects universal principles of sustainable landscape management and land use; promoting these principles in agriculture can establish a robust system of sustainable soil use and contribute to policymaking aimed at achieving the objectives of the Soil Monitoring and Resilience Directive.

**Objectives:** To present the concept of a Nature Frame as a tool for modeling and optimizing the intensity of agroecosystem use and prioritizing agricultural measures in order to ensure their sustainable functioning, biodiversity dispersal, and the preservation of Soil Organic Carbon (SOC).

**Methodology:** An analysis of the pilot area (Kelmė distr. mun., Lithuania) was performed, incorporating the 2025 crop declaration dataset of the National Paying Agency, and soil erosion and SOC distribution data from the Lithuanian Soil Information System database Dirv\_DR10LT. A Nature Frame model for the pilot area was developed to identify soil problems related to SOC migration and accumulation. The importance of the areas for the conservation and restoration of biodiversity was also identified. Based on this analysis, a landscape management model for the pilot area's agroecosystems was developed, incorporating measures to address these issues.

**Results:** The pilot area, as defined by the measures for managing the quality of agroecosystems and soils, is divided into the following categories: Priority 1 (areas of the Nature Frame), where intensive agriculture is practiced and where problems related to soil degradation are encountered. In these areas, the landscape structure must first be restored and soil degradation issues addressed. Within this priority, the following are distinguished: geoecological divides (agrarian forested hilly landscape) – measures for biogen accumulation and stabilization, anti-erosion measures; geoecological divides (agricultural hilly landscape) – measures for biogenic and carbon accumulation and stabilization, anti-erosion and biodiversity enhancement measures; Internal areas of geoecological stabilization – measures to support biodiversity and the ecological functions of the landscape; migration corridors – control of biogenic accumulation and biodiversity enhancement measures. Priority 2 (hilly areas with eroded soils outside the Nature Frame), where intensive agricultural

activity is carried out. Measures for biogens and carbon accumulation and stabilization, as well as anti-erosion measures, are planned for these areas.

**Conclusions:** The study revealed that the Natural Framework covers 75.16% of the territory of Kelmė distr. mun., while as much as 60.73% of all agricultural land within the municipality falls within the Natural Framework. Of this area, 61.24% of agricultural land is intensively used, being cultivated as arable land under crop rotation systems. Furthermore, 78.42% of all eroded soils are concentrated within Natural Framework territories, particularly in geoecological divides and migration corridors. These findings indicate that the agroecosystems of the study area are being managed unsustainably and that landscape planning measures are required. The Natural Framework concept, operating through the identification of landscape geoecological potential as well as potential risks and environmental problems, provides a valuable basis for the targeted differentiation of areas where restrictions on agricultural intensification are environmentally justified. Priority should be given to measures aimed at soil conservation, biodiversity enhancement, and the restoration of ecosystem functions. Its application may contribute to more effective agroecosystem management, SOC preservation, soil degradation reduction, and the achievement of European Green Deal objectives.

**Implications:** Applying the Nature Frame concept allows support and environmental protection requirements to be specifically directed to areas where soil degradation is most severe, thereby increasing the cost-effectiveness of agricultural investments. This approach integrates ecosystem services into intensive agriculture, rather than simply setting aside protected areas. This enhances the effectiveness of environmental protection. Linking agricultural policy to the Nature Frame becomes a practical tool for restoring soil health. It not only halts erosion but also actively contributes to restoring soil properties and increasing the resilience of agroecosystems.

#### KEYWORDS

agrarian forested hilly landscape, agricultural (productive) landscape, agricultural areas, agricultural hilly landscape, agricultural land, agricultural policy, agroecosystem internal resources, nature frame

## 1 Introduction

Soil health is one of the most complex terms in sustainable soil use. Its definition is highly context-dependent: the geo-ecological context emphasizes multifunctional systemic functionality, whereas the agronomic context understands health in terms of economic monofunctionality and productivity. The dominance of the agronomic concept means that increasing soil fertility and maintaining related properties become essential factors in achieving soil health and its sustainable use. This concept should not be underestimated, as soil fertility is one of its essential functions; however, the implementation of this concept is associated with specific agricultural measures whose implementation is not related to the landscape and its geo-ecological characteristics. If landscape-specific data are not incorporated into decision-making (1), agricultural measures become ineffective or even counterproductive.

Therefore, to achieve genuine soil health, agricultural policy and support measures must be linked with environmental protection

concepts. This alignment directly supports the EU Green Deal's (2) Biodiversity Strategy (3), which mandates that at least 10% of agricultural land be dedicated to high-diversity landscape elements (e.g., buffer strips, hedges) to improve connectivity.

The Nature Frame concept is a set of landscape management principles based on the principles of energy and material cycles in the landscape, as well as the migration and polarization of biodiversity within a given area. The application of these principles allows the identification of the areas most critical to the functioning of the landscape—that is, those characterized by the greatest geo-ecological potential but also high sensitivity to the impacts of economic activity. This concept is based on the assumption that integrating such areas into a unified system and regulating activities within them will ensure the reliability of ecological compensation functions in the landscape (and consequently in agroecosystems), the protection of biodiversity, and the quality of other landscape components, including soil.

The fundamental basis for this concept was created by B. B. Rodaman (4–6) when he developed the concept of the polarized landscape. In Lithuania, this idea was developed and applied to the territory by P. Kavaliauskas (7, 8), who formulated the concept of

**Abbreviations:** SOC, soil organic carbon; OM, organic matter; N, nitrogen; CO<sub>2</sub>, carbon dioxide; EU, European Union.

the Nature Frame. This concept describes the principles (9) of how natural, urbanised, and agricultural areas should be differentiated territorially to ensure the sustainable development of the landscape. Essentially, this concept is based on the polarization of the landscape's geoecological potential, which has become particularly evident as the landscape has been intensively transformed for urbanisation and agricultural needs, without taking into account the spatial heterogeneity of soil properties and their varying resistance to the impacts of economic activity.

In Lithuania, this concept, as one of the fundamental principles of environmental management and urban planning, is codified in the regulations on the Nature Frame (10). Only the new version currently being drafted includes measures aimed at ensuring the sustainable use of agroecosystems and the protection of soil quality (preservation of SOC stocks and nitrogen accumulation).

Globally, the Nature Frame concept has no direct equivalent as an applied measure, but various countries and regions have adopted similar landscape management measures aimed at achieving sustainable land use and, at the same time, soil preservation.

"Ecological Network" is the most widely used term, particularly within the European Union (11), where it is associated with the Natura 2000 network of sites. Its main priority is the protection of biodiversity and the preservation of its migration routes. This concept is based on the spatial structure of biodiversity Core Areas, its migration Corridors, and Buffer Zones (12).

The term and concept of "green infrastructure" are most commonly used in the context of strategic planning and sustainable development and are primarily associated with the urban landscape. This concept is primarily associated with ecosystem services and their implementation through specific natural, natural/engineering, and engineering measures aimed at managing the moisture and temperature balance of the urban landscape and creating local islands of biodiversity (13).

In North America, the concept of Greenways dominates, combining the ecological and recreational functions of the landscape (14, 15). This concept is oriented toward local linear elements that also perform environmental functions in the context of the protection of agricultural areas and their soils (16, 17).

The integration of environmental protection network concepts (ecological networks, nature frame, green infrastructure) is one of the most relevant research topics in the context of finding relations between the use and conservation of agroecosystem resources, as well as in the context of finding ways to create relations between protected areas and agricultural land. J. Fischer (18), together with his co-authors, presents principles for the integration of the agricultural (productive) landscape and the ecological network, which link protected areas with agricultural land. His principles emphasize measures aimed at strengthening biodiversity and its connections within agroecosystems.

L. Fahrig, together with his colleagues (19), continues to develop J. Fischer's ideas and presents the concept of agro-ecological micro-networks and methods for integrating agricultural land into an ecological network, thereby addressing issues related to biodiversity and the functions of ecological services.

The concept of a Nature Frame, which is being developed in Lithuania and applied in landscape planning, is broader than the

concepts of ecological networks, green infrastructure, greenways, or agro-ecological micro-network, as it encompasses not only biodiversity principles but also geo-ecological ones, such as moisture migration, control of nutrient and pollutant movement, soil erosion prevention, and visual quality. The concept can be applied across local, regional, and national levels. In essence, this concept integrates the concepts discussed above and offers comprehensive solutions for the sustainable development of agroecosystems, one of the key elements of which is the preservation of soil functions and quality – as fundamental conditions for the sustainability of agroecosystems – as well as the restoration of damaged areas and the recovery of lost functions.

While the Greenway concept in the agricultural context is primarily oriented toward the integration of linear ecological elements into agroecosystems and the strengthening of connections between humans and nature, the Nature Frame concept is fundamentally focused on maintaining and restoring ecological functions within systems and regulating the intensity of agricultural activities. This concept promotes the development of systems of both areal and linear elements, thereby expanding the range of spatial planning solutions and enabling a broader spectrum of ecological functions to operate. Furthermore, the inclusion of areal elements within the system creates greater ecological added value for agroecosystems.

Despite the existence and widespread application of ecological networks and green infrastructure concepts across Europe and worldwide, most of these approaches are primarily focused on biodiversity conservation and habitat connectivity. Within these concepts, less attention is given to the maintenance of soil functions, the preservation of SOC stocks, erosion control, and the optimization of agricultural land-use intensity. In contrast, the Nature Frame concept offers an integrated landscape-based approach. Although its implementation measures are largely aimed at managing geosystem sustainability and maintaining biodiversity, they also directly contribute to addressing soil-related problems through the management of agricultural land-use intensity, including the maintenance and enhancement of SOC content.

The main objective of this paper is to present the Nature Frame concept as a tool for modeling and optimizing the intensity of agroecosystem use and the prioritization of agricultural measures to ensure their sustainable functioning, the promotion of biodiversity, and the preservation of soil organic carbon (SOC) in the soil.

## 2 Materials and methods

### 2.1 Study site

The territory of Kelmė distr. mun., as the subject of this study, is located in the western part of central Lithuania and encompasses part of the Samogitian uplands and the Eastern Samogitian undulating plateau (Figure 1). The coordinates of the municipality's administrative center are: 55°37'51.2"N 22°55'59.2"E. The agro-climatic indicators of the study area (20) are presented in Table 1. This area was selected for its significant natural diversity, featuring

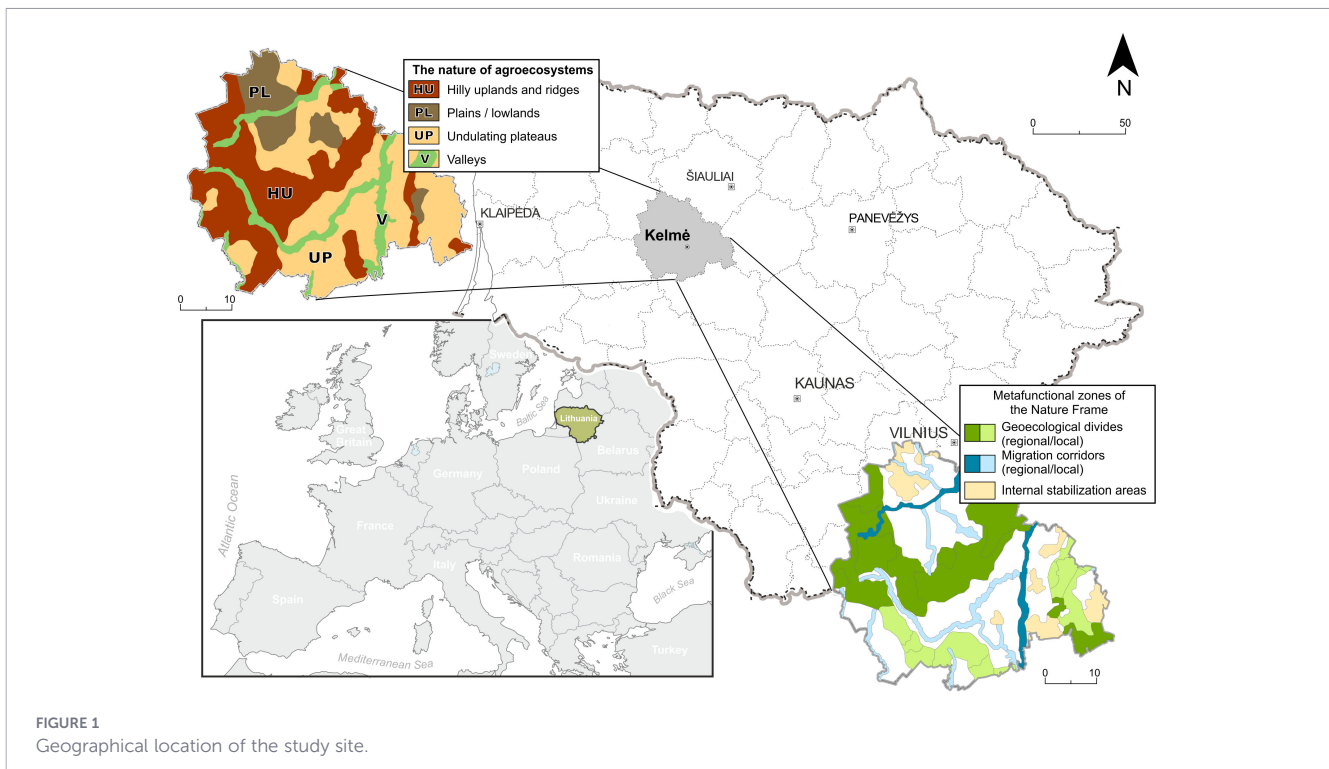


FIGURE 1  
Geographical location of the study site.

10 different landscape types (Table 2). Consequently, this area possesses a high diversity of agroecosystems and varying relationships with geologically and ecologically significant areas, which in Lithuania are integrated into the system of Nature Frame territories. In this regard, the landscape of Kelmė distr. mun. stands out from other administrative units of local self-government in Lithuania.

According to the Lithuanian Soil Information System database (2026) (21), the agricultural land of Kelmė distr. mun. comprises eleven soil typological groups distinguished in the Lithuanian Soil Classification System (LTDK-99): Regosols, Leptosols, Cambisols, Luvisols, Retisols, Planosols, Arenosols, Podzols, Gleysols, Histosols, and Fluvisols. No single dominant soil group can be identified. However, the largest areas are occupied by Luvisols (36.27%), Retisols (16.53%), and Gleysols (13.60%), which together account for more than two-thirds of soils within agricultural land. In terms of texture, loamy soils dominate (approximately 59%), while sands account for about 18%, clays for 10%, sandy loams for 4%, and peat soils for 8%. Due to the diversity of relief and parent materials, a mosaic-like complex of well-drained, moist, and wet soils has developed across the territory. Well-drained soils predominate, accounting for 42.66% of the total agricultural land area.

The largest part of the municipality's territory is occupied by the boggy, agricultural, and slightly urbanized plateau of Eastern Samogitia (40.30%), but there is no single dominant morphological landscape unit. The rugged relief covers about 40% of the territory, while the other 60% consists of a more flat surface.

Undulating landscapes (40.62%) and hilly uplands (37.66%) dominate the territory. And although the absolute majority of these areas are characterized by clay and loam deposits, sandy landscapes still account for about 20% of the territory. In terms of the natural composition of the landscape of the Kelmė distr. mun., the western

loamy hilly part, the central and eastern loamy/clayey undulating parts, and the sandy hilly and undulating relief features interspersed within them stand out very clearly. The entire territory is dissected by very expressive river valleys and lake basins (12.80%).

Functional components of the Nature Frame cover 75.16% of the total area, with geoecological divides (watersheds) making up the largest portion (Figure 1; Table 3).

Geoecological divides (watersheds) cover 58.49% of the total area of the Nature Frame within the territory of the Kelmė distr. mun. The largest part of these territories consists of divides of regional relevance. Almost half of these territories (35,044.18 ha, 46.77%) are characterized by reliable and sufficient ecological compensation functions (Table 3).

Internal stabilization areas account for approximately 15.98% of the total Nature Frame. 92.74% of these areas (18,989.82 ha) are in sufficient and reliable condition.

Migration corridors cover 25.54% of the total Nature Frame. 57.86% of these corridors (16,527.46 ha) have limited geoecological potential or are degraded.

Although the territory of Kelmė distr. mun. contains a considerable proportion of ecologically important and sensitive areas (Table 3), approximately 50% of the municipality's total area is used for agriculture (Table 4). Of all agricultural land, as much as 60.7% is located within the Nature Frame. From the perspective of Nature Frame regulations, agricultural land can be divided into land uses that are favourable to the objectives of the Nature Frame (grasslands and pastures) and less favourable land uses (arable land). Grasslands and pastures account for 38.76% of the agricultural land within the Nature Frame, whereas arable land account for 61.24%. This indicates that a substantial part of the Nature Frame territory in Kelmė distr. mun., where sustainable agricultural

TABLE 1 Agro-climatic indicators of the studied area (20).

| Agro-climatic indicators                                                  |                 | Values          |
|---------------------------------------------------------------------------|-----------------|-----------------|
| Sum of active temperatures (>10 °C), °C                                   | In the air      | 1970–2100       |
|                                                                           | Loamy soil      | 2200–2300       |
|                                                                           | Sandy loam soil | 2300–2400       |
| Average annual temperature, °C                                            |                 | 6.0–6.6         |
| Amount of precipitation, mm                                               |                 | ~685            |
| Average absolute minimum temperatures, °C                                 |                 | –19.0 ... –21.4 |
| Duration of frost-free periods on the soil surface, annual number of days |                 | 132–140         |
| Amount of precipitation when air t>10 °C, mm                              |                 | 330–350         |
| Maximum depth of soil freezing, cm                                        |                 | 34–39           |

practices should be prioritized, is currently dominated by intensive agricultural land use. Such land use is associated with increased risks of soil erosion, SOC loss, and biodiversity decline.

Soil erosion is also a significant issue within the territory of Kelmė distr. mun. and its agricultural land. According to the Lithuanian Soil Information System database (21), as much as 23,821.1 ha of agricultural land in Kelmė distr. mun. is affected by soil erosion. This represents approximately 28% of all agricultural land within the municipality. Of all eroded soils, as much as 78.4% are located within Nature Frame territories (Table 4).

Therefore, a situation exists in which a municipality dominated by Nature Frame territories (75.16% of the total area; Table 3) is also characterized by intensive agricultural land use. Approximately 60.7% of all agricultural land is located within the Nature Frame,

TABLE 2 The structure of the natural landscape in the Kelmė distr. mun.

| Landscape character               | Area (ha)  | Percentage of district (%) |
|-----------------------------------|------------|----------------------------|
| <b>Plain landscapes:</b>          |            |                            |
| PL' – Clayey plan                 | 15,200.99  | 8.92                       |
| <b>Plateau landscapes:</b>        |            |                            |
| UP' – Clayey undulating plateau   | 64,809.66  | 38.02                      |
| UP – Sandy undulating plateau     | 4,431.43   | 2.60                       |
| <b>Hilly upland landscapes:</b>   |            |                            |
| HU' – Loamy morainic hilly upland | 46,229.25  | 27.12                      |
| HU – Sandy hilly upland/dune      | 14,307.57  | 8.38                       |
| R – Morainic/fluvioglacial ridge  | 3,659.37   | 2.15                       |
| <b>Valley landscapes:</b>         |            |                            |
| RV – River valley                 | 18,002.99  | 10.56                      |
| RV' – Ancient river valley        | 399.79     | 0.23                       |
| <b>Lake landscapes:</b>           |            |                            |
| LV – Lake-filled basin            | 3,197.51   | 1.88                       |
| LV' – Lake district               | 225.31     | 0.13                       |
| Total:                            | 170,463.87 | 100.00                     |

TABLE 3 The structure of the Nature Frame areas in the Kelmė distr. mun.

| Metafunctional components and their geoecological potential | Area (ha)         | Area (%)      |
|-------------------------------------------------------------|-------------------|---------------|
| <b>Geoecological divides</b>                                | <b>74,927.09</b>  | <b>58.49</b>  |
| Realiable                                                   | 12,185.43         | 9.51          |
| Sufficient                                                  | 22,858.75         | 17.85         |
| Limited                                                     | 38,822.05         | 30.30         |
| Disturbed                                                   | 799.31            | 0.63          |
| Degraded                                                    | 251.54            | 0.20          |
| <b>Internal stabilization areas</b>                         | <b>20,477.34</b>  | <b>15.98</b>  |
| Realiable                                                   | 7,045.96          | 5.50          |
| Sufficient                                                  | 11,943.86         | 9.32          |
| Limited                                                     | 1,487.52          | 1.16          |
| Disturbed                                                   | –                 | –             |
| Degraded                                                    | –                 | –             |
| <b>Migration corridors</b>                                  | <b>32,710.83</b>  | <b>25.54</b>  |
| Realiable                                                   | 4,543.40          | 3.54          |
| Sufficient                                                  | 11,984.06         | 9.36          |
| Limited                                                     | 15,919.65         | 12.43         |
| Disturbed                                                   | 258.15            | 0.20          |
| Degraded                                                    | 5.07              | 0.00          |
| <b>Total:</b>                                               | <b>128,115.25</b> | <b>75.16*</b> |

\*Percentage of the total area of the district municipality.

Bold values is used to structure the table and highlight different land-use groups.

of which 61.24% is associated with land-use practices that weaken the ecological compensation functions of the Nature Frame. Furthermore, the majority of eroded soils (97.6%) are concentrated within the most ecologically important components of the Nature Frame – geoecological divides and migration corridors – where the principal ecological compensation functions are concentrated.

## 2.2 Spatial data and analysis

The study was based on the analysis of existing open-access spatial datasets, including the 2025 crop declaration dataset of the National Paying Agency (22), and soil erosion and soil organic carbon (SOC) data obtained from the Lithuanian Soil Information System database Dirv\_DR10LT (21). Nature Frame territories were delineated according to the Nature Frame delineation methodology (9).

Spatial analyses were performed using ArcGIS Pro 3.6 (ESRI). Spatial overlay analysis was applied to integrate Nature Frame territories, agricultural land-use data, soil erosion data, and SOC data. Based on this analysis, a unified geodatabase was created, enabling the assessment of the distribution of agricultural land, arable land, grasslands and pastures, and eroded soils across different metafunctional components of the Nature Frame.

Descriptive statistical methods were applied in the study. Area calculations and percentage shares were used to evaluate the distribution of agricultural land, eroded soils, and other analysed variables. These indicators were subsequently used to assess the

TABLE 4 Distribution of agricultural land within the Nature Frame in Kelmė distr. mun. [according to: NMA Crop Declaration Dataset, 2025 (22); Dirv\_DR10LT, 2026 (21)].

|                                                                                  | Area (ha)       | Area (%)     |
|----------------------------------------------------------------------------------|-----------------|--------------|
| <b>Total area of Kelmė distr. mun.</b>                                           | <b>170500</b>   |              |
| <b>Total agricultural land area</b>                                              | <b>84973.50</b> | <b>49.84</b> |
| <b>Of which within the Nature Frame</b>                                          | <b>51600.80</b> | <b>60.73</b> |
| Of which arable land                                                             | 31599.30        | 61.24        |
| Of which grasslands (<5 years), perennial grasslands (>5 years), and pastures    | 20001.50        | 38.76        |
| <b>Agricultural land within geoeological divides</b>                             | <b>35392.70</b> |              |
| Of which arable land                                                             | 22099.60        | 62.44        |
| Of which grasslands (<5 years), perennial grasslands (>5 years), and pastures    | 13293.20        | 37.56        |
| <b>Agricultural land within migration corridors</b>                              | <b>12181.00</b> |              |
| Of which arable land                                                             | 6410.50         | 52.63        |
| Of which grasslands (<5 years), perennial grasslands (>5 years), and pastures    | 5770.50         | 47.37        |
| <b>Agricultural land within internal stabilization areas</b>                     | <b>4027.10</b>  |              |
| Of which arable land                                                             | 3089.20         | 76.71        |
| Of which grasslands (<5 years), perennial grasslands (>5 years), and pastures    | 937.90          | 23.29        |
| <b>Total area of eroded soils within agricultural land</b>                       | <b>23821.10</b> | <b>28.03</b> |
| <b>Area of eroded soils within agricultural land located in the Nature Frame</b> | <b>18681.70</b> | <b>78.42</b> |
| Of which within geoeological divides                                             | 15701.18        | 84.05        |
| Of which within migration corridors                                              | 2526.66         | 13.52        |
| Of which within internal stabilization areas                                     | 453.90          | 2.43         |

Bold values is used to structure the table and highlight different land-use groups.

relationships between land-use intensity, the structure of the Nature Frame, soil erosion, and SOC distribution.

No field surveys were conducted as part of this study. The analysis relied exclusively on national spatial datasets and was designed to assess the potential of the Nature Frame concept as a spatial framework for agroecosystem management.

## 2.3 Research and Nature Frame concept

The pilot area (Kelmė distr. mun., Lithuania) was analyzed: the natural landscape base, relief model, distribution and degree of soil erosion, and SOC distribution (modeled based on Lithuanian data). The Nature Frame model of the pilot area was developed based on the Nature Frame concept. The data from the pilot area analysis were used to identify soil problems related to SOC migration and accumulation. The importance of the areas for the preservation and restoration of biodiversity was also identified. Based on this analysis, a landscape management model of the pilot area's agroecosystems was developed, incorporating measures to address these issues.

### 2.3.1 The concept of a Nature Frame

The study is based on a landscape management/ecogeographic approach to the regulation of agroecosystem use, assuming that applying this approach in the planning of agricultural activities would allow for the preservation of SOC in the soil, control of N migration, and, on that basis, ensure soil health in general.

Agronomists suggest agronomic measures (crop rotation systems, organic fertilisers, and other soil improvement and agrotechnical measures) to balance SOC content in agricultural land use (23–27). However, they face a fundamental problem: how to select the optimal measures for maintaining and/or restoring soil productivity and, at the same time, how to differentiate them geographically to maintain the potential and profitability of the farm while restoring the structure and functions of the landscape.

The Nature Frame concept is essentially focused on managing landscape material and energy flows to control pollution and nutrient migration while ensuring the spread of biodiversity. Therefore, it can be applied to the management of agroecosystems in general and to the localisation of agricultural activities and their intensity on farms. In agroecosystems, the application of this concept should be linked to recommendations on the differentiation of the type and intensity of agricultural practices (agrotechnical, agrochemical, crops and perennial grasslands, ecological land use). Some measures should be recommended in more ecologically sensitive agroecosystems or locations, while others should be recommended in less sensitive areas.

The Nature Frame concept provides three types of metafunctional zones (Figure 2), interconnected by the toposystemic principle:

1. Geoeological divides (hills, hilltops/ridges) – geoeological “windows” through which water and energy enter. They must function as a filter ensuring the supply of clean water and nutrients and the elimination of sources of pollution. In terms of Lithuania's territory, the landscape is predominantly agricultural and agricultural/forested, characterized by eroded soils, and the preservation and enhancement of soil organic carbon (SOC) is a key challenge.
2. Areas of internal stabilisation (relatively flat, relatively flat forested surfaces) – function as biological barriers and biodiversity hotspots. Areas of internal stabilization also create additional connections in urbanized and agricultural landscapes, through which additional biodiversity migration corridors are created. In terms of soil sensitivity to agricultural impacts, these are the least significant areas. Their primary role is to promote biodiversity and regulate nutrient cycling within the system. Furthermore, within agricultural areas, they are most often associated with forested areas.
3. Migration corridors (river valleys, lake systems, and drainage channel slopes) ensure biodiversity and balanced migration of materials and energy, ensuring that only as many nutrients migrate as the ecosystem can assimilate. Most often, this is a forested agricultural landscape (excluding surface drainage

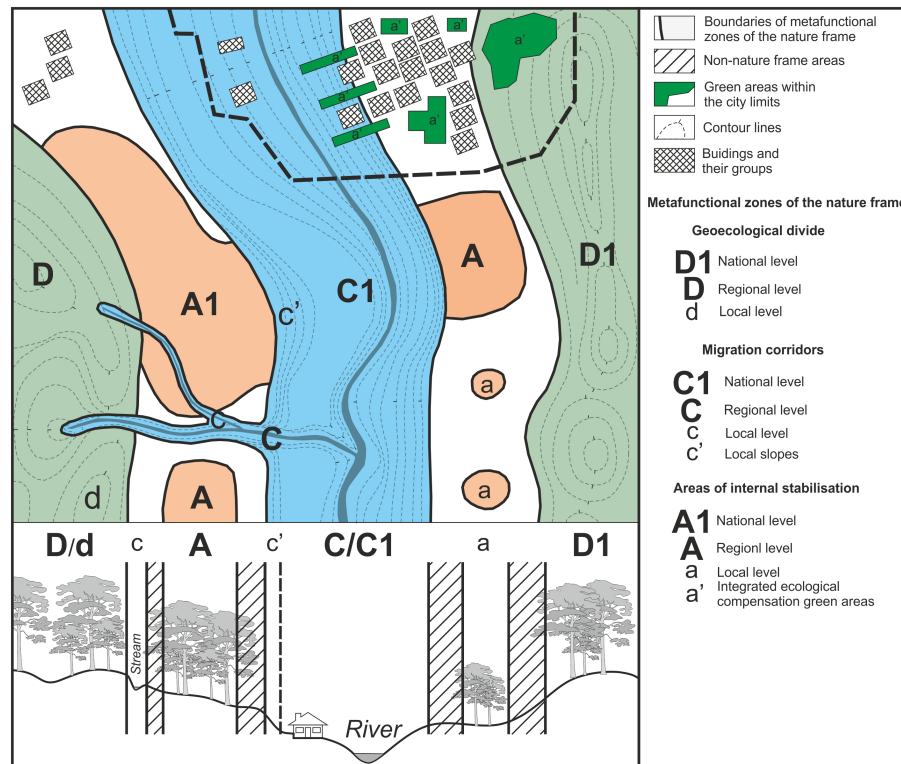


FIGURE 2  
Geoeological concept of nature frame [illustration prepared by (9)].

networks), where agricultural land and soils are exposed to increased risks of soil erosion, and thus a risk of SOC loss, as well as a limited capacity to accumulate SOC and nutrients in accumulation landscapes.

### 2.3.2 Research principles

Although the Nature Frame (10) has been legislated in Lithuania as one of the legal measures regulating spatial planning processes in terms of environment protection requirements, it is primarily used to manage urbanization processes. Although various measures to protect the environment (e.g., eco-schemes) are used in Lithuanian agriculture, their effectiveness is limited because they are not specifically tied to a particular area and therefore do not always address the specific problems. The prime example of this is no-till farming, which dominates in the fertile loamy agroecosystems of the Central Lithuanian morainic plains. However, this measure would be most relevant in the agroecosystems of hilly uplands, where eroded soils prevail. The application of the Nature Frame concept in agriculture makes it possible to purposefully link environmentally sustainable agricultural measures with the achievement of environmental protection goals (Figure 3, concept part).

From a practical viewpoint (Figure 3, analysis part), the concept is applied in the following stages:

1. The origin of the agroecosystems in the analyzed territory is identified. In this case, the most important thing is to distin-

guish between hilly, undulating, and plain surfaces, as well as the water flow system (both the natural river network and the artificial one – the surface agricultural drainage system). The systems can also be further detailed based on soil texture. In this conceptual analysis, this was not done.

2. Based on the agroecosystem origin model and the Nature Frame concept, a network of Nature Frame territories is formed. In this network, territories are grouped into two categories: territories where the accumulation, stabilization, and transformation of organic matter (OM) and nutrients occur or should occur; and territories where accumulation and migration occur or should occur.
3. Eroded soils are identified based on the Lithuanian Soil GIS database (21).
4. Soils are classified by soil organic carbon (SOC) content. In Lithuania, soils with a SOC content of <2% are considered damaged and degraded. This classification correlates with eroded soils and allows for the identification of agricultural areas and soils where measures to increase SOC content should be planned, as well as soils where measures to stabilize and preserve SOC should be planned.

These stages of the study reflect the key principles of territory typification and the identification of priority measures for soil protection, which were applied in this study:

- Toposystemic principle of territory identification. This is the principle of nutrient migration control, which ensure their

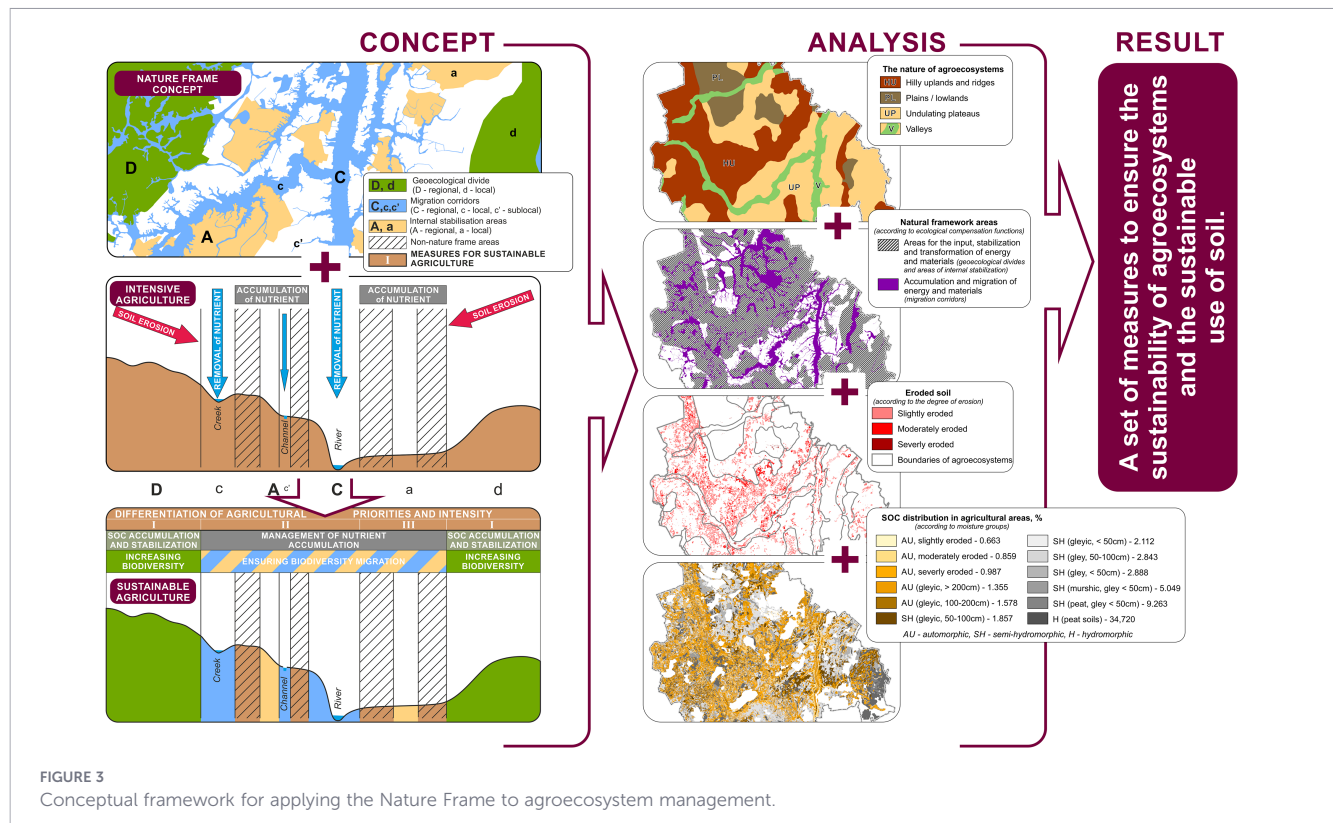


FIGURE 3  
Conceptual framework for applying the Nature Frame to agroecosystem management.

preservation and increase in hilltops and accumulation/sorption in wet areas.

- Principle of territory prioritization. Priority is given to Nature Frame territories. This ensure the complexity of measures for the sustainable use of soil and the restoration/revitalization of agroecosystem ecological services.
- Principle of differentiation of measures. Measures are differentiated according to the problems that are relevant to different toposystemic surfaces (top, bottom, slope) and meta-functional units of the Nature Frame.
- Principle of measure localization. Measures should be localized according to the characteristics of the soil typological unit (fertility, degree of erosion, identification of peat material and etc.) and their fragmentation should be ensured, especially when it is the case of measures that affect the biodiversity of agroecosystems (perennial grasslands, agroforestry, etc.).

### 3 Results and discussion

The analysis revealed three major patterns. First, Nature Frame territories occupy 75.16% of the total area of Kelmė distr. mun. and contain 60.73% of all agricultural land. Second, intensive agricultural land use remains dominant within these territories, where arable land accounts for 61.24% of agricultural land. Third, 78.42% of all eroded soils are concentrated within Nature Frame territories, particularly within geoeological divides and migration corridors.

These findings indicate a strong spatial overlap between environmentally sensitive areas and territories currently exposed to intensive agricultural use.

The results of this pilot study indicate that ensuring the sustainable use of agricultural soils and addressing existing soil-related problems requires agricultural land management to be viewed through the prism of agroecosystem and management-measure polarization, applying a landscape management approach (28). A “one-size-fits-all” approach is not suitable for this purpose. Our results demonstrate that, under the conditions of a complex agricultural landscape (Figure 1), the application of the Nature Frame concept in agricultural land management provides a reliable basis for the spatial polarization of environmental and land-use measures. The polarization of agricultural measures within the framework of the Nature Frame concept is consistent with soil health management principles (29–35), which emphasize improving SOC management efficiency, reducing soil erosion, simplifying or abandoning intensive tillage technologies, maintaining permanent vegetation cover, and implementing similar soil-conservation measures. The polarized application of soil-conservation practices across different agroecosystems ensures their maximum effectiveness and ecological compensation return, including SOC accumulation, nutrient retention, and biodiversity enhancement, while simultaneously avoiding the withdrawal of productive agricultural land from agricultural production.

According to the Nature Frame methodology (9) and the Regulations of the Nature Frame of Lithuania (10), agroecosystem territories are considered to provide reliable ecological compensation functions when they contain  $\leq 10\%$  arable land,  $\leq 30\%$  grasslands and pastures, and  $\geq 70\%$  forest cover. The spatial analysis demonstrates

TABLE 5 Distribution of environmental measures within agroecosystems in Kelmė distr. mun.

| Set of measures for managing quality of agroecosystems,                                                                                | Total zone area, ha/% | Land-use structure within the zone, ha/% |                                  |                    |
|----------------------------------------------------------------------------------------------------------------------------------------|-----------------------|------------------------------------------|----------------------------------|--------------------|
|                                                                                                                                        |                       | Arable land                              | Perennial grasslands and pasture | Forest             |
| Geoeological divides – measures for biogens and carbon accumulation and stabilization, anti-erosion measures                           | 31074.31<br>/23.24    | 10098.16<br>/32.50                       | 6850.51<br>/22.05                | 14125.64<br>/45.46 |
| Geoeological divides – measures for biogens and carbon accumulation and stabilization, anti-erosion and biodiversity increase measures | 20319.57<br>/15.19    | 9740.26<br>/47.94                        | 4513.88<br>/22.21                | 6065.43<br>/29.85  |
| Internal areas of geoeological stabilisation – measures to support biodiversity and the ecological functions of the landscape          | 13136.97<br>/9.82     | 2213.49<br>/16.85                        | 612.10<br>/4.66                  | 10311.38<br>/78.49 |
| Migration corridors – control of biogenic accumulation and biodiversity enhancement measures                                           | 21996.29<br>/16.45    | 5632.58<br>/25.61                        | 4709.54<br>/21.41                | 11654.18<br>/52.98 |
| Non-nature frame areas – measures for biogens and carbon accumulation and stabilisation, anti-erosion measures                         | 15200.96<br>/11.37    | 7458.77<br>/49.07                        | 6579.42<br>/43.28                | 1162.77<br>/7.65   |
| Non-nature frame areas – agricultural land not required special environmental regulations                                              | 32005.79<br>/23.93    | 20431.69<br>/63.84                       | 6133.11<br>/19.16                | 5440.99<br>/17.00  |

that environmental measures aimed at maintaining agroecosystem quality are most relevant within geoeological divides (Table 5) and in other ecologically sensitive agricultural lands located outside Nature Frame territories. The results indicate that, according to the sustainable agroecosystem provisions established in Lithuanian legislation for Nature Frame territories (10), the area of arable land exceeds the recommended threshold by two to five times, whereas the area of grasslands and pastures remains only slightly below the recommended level. This reflects a negative trend within the study area, where the decline of grasslands is not being compensated by increasing forest cover on eroded and unproductive land, but rather by the continued expansion of arable land.

The applicability of the Nature Frame concept and the corresponding results are presented in Figure 4 and Table 5, while their interpretation and detailed explanation are provided further below. Nature Frame areas are necessarily integrated into agroecosystems because they are part of the overall landscape structure, therefore:

Soils in agricultural areas located in geoeological divides (in Lithuania), which occupy 31,074.31 ha (23.24% of the study area), including 10,098.16 ha of arable land and 6,850.51 ha of perennial grasslands and pastures (Table 5), are highly erodible, therefore measures should be taken to reduce the risk of erosion: anti-erosion ploughing, no-till technologies, perennial grasslands, pastures, and livestock farming. This not only restores soil productivity, but also restores ecological compensation functions – SOC accumulation, CO<sub>2</sub> sorption, biogen accumulation, and filtration properties (Figure 4).

Soils in internal stabilisation areas, which occupy 13,136.97 ha (9.82% of the study area), with forests accounting for 10,311.38 ha (78.49%) and arable land for only 2,213.49 ha (16.85%) (Table 5), are not at high risk of productivity loss, but some places (local depressions) have conditions that are not suitable for farming, therefore, to achieve economic CO<sub>2</sub> emission reductions from agriculture, their functions could be converted into ecological land use. This would not only increase the biodiversity of the landscape but also create additional ecological functions for the

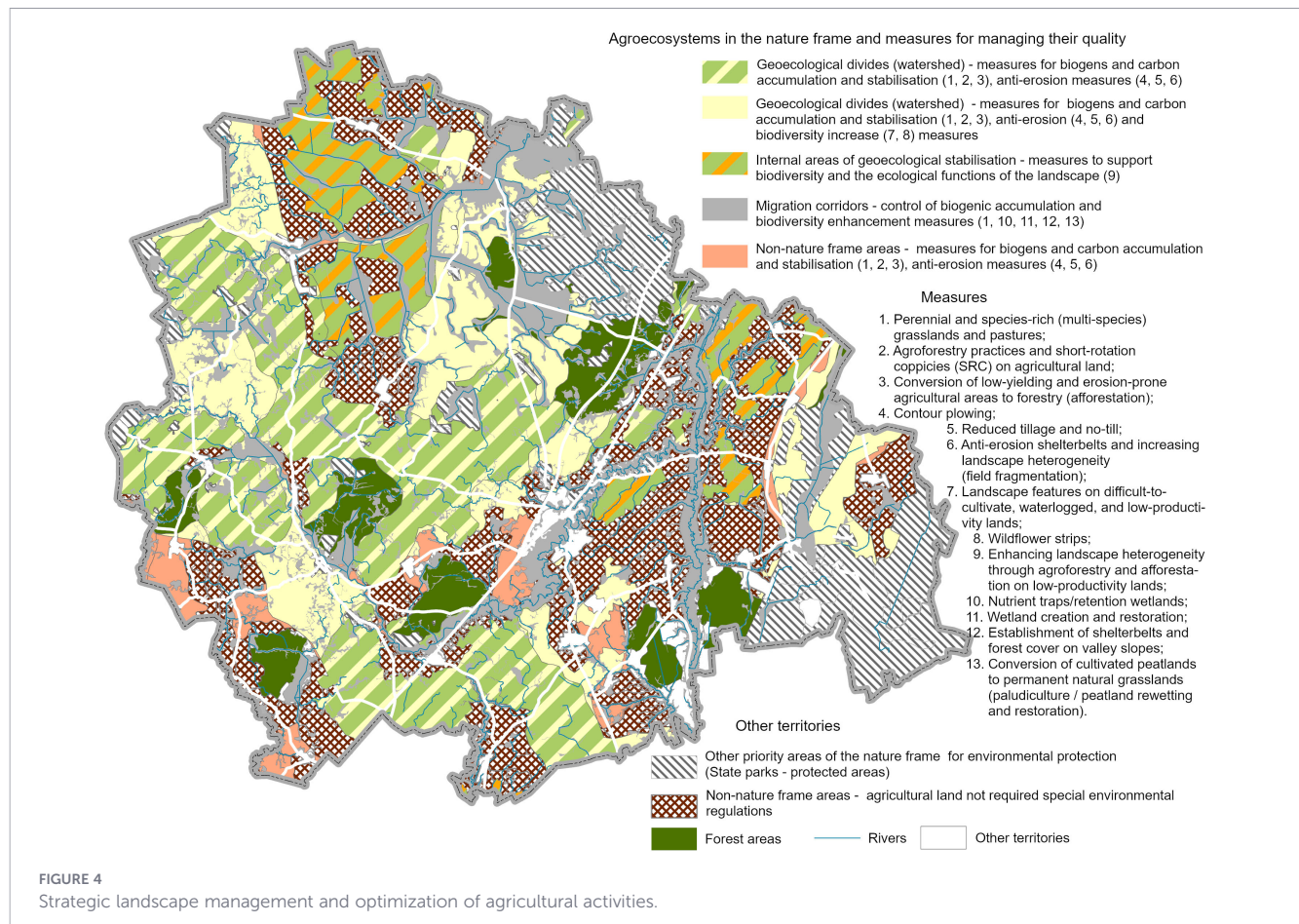
soil – local biogen accumulators and hotspots of soil biodiversity would be created (Figure 4).

Migration corridors occupy 21,996.29 ha (16.45% of the total study area), including 5,632.58 ha of arable land and 4,709.54 ha of perennial grasslands and pastures (Table 5). Agricultural pollution and nutrients (nitrogen, phosphorus) migrate through migration corridors (river valleys and drainage channels), making these areas the last barrier to catch them. By locating perennial grasslands, agroforestry, and organic farming measures on agricultural land in these areas, the filtration and nutrient accumulation properties of the soil would be ensured, and the moisture potential of these areas would be used for biological CO<sub>2</sub> accumulation (Figure 4).

The spatial distribution of land-use categories within Nature Frame components demonstrates that environmentally sensitive territories are currently subject to substantial agricultural pressure. Therefore, the implementation of targeted management measures requires not only ecological planning but also effective policy instruments capable of supporting their practical application. The integration of ecological networks into intensive agricultural systems and agricultural landscapes requires complex solutions capable of addressing social, economic, and legal challenges.

The study highlights three pathways for change: awareness-raising, political regulation, and the “seeing is believing” principle. While education is slow and regulation is complex due to private property rights, the “seeing is believing” approach – where farmers adopt proven practices from peers – is often the most effective (36, 37).

The implementation of political regulatory measures is also highly complex, as it involves regulations that restrict the nature of activities on private property. However, if these measures were combined with economic instruments – such as payments for ecological services – this would be feasible. For now, the compatibility of political decisions and practical farming is complicated (38). It is important that sustainable farming measures initiated by political decisions be promoted and implemented in line with the concept of environment protection networks (39) and our



recommended geo-ecological concept of a Nature Frame, as well as based on the natural characteristics of the area in question (40, 41). Nevertheless, sustainable agricultural measures established by political regulation (regional policy tools) are effective only when they are linked to financial instruments.

In our opinion, the “seeing is believing” principle is the most effective. Farmers often tend to adopt proven technological solutions or best practices from one another (42–44), especially when this helps them save money. Therefore, it is very important to publicize such examples.

The development and implementation of the concept presented in this study may have both advantages and disadvantages.

The main advantages of applying the Nature Frame concept are associated with its ability to differentiate agroecosystems according to geoecological potential and environmental sensitivity. The division of agroecosystems into Nature Frame metafunctional zones creates conditions not only for differentiating territories according to their geoecological potential and sensitivity, but also for identifying existing and potential land-use risks associated with soil degradation. The development of a digital model of this concept in the future would create opportunities to evaluate the effectiveness and appropriateness of environmental measures implemented through eco-schemes under the EU agricultural policy. This aspect is currently one of the most strongly criticized elements of EU agricultural policy. Researchers investigating EU agricultural policy (45–47) argue that farmers’ decisions to implement environmental measures are often driven

by pragmatic motivations, such as additional payments, low administrative burdens, and ease of implementation, rather than by environmental objectives. As a result, the environmental effectiveness of these measures remains limited. The implementation of this concept would restore and strengthen ecosystem services in agroecosystems (agricultural landscapes) by contributing to the spatial targeting of eco-scheme measures.

At the same time, several limitations and implementation challenges should be acknowledged. The principal methodological limitation is the national character of the concept itself, as it is currently known and applied only in Lithuania. Consequently, its applicability and potential risks remain insufficiently studied. No such studies have yet been conducted in the agricultural sector. Therefore, there is currently no possibility of building upon the work of other researchers or developing a broader scientific discussion. The possibilities for implementing the concept in the agricultural sector are also very limited, even when linked to EU eco-scheme measures, because it introduces additional conditions and restrictions for farmers when selecting environmental measures. As repeatedly noted in previous studies (45, 48), farmers generally do not base their decisions on ecological imperatives. Therefore, the implementation of Nature Frame principles may be perceived not as an additional environmental guideline but rather as an administrative restriction.

At present, the application of the concept in agroecosystem sustainability research remains at a methodological stage.

Consequently, a digital model has not yet been developed that would expand its geographical applicability across different geographical regions, landscapes, and soil taxonomic units beyond Lithuania.

At the same time, we believe that the present study makes a substantial contribution to the development of sustainable agroecosystem management by introducing a new conceptual framework together with its geoecological application criteria. In doing so, it expands the two currently dominant approaches – ecocentric and technocentric (49). Furthermore, it contributes to the development of holistic agroecosystem management models (50) and to the incorporation of spatial dimensions into sustainability research (51) by introducing a polarized spatial perspective for identifying sustainable solutions.

Our findings, demonstrating the necessity of applying spatially polarized measures in Kelmė distr. mun., confirm and complement broader international research in the context of ecological networks and green corridors. In several European countries (e.g., the Netherlands and Germany), the Ecological Network (Econet) concept has traditionally focused on ensuring biodiversity migration and abundance (52). However, recent studies increasingly emphasize the need to integrate these networks with soil-related ecosystem services, including soil erosion control and the enhancement of SOC stocks (53). This trend brings the ecological network concept closer to the Nature Frame concept.

Research conducted in the United Kingdom and other countries within agricultural landscapes (54–56) has shown that green corridors designed along river systems not only function as biodiversity pathways but also effectively retain up to 65% of diffuse agricultural pollution. These findings are consistent with our conclusions regarding the role of migration corridors as the final barrier for nutrient retention.

One of the key measures highlighted in our study for increasing the SOC sequestration potential of Nature Frame structures located within agricultural areas is the establishment of perennial grasslands and pastures. This finding complements the work of Lithuanian and international researchers (57–59). These authors demonstrated that no-till technologies and the establishment of perennial vegetation in erosion-prone areas (in our study, geoecological divides) can increase SOC stocks in the upper soil layer by up to 20–30% over a decade (60).

## 4 Conclusions

The study demonstrated that Nature Frame territories occupy 75.16% of the total area of Kelmė distr. mun. and contain 60.73% of all agricultural land. It was found that more intensive forms of agricultural activity predominate within Nature Frame territories, with arable land accounting for 61.24% of all agricultural land located within these areas. The results also showed that 78.42% of all eroded soils are associated with Nature Frame territories, with the majority concentrated in geoecological divides and migration corridors, where the most important ecological compensation functions are located.

The obtained results indicate that, in many agroecosystem areas, the current pattern of land use is not aligned with the geoecological sensitivity of the landscape and the requirements of ecological compensation. This suggests that the Nature Frame concept can be used as a spatial planning instrument for identifying areas where agricultural land-use intensity should be limited, soil conservation measures should be prioritized, and the maintenance of biodiversity and ecosystem functions should be strengthened.

Unlike many ecological network and green infrastructure concepts, the Nature Frame integrates not only biodiversity-related principles but also geoecological principles associated with the regulation of material and energy flows, soil protection, and landscape stability. Therefore, its application may contribute to more effective agroecosystem management, the preservation of SOC, the reduction of soil degradation, and the achievement of the objectives of the European Green Deal.

Future research should expand the analysis to larger territories and quantitatively evaluate the effects of land-use measures differentiated according to the Nature Frame framework on soil organic carbon accumulation, erosion reduction, biodiversity status, and ecosystem service provision.

## Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## Author contributions

JV: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. MK: Data curation, Formal analysis, Funding acquisition, Investigation, Writing – review & editing. JM: Methodology, Writing – original draft, Writing – review & editing.

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## Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Generative AI statement

The author(s) declared that generative AI was used in the creation of this manuscript. The author(s) declared that generative AI was used to improve wording and edit English language and

check final versions. All scientific ideas and interpretations presented in this work are original intellectual contributions of the authors.

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