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Data collection for assessment of the natural capital at the regional level: case study of LTSER Trnava region

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Abstract

Context The landscape provides not only a living space for all life forms, including humans, but also a spatial base and set of resources for the implementation of individual human activities. Inappropriate implementation of human activities, disrespecting the properties of the landscape's natural resources, causes the degradation of natural resources and, consequently, the human living.

Objectives The aim of this paper is to develop new methodological procedures and algorithms for effective assessment of natural capital based on the geosystem approach.

Methods Each territorial unit (geosystem) represents a unique combination of natural assets that create a certain potential for the development of individual activities and eco-stabilization functions. In this study, we developed a new approach and algorithms to assess the natural capital of landscapes for sustainable use. This involves selecting indicators and their functional interpretation, as well as collecting available spatial data and statistics for GIS analysis, synthesis, and modeling.

Results The methodological procedure consists of the determination of indicators for natural capital assessment, the determination of their functional values and weighting coefficients, the determination of the suitability of the geosystem for the implementation of individual activities based on the value of natural capital, and the determination of restrictions and limiting factors. The set of data on landscape assets can be categorized into abiotic, land cover and biotic, and socio-economic indicators, which can either support human activities or limit them. Options for sustainable use of natural capital were split into two groups of potential activities: (I) natural capital for landscape planning activities and (II) specific activities or functions (e.g., natural capital for energy use, recreation, regulation services). The modeling of eco-stabilizing natural capital in Trnava LTSER pointed to low spatial ecological stability, mainly in the central part of the district.

Discussion Discussion pointed to strength, novelty and opportunities of implementing methodological approach to natural capital assessment.

Conclusions As an output of this methodological approach, a comprehensive digital spatial database of landscape-ecological data for the assessment of natural capital and the suitability of its use for socio-economic activities has been created in Slovakia. The database represents a set of consistent spatial information on natural capital assets

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and other indicators, including land cover and socio-ecological indicators. The methodological approach can be applicable to any territory on the basis of a modification.

Keywords Natural capital, Geosystem services, Long-term socio-ecological research (LTSER)

Introduction

People and their activities significantly affect the use of the natural capital of the landscape, i.e., the stock of renewable and non-renewable resources that combine to yield a flow of benefits to people [1]. Human activity in the landscape can be considered bipolar, on one hand, there are activities that enhance and improve the natural capital; on the other hand, there are activities that threaten the capacity of the natural capital of the landscape and cause its degradation [2]. Understanding how benefits and capacity for individual activities interact is fundamental to planning the conservation and use of natural resources [3–5].

According to the OECD [6], natural capital is "natural assets in their role of providing natural resource inputs and environmental services for economic production." The natural capital of a landscape can be defined as the stocks of natural assets, which include geology, soil, air, water, and all living things. It is from this natural capital that humans derive a wide range of services, often called ecosystem services that directly or indirectly benefit people and make human life possible. The term is often used as a synonym for natural resources, but it is associated with a particular component of the landscape and is often assigned a value (financial, biophysical, or benefits) [7]. Historically, the term ecosystem services focused on the living (biotic) elements of ecosystems, although the latest version of the CICES v5.1 framework does include some services associated with abiotic elements [8]. Recently, the term geosystem service has been adopted to focus on abiotic elements provided by the subsurface of the earth [9]. Following a literature review, Frisks and co-workers identified eight abiotic services not included in the CICES v5.1 framework. These were primarily associated with the supporting and regulating categories of services, e.g., soil services such as nutrient and water retention and stable platforms to build. The ecosystem and geosystem services approaches tend to consider the components of a landscape separately, while the landscape potential attempts to integrate the component parts. Haase [10] defined landscape potential as "the sum of all the characteristics of a landscape that create the conditions for the economic valorization of the landscape with its components and energies." Landscape potential expresses the capacity of the natural environment, landscape, and its components to meet current and planned societal demands, in particular, the production of natural resources and the fulfillment of non-productive functions, but also the provision of space for activities of different natures (urbanization, industry, transport, recreation, etc.) [11, 12].

To conduct a qualitative assessment of the natural capital of an area, we need high-quality spatial and temporal data on natural assets and the impacts of human activities [13]. The use of spatial information in geography, ecology, landscape ecology, and environmental science for the assessment of landscape resources and natural capital has significantly increased in recent times [14]. Such data increase the possibilities for better assessment and improvement of landscape management. New technologies and open access to a variety of statistical and spatial data are important steps toward evaluating a landscape's natural capital.

Landscape planning has been the subject of numerous authors, both on the international and national level [10, 15–18]. The comprehensive approach of landscape-ecological planning (LANDEP), which was developed in Czechoslovakia [19], was later internationally recognized and was included in Agenda 21 as one of the recommended methods for integrated landscape management. The methodology presents a set of open steps for optimal use of a territory, but it does not sufficiently take into account the current environmental trends affecting the landscape, the use of new technologies for modeling, and more accurate and objective adjustment of optimization processes [20, 21]. The international focus on land use and human benefits, as well as human perception of landscapes, has become increasingly recognized in recent years [22]. The integration of landscape-ecological concepts into landscape planning has great potential to integrate new sources of spatial information. Also, the theoretical and methodological elaboration of special-purpose landscape characteristics for optimizing the land use and protection of the landscape, as well as methods for evaluating the relationships between landscape assets, are not sufficiently developed [13]. Many special-purpose indicators, such as habitat effects on water retention in the landscape and carbon storage, are determined either by complex models (e.g., [23, 24]) or only on the basis of expert judgment and not on the basis of exact measurements and observations.

This gap could be filled by long-term socio-ecological research (LTSER) platforms [25]. These research platforms represent entire regions in the sense of cultural, land use, historical, natural, administrative, and economic units that are hosting place-based socio-ecological research and feature three functional layers: (1) physical infrastructure, such as one or more in situ environmental long-term monitoring sites (LTER sites), technical infrastructure, laboratories, monitoring networks, collections, museums, visitor centers, databases, etc. (2) active participation of the research community on the regional, national, and international levels; and (3) integrative management serving as an interface between all the above elements [26]. The management should enable an open communication space and the implementation of transdisciplinary and participatory approaches. Research agendas should be adapted to regional and local needs, and for the regional population, key stakeholders and decision-makers should be involved, all of whom can be seen as beneficiaries of the knowledge produced. Currently, there are over 50 acknowledged LTSER platforms in the Europe database [27], one of them is the LTSER Trnava region, which we used as a case study in this study.

The importance of interdisciplinary and transdisciplinary approaches is increasingly recognized in landscape research [28–30], based on geosystem landscape research. The geosystem approach to landscape assessment is focused on the landscape as an integration of natural resources in a particular space [31]. The integrated approach integrates landscape assets, including abiotic, biotic, and socio-resources, to meet people's needs and act as natural resources in relation to human society [9, 32] and their implementation into landscape planning [33–35]. The decision-making process for landscape-ecologically optimal use involves balancing the complex properties of the landscape as a natural resource with the demands and impacts of human activities. The decision-making process requires the processing of a large amount of data on the properties of individual landscape components. Spatial analyses in a GIS environment reveal patterns of collected data, predict the future development of various spatiotemporal phenomena, model, experiment with input parameters, and evaluate the responses to collected data [36].

The methodology for the assessment of natural capital and geosystem services for different landscape types has been developed, for example, in the framework of the international OpenNESS project 7th Framework Programme [9, 37–39]. The scientific monograph Catalogue of Ecosystem Services in Slovakia [12] goes into more detail about Slovakia's potential to provide three types of ecosystem services: production, regulation, and cultural ES. Ecosystem services assessment was most often processed for spatial units of current land cover, which is insufficient for landscape planning in the twenty-first century. This paper proposes to progress from evaluating ecosystem services to a comprehensive assessment of the benefits and landscape geosystem services [40], utilizing the knowledge and lessons learned from OpenNESS and e-LTER. Some of the research methods used in these projects was inspiring for the development of our new methodological approach.

Based on geosystem landscape research, the aim of the paper is to develop new methodological procedures and algorithms for effective assessment of the natural capital of the landscape for sustainable use. It incorporates state-of-the-art environmental modeling methods into the framework, eliminating shortcomings and anachronisms. This improves accuracy, objectivity, and the argumentative weight of outputs, which will increase their applicability in practice, especially in landscape management.

Methods

In this study, we developed a new approach and algorithms to assess the natural capital of landscapes for sustainable use. This involves selecting indicators and their functional interpretation, as well as collecting available spatial data and statistics for GIS analysis, synthesis, and modeling (Fig. 1).

Data collection includes the following:

- Mapping and assessment of the attributes and the spatial distribution of abiotic assets in the landscape;
- Mapping and assessment of the attributes and the spatial distribution of current land cover and biotic assets in the landscape;
- The development of methods for assessing relationships between individual landscape assets, such as the attributes of individual landscape components that can be supporting, limiting, or indifferent;
- Research and validation of methods for assessing the services and benefits provided by different types of geosystem.

The methodology not only evaluates natural capital, which is the result of evolutionary processes of the landscape, but also determines limits and restrictions on the use of natural capital, which result from the current land use (i.e. it evaluates the current, real state of natural capital). Human interactions in relation to natural assets can be enhanced, or they can act as stress factors, so we focused our research on the following:

- Analysis and interpretation of nature conservation and biodiversity drivers in relation to the landscape and natural capital of the potential activities;

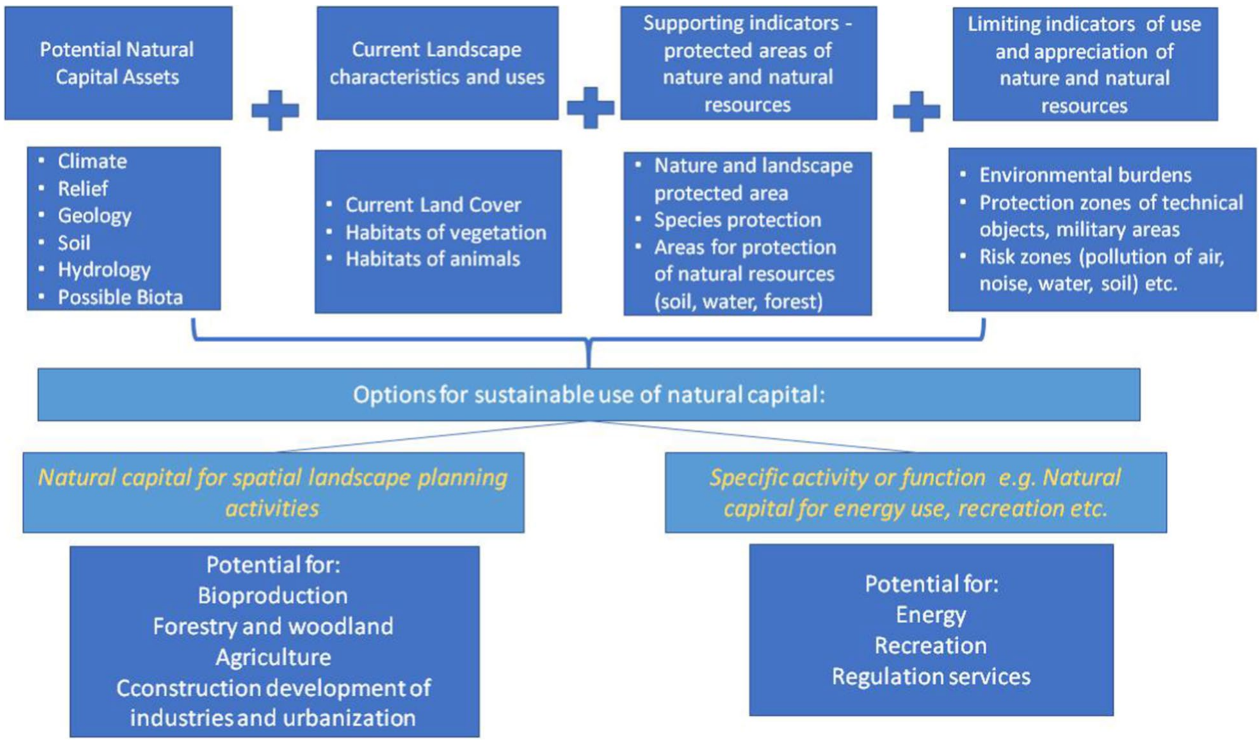

Fig. 1 Methodological approach to natural capital assessment

– Analysis and interpretation of natural resource protection drivers in relation to the landscape natural capital of the potential activities;
– Analysis and interpretation of primary stressors in relation to threats to and degradation of natural capital;
– Analysis and interpretation of secondary stressors in relation to threats and degradation of natural capital.

The proposed methodological approach focuses on the benefits of natural capital and on the optimal use of natural capital using GIS and modeling tools so that the utilization of one resource does not pose a threat to the other and the ecological balance and stability of the landscape are maintained.

Indicators of individual natural assets for assessing the suitability of landscapes for human activities are considered determinants of actual natural landscape capital.

Study area

LTSER Trnava is a part of the long-term research network of LTSER platforms in Europe and was established in 1985. It is located in south-west Slovakia, in the territory of Trnava city and 44 rural municipalities, with a total area of 741.33 km^2 (Fig. 2). Arable land dominates, occupying 65.13% of the land cover with the remaining classified as forests (17.78%), built-up area (7.84%), grassland (2.15%), gardens (1.83%), water bodies (1.38%), vineyards (0.81%), orchards (0.2%), and other plots (2.9%). The main part of the LTSER (central and southern parts) is located in the Danubian Lowland. The fertile soils and favorable climatic conditions make this part of LTSER an ideal location for agriculture, especially as intensively managed arable land.

Trnava city represents the administrative center of the county and region with the highest population density, trade, and industry. Trnava is the center of the automotive industry (Citroën-Peugeot). The Malé Karpaty Protected Landscape Area (PLA), located in the Malé Karpaty Mts., occupies the hilly northwest part of the LTSER. This is the only large protected area with vineyard character in Slovakia; vineyards form a transition belt between lowland arable land and forested hills and mountains, covered mostly by oak-hornbeam and beech forests. As a result of intensive use, the LTSER includes industrial and agricultural areas that face specific environmental problems, such as a high level of pollution and land degradation processes associated with agriculture. These areas also have a low level of ecological stability. The use of the most productive soils for the construction of industrial parks, logistics and business centers, and residential areas represents a significant environmental issue.

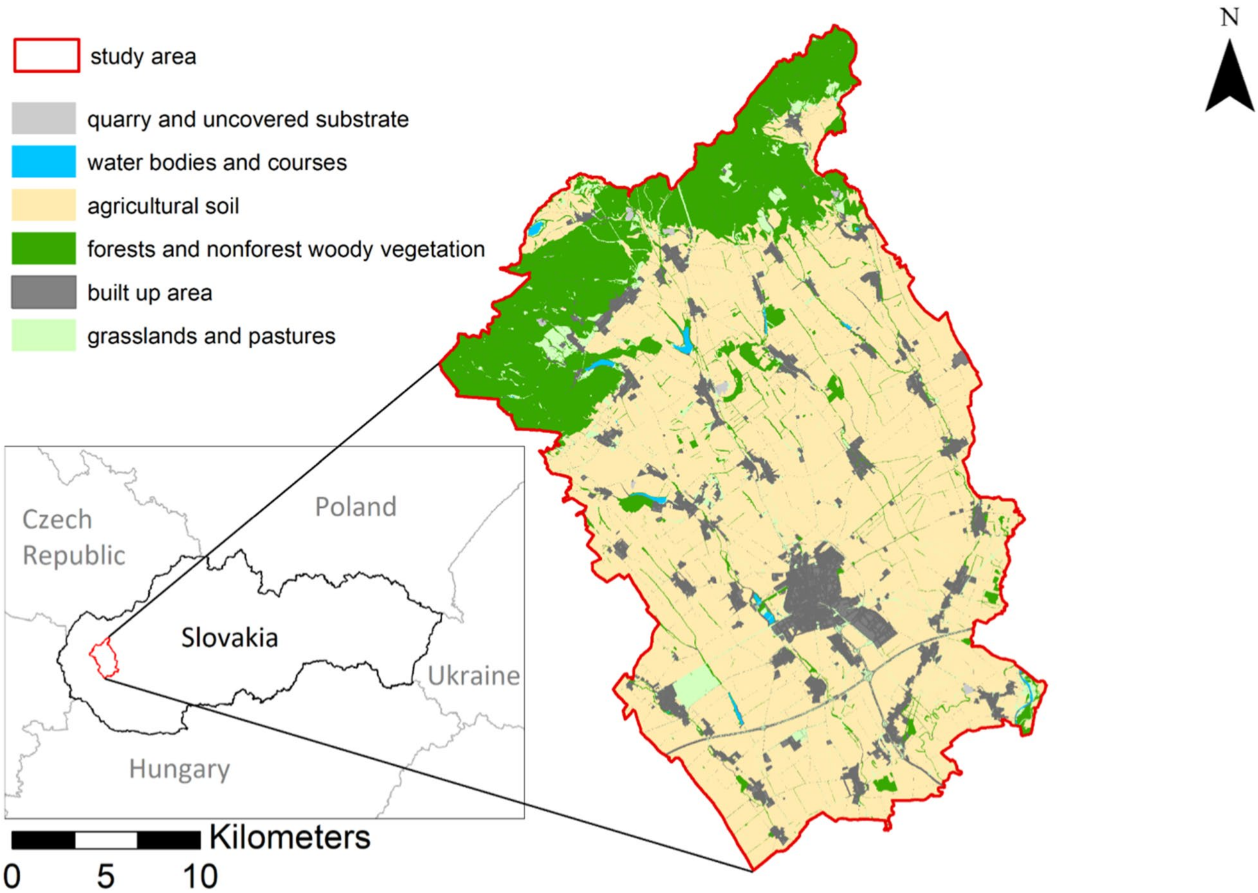

Fig. 2 Current landcover of the study area of Trnava LTSER platform (processed by authors in 2019)

Natural capital valuation models

The main steps of the methodological approach are as follows:

- Selection and brief justification of the potential activities to be evaluated;
- Characterization of land cover indicators;
- Assessment of options for sustainable use of landscape natural capital:
- Determination of the functional values of the indicators for the selected potential activities;
- Determination of weighting coefficients of the indicators;
- Determination (calculation) of benefits of selected potential activities without limits and constraints;
- Determination of the indicators—limits and constraints—from the current land cover;
- Determination of the socio-economic indicators—limits and constraints;
- Assessment of natural capital of selected potential activities with limits and constraints.

The expert project team, which consisted of more than 30 experts from the three partner organizations involved in the project (a research center, a university, and a business partner), selected more than 40 activities relevant to the optimal use of landscape and natural capital in Slovakia. The list of these activities was developed based on previous work on the use of natural capital to provide ecosystem services to society as well as activities related to landscape planning [8, 12, 16, 41–43]. Options for sustainable use of natural capital were split into two groups of potential activities: (I) natural capital for landscape planning activities and (II) specific activities or functions (e.g., natural capital for energy use, recreation, regulation services). Subsequently, these 30 experts were divided into five groups composed of scientist with biotic, abiotic, and socio-economic background and based on their expertise and literature review, they in face-to-face workshop collectively selected relevant indicators for each potential activity. The foundation for study planning, conduct, assessment, and selection of indicators was inspired by PRISMA protocol, with focus on data collection process and data items [44, 45]. The data collection includes the selection, creation, description, and spatial differentiation of indicators of landscape natural assets and their individual landscape components.

The indicators selected in this study express diagnostic characteristics of the landscape that can be parameterized and expressed cartographically. Some are derived from existing mapping sources, others from available statistical data or directly from in situ research. Two sets of rules guided the selection of indicators: (1) indicators had to be relevant, which means they were considered determinants of a geosystem service for the assessment of natural capital for the selected potential activities and were important for its implementation; and (2) data were available for the whole country. The set of data on landscape assets was categorized into abiotic (Table 1), landscape cover and biotic (Table 2), and socio-economic indicators, which can either support human activities (Table 3) or limit them (Table 4). The list of indicators is not exhaustive; we have selected only those that were related as determinants to specific activities. For example, for LTSER a number of climate indicators are monitored, including relative air humidity, precipitation, air temperature, wind speed / wind direction, and surface atmospheric pressure, but we selected eight climate indicators that were used for the natural capital valuation models.

A standard set of indicators for landscape planning activities describes the natural assets of landscape-ecological complexes and determines the size and shape of functional areas in the field of spatial planning (Table 5). Variable indicators, including abiotic, biotic, current land use, and specific indicators, are used to assess group II of specific activities and functions (Table 6).

The methodological approach optimizes analytical data utilization for natural capital assessment while also considering socio-economic determinants to ensure natural asset utilization does not pose a threat to other resources. Since we follow the concept that the potential of a landscape refers to its potential for human activities, the key term for a realistic assessment of the theoretical concept of potential used throughout this paper is "landscape capacity for an activity."

Our approach results in classified areas for which we determine the potential suitability of an activity in a spatial unit. The process of determining the suitability of areas for different activities is based on how activities can be carried out according to the natural assets impact of the activity that is taking place, or is to take place, or even not take place (no activity, or passive activity, e.g., nature conservation, or grazing-free areas), or even to exclude

Table 1 Indicators of possible natural capital assets

Category of indicators	Basic indicators	Type of data or source
Climate	A01 Climate region	Atlas of the landscape of the Slovak Republic: https://app.sazp.sk/atlassr/ in situ research Climate Atlas of Slovakia [60]
	A02 Average temperature in January	
	A03 Average temperature in July	
	A04 Average daily temperatures May–October	
	A05 Relative duration of sunshine	
	A06 Windiness	
	A07 Temperature of the active soil surface	
	A08 Number of days with snow cover, snow cover height	
Relief	A09 Morphological and positional relief forms	Atlas of the landscape of the Slovak Republic: https://app.sazp.sk/atlassr/ Geodetic and Cartographic Institute Bratislava: digital elevation model https://www.geoportal.sk/en/zbgis/download/
	A10 Relief slope	
	A11 Exposure	
Geology	A12 Genetic and lithological substrate types	State geological institute of Dionýz Štúr: geological maps https://www.geology.sk/maps-and-data/mapovy-portal/geological-maps/
Soils	A13 Soil subtypes	Atlas of the landscape of the Slovak Republic: https://app.sazp.sk/atlassr/ in situ research Soil Science and Conservation Research Institute (web app) www.portal.vupop.sk/portal/apps/webappviewer/index.html?id=d89cff7c70424117ae01ddba7499d3ad
	A14 Depth of soils	
	A15 Skeletonization of soils	
	A16 Granularity of soils	
	A17 Permeability of soils	
Hydrology	A18 Permeability of hydrogeological types of sediments, weathered rocks and rocks	Slovak Water Management Enterprise, map service https://mpt.svp.sk/svp_vmapportal/
	A19Ability to float watercourses	Slovak Water Management Enterprise, map service https://mpt.svp.sk/svp_vmapportal/

Table 2 Indicators of current landscape characteristics and uses

Category of indicators	Basic indicators	Type of data or source
Land cover	B01 Land cover on various hierarchical level	Land cover (CORINE, https://land.copernicus.eu/), in situ research, https://www.openstreetmap.org/#map=8/48.674/19.709
	B02 Types of agricultural crops	https://portal.vupop.sk/portal/apps/webappviewer/index.html?id=32beed691b01498d9ebe11bf8f9b7b04 (Land Parcel Identification System)
Habitat of vegetation	B03 Possible biota	[65]
	B04 Habitat of actual vegetation	https://www.biomonitoring.sk/
		[61]
Habitat of animals	B05 Habitat of Animals and Zoocenoses	https://maps.sopsr.sk/ https://www.biomonitoring.sk/
	B06 Migration routes	[62], in situ research
Derived indicators		
Land cover	B07 Ecological stability coefficient	[46]
	B08 Naturalness degree	[46]
	B09 Surviving historical landscape structures	[63]
	B10 Density of hiking trails per area (m^2/km^2)	T-MAPY spol. s r.o., Hradec Králové 2016: Modeling density in GIS, using tool – Line density
	B11 Density of tourist attractions per area (number/km^2)	Natural Features from Open Street Maps (OSM, https://download.geofabrik.de/europe/slovakia.html: Modeling density in GIS, using Kernel density (density within a 50 km radius)
	B12 Types of settlements (urban, rural, and dispersed)	[64]
	B13 Ecological farming	https://gsaa.mpsr.sk/2021/
Habitat characteristic	B14 Ability of habitats to assimilate CO_2	Expert assessment Field research
	B15 Water retention potential of habitats	
	B16 Habitats in terms of biodiversity and attractiveness to pollinators	

altogether (e.g., building in areas with potential flooding, plowing on erosion-prone slopes, etc.).

Determination of the functional value of the indicators for the potential activities

The benefits of individual potential activities are determined by the entire set of indicators x_i. However, determining the appropriate value for a landscape natural asset can be challenging and subjective. The five groups of research team's expert used their knowledge to estimate the functional value of certain individual indicators (fx_i) for possible X_i to reduce subjectivity. However, this experience is also based on normative knowledge and, in some cases, quantitative assessments. In particular, the following basic groups of criteria were taken into account in determining functional capacity [46]:

- Location criteria: these are mainly criteria resulting from abiotic conditions, assessed as suitable, constraining, and limiting for the selected activities. Relief and soil play an important role here.
- Selective criteria—bioclimatic and bio-ecological—are both supportive criteria for biota-based potential activities, e.g., expected bioproductive potential and ecological importance of different vegetation units, stability and carrying capacity, conservation benefits, and limits and constraints for intensive use.
- Implementation criteria: these are indicators derived from socio-economic indicators. They are both supporting criteria for the nature of legislative provisions for the protection of nature and natural resources and stress phenomena associated with the degradation of natural assets. However, these same criteria also have a strong, clear limiting and constraining influence on the use of many other potential services.

A six-point scale is used to describe the functional capacity of indicators (fx_i): 6—the best or excellent potential assets; 5—good; 4—adequate; 3—limited; 2—severely limited; and 1—unsuitable, excluded capacity for activity or service.

To find the required potential activities, a semi-quantitative decision-making method is used. This method uses a two-dimensional matrix with evaluated potential activities, chosen indicators, and weighting coefficients. Equally, the weighting coefficients of the vx_i indicators

Table 3 Indicators of humans' appreciation of socio-economic protected areas of nature and natural resources

Category of indicators	Basic indicators	Type of data or source
Nature protection	S01 Categories of national protected areas S02 Internationally protected areas S19 Habitat significance	https://maps.sopsr.sk/ https://www.biomonitoring.sk/
Territorial network of ecological stability	S03 Biocentres/Biocorridors: national, regional, local; Interactive elements	https://maps.sopsr.sk/
Protection of forest resources	S04 Categories of protected forests	https://gis.nlcsk.org/islhp/mapa
Protection of water resources	S05 Categories of source drinking water protection	https://www.minzp.sk/voda/chvo/
Protection of healing and spa resources	S06 Categories of protection of natural medicinal resources S07 Categories of protection of spa sources and their protection zones	Act 538/2005 Coll. (on natural healing waters, natural healing baths, spa places and natural mineral waters)
Protection of soil resources	S08 Classes of protected soils S09 Land fertilized by investment S10 Less favored areas	http://www.podnemapy.sk/portal/verejnost/bpej/bpej.aspx Atlas of the landscape of the Slovak Republic: https://app.sazp.sk/atlassr/
Protection of gene pool resources	S11 Fishing areas S12 Hunting areas S13 Game parks S14 Pheasant farms	https://rybarskyrevir.sk/ https://gis.nlcsk.org/islhp/registre-polovnictvo
Species protection	S15 Protected and vulnerable plant species S16 Protected and vulnerable animal species	https://www.biomonitoring.sk/
Protection of mineral resources	S17 Protected deposit area of reserved and non-reserved mineral	The State Mining Office https://www.hbu.sk/?en
Protection of cultural monuments	S18 Category of protection of cultural monuments	Monuments Office of the SR https://www.pamiatky.sk/nk/p-a-po/

for the X_i potential activities evaluated also entered into the modeling. The weighting coefficients were determined according to the order of importance of the indicator for the activity, from 1 to 5, by 15 experts from the project team, who provide the weights independently in the form of survey. The final weight value was set based on the mean, median, and most frequently used value of indicator importance as evaluated by 15 experts. Subsequently, the ranking values were converted to vx_i values ranging from 1 to 0.2 (Table 7 for the natural capital of landscape planning activities, Additional file 1—for natural capital assessment of specific activities and functions).

The overall natural capital of each potential activity X_i was calculated according to activity-specific indicators, also with weighting coefficients, according to the formula

$$PotX_i = \sum fx_i * v_{xi},$$

when only selected indicators for a specific activity enter the calculation. As an example for natural capital assessment of the total eco-stabilizing natural capital, we carried out an assessment in the case study of the LTSER Trnava region (the GIS modeling workflow and the set of indicators and their functional value are in Additional file 2).

In terms of limits and constraints resulting from current land cover and socio-economic indicators, we assessed limits on a 3-degree scale: 0—no limits; 1—limited; and 2—excluded. If at least one limit excluded the conditions for potential activity, the overall assessment of the target area was unsuitable for potential activity.

A computational algorithm was developed to assess the overall realistic natural capital for a particular potential activity based on the natural assets of the landscape for the target activity and limits derived from socio-economic indicators.

Case study: LTSER Trnava region

The LTSER Trnava region is dominated by high-quality soils (chernozems and chernozems on alluvial soils), which, together with lowland landforms and favorable climatic conditions, create a high potential for the development of agriculture. The agricultural land in the region is one of the best quality and most fertile soils, with a high production potential from a national point of view. The most suitable use of the agricultural potential is for arable crops and, in the vicinity of settlements, also for orchards and gardens. Stress phenomena limit direct cultivation of crops in the area, requiring priority for industrial crops in contaminated areas.

There is high forestry potential in the northern part of the study area. Parts of the forests are protective forests and parts are special-purpose forests. Protective forests are found on the ridge of the Malé Karpaty Mts., where

Table 4 Socio-economic indicators limiting human appreciation of nature and natural resources: limiting stress determinants

Category of indicators	Basic indicators	Type of data or source
Environmental burdens	L01 Type of environmental burden (probable, real, remedied)	https://www.enviroportal.sk/en/environmental-burdens
Protection zones of technical objects, e.g., cemeteries, electric plants etc	L02 Type of protection zone based on object type and size	Spatial planning documentation and protection zones based on decrees and laws
Military areas	L03 Military objects and their protection zones, Military zones	Ministry of Defense of the Slovak Republic: https://www.mosr.sk/
Air quality	L04 Air pollution zones based on the degree of pollution	Slovak Hydrometeorological Institute: https://www.shmu.sk/en/?page=1799, in situ research
Noise load	L05 Levels of environmental noise pollution	Public Health Authority of the Slovak Republic: https://www.uvzsr.sk/sk/web/uvzen
Quality of water resources	L06 Profiles of physical and chemical waters characteristics L07 Degrees of ecological and chemical status of surface water bodies L08 Classification of the ecological potential of groundwater bodies	State hygiene institute, city authorities https://www.enviroportal.sk/agendy/obcan/kvalita-pitnej-vody In situ research
Soil contamination	L09 Categories of soil contamination	https://www.enviroportal.sk/en/about-enviroportal in situ research
Vegetation damage	L10 Degrees of vegetation damage	https://gis.nlcsk.org/islhp/mapa
Radon risk	L11 Levels of radon risk	https://apl.geology.sk/radio/
Seismic risk	L12 Degrees of seismic activity	Atlas of the landscape of the SR: https://app.sazp.sk/atlassr
Slope deformations	L13 Levels of activity type of slope deformation	Atlas of the landscape of the SR: https://app.sazp.sk/atlassr
Erosion	L14 Threats by water erosion L15 Threats by wind erosion	Atlas of the landscape of the SR: https://app.sazp.sk/atlassr
Areas at risk of avalanches	L16 Risk degree of avalanches L17 Threats by landslides	Atlas of the landscape of the SR: https://app.sazp.sk/atlassr
Old mine loads	L18 Old mining works L19 Mined territories	https://envirozataze.enviroportal.sk
Flood risk	L20 Geographical areas with an existing potentially significant flood risk L21 Inundation area	https://www.minzp.sk/voda/ochrana-pred-povodnami/manazment-povodnovych-rizik/povodnove-mapy.html
Derived indicators		
Quality of the environment	L22 Environmental quality coefficient	the cumulative degree of stress indicators and the ecological stability coefficient
	L23 Road traffic load coefficient L24 Rail transport load coefficient	The total length of traffic lines in a linearly weighted circular neighborhood 1 km from each point
Natural risks and hazards	L25 Coefficients of threats to the territory by natural risks and hazards	https://www.minzp.sk/voda/ochrana-pred-povodnami/manazment-povodnovych-rizik/povodnove-mapy.html
	L26 Surface runoff curve number (CN)	https://geoportal.vumop.cz/docs/Metodika_vysledku_Nmap.pdf

they provide soil protection and are part of the Malé Karpaty PLA. The special-purpose forests are linked to protected areas and to protected zones of water resources. The forest ecosystems are also characterized by high nature conservation, gene pool, and eco-stabilization potential. There are also several protected areas at the 4th and 5th levels of protection: three protected areas, eight nature reserves, two national nature reserves, three sites of natural monuments, and four Natura 2000 sites. The management of forests is limited due to the existence of protected areas. The area has significant potential for grassland, but due to protected areas and water protection zones, its use for grazing is limited. The Malé Karpaty Mts. foothills offer potential for viticulture development, which was extensively used, especially in the pre-transformation period before EU accession. It is one of the most important Slovak wine-growing areas along the Malé Karpaty Wine Route. In the post-transformation period, as a result of socio-economic conditions (physically strenuous work, falling wine prices,

Table 5 Set of natural capital indicators for landscape planning activities (I.)

Code	Name of potential activity	Indicators
Bioproductive potential activity		
B1	Absolute bioproductive potential	A01, A09, A10, A11, A12, A13, A14, A15, A16, A18, B03
B2	Realistic bioproductive potential	A01, A09, A10, A12, A13, A14, A15, A16, A18, B03 Limits: L01, L04, L07, L08, L09, L10, L14, L16, L17, L23, L24
Potential activity for forestry and woodland		
F1	Production forests: timber production and harvesting	A01, A12, A14, A15, A17, A18, A19, A20, A21, B06 Limits: B10, L01, L10, L15, L17, S01, S02, S03, S04, S05, S06, S07, S08, S09, S10, S12, S13, S14, S15, S16, S17, S18, S19, S20, S21, S23
F2	Protective and special-purpose forests	A01, A09, A10, A12, A13, A14, A15, A16, A18, B03 Limits: B07, L01, L10, L14, L15, L17, S01, S02, S03, S04, S05, S06, S07, S13, S14, S15, S16, S17, S18, S19
F3	Small woodland and scrubland	A01, A09, A10, A12, A13, A14, A15, A16, A18, B03 Limits: S04, S08, S14, S18
Potential activity for agriculture		
A1	Arable land for food crops	A01, A09, A10, A12, A13, A14, A15, A16, A18, B03 Limits: L01, L04, L08, L09, L10, L14, L15, L16, L17, L23, L24, S01, S02, S03, S04, S05, S06, S07, S11, S14, S15, S16, S18, S19
A2	Permanent crops: orchards, fruit plantations	A01, A09, A10, A12, A13, A14, A15, A16, A18, B03 Limits: L01, L04, L08, L09, L14, L16, L17, L23, L24, S01, S02, S03, S04, S05, S06, S07, S11, S14, S15, S16, S18, S19
A3	Permanent crops: vineyards	A01, A09, A10, A12, A13, A14, A15, A16, A18, B03 Limits: L01, L04, L08, L09, L10, L14, L15, L16, L17, L23, L24, S01, S02, S03, S04, S05, S06, S07, S11, S14, S15, S16, S18, S19
A4	Arable land for industrial crops	A01, A09, A10, A12, A13, A14, A15, A16, A18, B03 Limits: L01, L10, L14, L15, L16, L17, S01, S02, S03, S04, S05, S06, S07, S11, S14, S15, S16, S18, S19
A5	Grassland: meadows or mixed use	A01, A09, A10, A12, A13, A14, A15, A16, A18, B03 Limits: L01, L04, L09, L10, L14, S04, S05, S11, S15, S16, S18, S19
A6	Grassland: pasture	A01, A09, A10, A12, A13, A14, A15, A16, A18, B03 Limits: L01, L04, L07, L09, L10, L14, L17, L23, L24, S01, S02, S03, S04, S05, S06, S07, S12, S15, S16, S18, S19
A7	Energy trees or shrubs plantations	A01, A09, A10, A12, A13, A14, A15, A16, A18, B03 Limits: L01, L17, S01, S02, S03, S04, S05, S06, S07, S08, S11, S14, S15, S16, S18, S19
Potential for the construction development of industries and urbanization		
U1	Residential construction	A01, A09, A10, A12, A13, A14, A15, A16, A18, B03 Limits: B07, L01, L04, L07, L08, L09, L10, L11, L12, L14, L15, L16, L17, L23, L24, S01, S02, S03, S04, S05, S06, S07, S08, S09, S11, S12, S14, S15, S16, S17, S18, S19
U2	Industrial estates	A01, A09, A10, A12, A13, A14, A15, A16, A18, B03 Limits: L01, L12, L14, L16, L17, S01, S02, S03, S04, S05, S06, S07, S08, S09, S11, S12, S13, S14, S15, S16, S17, S18, S19
U3	Agricultural-technical buildings	A01, A09, A10, A12, A13, A14, A15, A16, A18, B03 Limits: L01, L12, L14, L16, L17, S01, S02, S03, S04, S05, S06, S07, S08, S09, S11, S12, S13, S14, S15, S16, S17, S18, S19
U4	Livestock farms	A01, A09, A10, A12, A13, A14, A15, A16, A18, B03 Limits: L01, L04, L07, L08, L09, L12, L14, L16, L17, L23, L24, S01, S02, S03, S04, S05, S06, S07, S08, S09, S11, S12, S13, S14, S15, S16, S17, S18, S19

Table 5 (continued)

Code	Name of potential activity	Indicators
U5	Transport complexes, objects and areas	A01, A09, A10, A12, A13, A14, A15, A16, A18, B03 Limits: L01, L12, L14, L16, L17, S01, S02, S03, S04, S05, S06, S07, S08, S09, S11, S12, S13, S14, S15, S16, S17, S18, S19

imports of wine from abroad, volatile weather), there was a decline in viticulture, and many vineyard plots were gradually converted into cottages and chalets as second homes or weekend houses.

The natural capital for tourism development is represented by the mountain ecosystem of the Malé Karpaty PLA, which is particularly suitable for the development of summer tourism as well as for the development of winter sports such as sledging, downhill skiing, and cross-country skiing. The presence of protected landscape areas conditions the development of cognitive tourism, focused, for example, on individuals' appreciation of the natural or cultural heritage, landscape, and history of a place. The Driny Cave or the archeological site of Molpír is also attractive features of the Malé Karpaty Mountains. At the same time, the presence of these nature and landscape protection zones is restrictive or even limiting in relation to recreational and tourist activities.

The central and southern parts of the region, with predominantly agricultural production, are particularly suitable for the development of agro-tourism and rural tourism. This natural capital is also enhanced by the location of the area on the Malé Karpaty Wine Route, as well as the rich wine-growing tradition. However, this natural capital is insufficiently utilized in the region, and forms of agro-tourism are very poorly developed.

The flat area also creates a high potential for the development of socio-economic activities associated with the development—housing, industry, agriculture, etc., which were also intensively used. Many industrial centers—Peugeot, Samsung, etc.—and logistic and commercial centers have sprung up in the area. In the post-transformation period, housing construction and the built-up area also increased significantly. The restrictions and limits resulting from the protection of soil resources were often not respected.

The expansion of construction has led to an increase in anthropization and a decrease in the ecological stability of the study area. The overall eco-stabilization of natural capital would be positively complemented, in particular, by new green infrastructure, which would support the existing ecosystems with a high eco-stabilization effect. Planting new lines and plots of green infrastructure can enhance ecological stability by reducing the homogeneity of the intensive farmland and promoting the use of the region's natural capital for agriculture and biodiversity conservation.

Eco-stabilizing natural capital expresses the ability of landscape elements to ensure the ecological stability of spatial units (Fig. 3). Other supporting indicators are positive socio-economic indicators aimed at nature and landscape protection, ensuring the preservation and protection of rare natural ecosystems. Land cover elements with eco-stabilizing potential include forests, non-forested woody vegetation, permanent grasslands, wetlands, orchards and gardens, mosaics, preserved traditional agricultural landscapes, and natural water bodies. The natural waterways Parná, Trnávka, Gidra, Blava, Dudváh, Krupiansky Brook, and Ronava make up the linear green infrastructure. They are formed by typical stands of floodplain forests that connect the Malé Karpaty Mountains to the Váh River's floodplain. These parts of nature are often part of protected areas and ecological networks. They are known as biocenters, biocorridors, gene pool sites, and important landscape features and show the highest natural capital for ecological stability.

Stress determinants, both natural and anthropogenic, whether primary or secondary, act as constraints and limits in relation to the eco-stabilization of natural capital. Natural stress factors, like floods, landslides, erosion, and wind storms, can cause sudden degradation of ecosystems and their living conditions.

Anthropogenic stress determinants have a similar effect. Primarily, they are connected with the occupation of natural ecosystems for the implementation of anthropogenic objects and lines. Secondly, they show up in the degradation of ecosystems by the production of different foreign substances that pollute different parts of the environment and natural resources. The lowest ecological stability was observed in settlements. Barriers and limits include paved and degraded areas (residential, industrial, and mining areas), large arable land, and linear features like transport networks and infrastructure, and regulated watercourses. The Trnava region faces significant barriers for animal migration due to various factors such as watercourses, roads, railways, settlements, industrial complexes, mining complexes, farm complexes, horticultural settlements, and waste dumps and landfills. Stress determinants are intense in areas surrounding Trnava city, including settlements with industrial plants

Table 6 Set of natural capital indicators for specific activities and functions (II.)

Code	Name of potential activity	Indicators code
Energy potential (suitability for the implementation of energy plants and facilities)		
EN1	Wind energy	A06, A09, B01 Limits: B06, B07, B09, L01, L02, L14, L15, L16, L17, S01, S02, S03, S04, S05, S06, S07, S08, S09, S11, S14, S15, S16, S17, S18, S19
EN2	Solar energy	A01, A05, A08, A09, A10, A11 Limits: L01, L14, L15, L16, L17, S01, S02, S03, S04, S05, S06, S07, S08, S09, S11, S14, S15, S16, S17, S18, S19
EN3	Geothermal energy	A12, A18 Limits: L01, L07, L08, L09, S01, S02, S03, S04, S05, S06, S07, S08, S09, S11, S14, S15, S16, S17, S18, S19
EN4	Hydropower energy	A18, L26 Limits: B07, B09, L01, L12, L15, L16, S01, S02, S03, S04, S05, S06, S07, S08, S09, S11, S14, S15, S16, S17, S18, S19
Recreation potential activity		
R1	Winter/Snow-related sports	A01, A02, A07, A08, A09, A10, B01, B04 Limits: B07, L01, L04, L14, L15, L16, L17, L23, L24, S01, S02, S03, S04, S05, S06, S07, S08, S09, S11, S14, S15, S16, S17, S18, S19
R2	Summer hiking	A03, A05, A10, B01, B04, B10, B11 Limits: L01, L04, L07, L10, L14, L15, L16, L17, L23, L24, S01, S02, S03, S04, S05, S06, S07, S08, S09, S11, S14, S15, S16, S19
R3	Holiday resorts (cottages)	A01, B01, B09, B12, L22 Limits: B07, L01, L04, L07, L09, L10, L11, L14, L15, L16, L17, L23, L24, S01, S02, S03, S04, S05, S06, S07, S08, S09, S11, S14, S15, S16, S17, S18, S19
R4	Sightseeing and scientific tourism	B01, B04, B08, B09, B10, B11, S01, S02, S03, S06, S07, S11, S12, S14, S15, S16, S17, S18 Limits: L01, L04, L07, L14, L15, L16, L17, L23, L24, S04, S05, S08, S09
R5	Water sports	A04, A19, B01, B04 Limits: L01, L04, L07, L08, L10, L14, L15, L17, L23, L24, S01, S02, S03, S04, S05, S06, S07, S08, S09, S11, S14, S15, S16, S17, S18, S19
R6	Hunting	B01, B05, S12, S13, S14 Limits: L01, L17, S01, S02, S03, S04, S05, S06, S07, S08, S09, S11, S14, S15, S16, S17, S18, S19
R7	Fishing	B01 (Waters), B05, S11, L06, L07 Limits: L01, L04, L07, L08, S01, S02, S03, S04, S05, S06, S07, S08, S09, S11, S14, S15, S16, S17, S18, S19
Ecological regulation services		
W1	Surface water supply to the population	Limits: L01, L04, L07, L08, L09, L11, L23, L24, S06, S07, S08, S09, S15, S16, S17, S18
W1	Groundwater supply to the population	Limits: L01, L04, L07, L08, L09, L11, L17, L23, L24, S06, S07, S08, S09, S15, S16, S17, S18
E1	Air quality regulation	A06, A09, B01, B07, B14 Limits: B07, L01, L04, L07, L09, L10, L15, L23, L24, S01, S02, S03, S05, S06, S07, S08, S09, S11, S14, S17, S18
E2	Climate change mitigation	B01, B04, B07, B14, S04 Limits: B07, L01, L04, L07, L09, L10, L14, L15, L17, L23, L24, S01, S03, S05, S06, S07, S08, S11, S14, S17, S18
E3	Water retention	A10, A17, B01, B07, B15, L26 Limits: B07, L01, L10, L14, L17, S01, S03, S06, S07, S08, S11, S14, S17, S18
E4	Natural heritage	B01, B04, B07, B08, B09, S01, S02 Limits: B07, L01, L04, L07, L09, L10, L14, L15, L16, L17, L23, L24, S05, S06, S07, S08, S11, S14, S15, S16, S17, S18
E5	Eco-stabilization	A06, A09, B01, B04, B07, B09, B12 Limits: L01, L04, L07, L09, L10, L14, L15, L16, L17, L23, L24, S01, S03, S04, S05, S06, S07, S08, S11, S14, S17, S18
E6	Biodiversity and pollination support	B01, B02, B07, B09, B13, B16, S01, S04 Limits: L01, L04, L07, L09, L10, L14, L15, L17, L23, L24, S03, S05, S06, S07, S08, S11, S14, S17, S18

Table 7 Weighting coefficients of the indicators vx_i for the natural capital of landscape planning activities X_i

Potential activities (Table 5)/Indicators	B1	B2	L1	L2	L3	P1	P2	P3	P4	P5	P6	P7	U1	U2	U3	U4	U5
A01 Climate region	1	1	0.4	0.2	0.2	0.4	0.4	1	0.2	0.4	0.4	0.6	0.8	0.2	0.1	0.4	0.1
A12 Morphological and positional relief forms	0.6	0.6	0.6	0.4	0.6	0.6	0.4	0.4	0.6	0.6	0.6	0.4	0.8	0.7	0.5	0.5	0.2
A14 Exposure	0.6	0.6	0.6	1	1	1	0.6	0.4	1	1	1	0.8	1	1	1	0.8	1
A15 Genetic and lithological substrate	1	1	1	0.8	0.8	0.6	0.6	0.6	0.6	0.4	0.8	1	0.4	0.7	0.6	0.8	0.5
A17 Permeability of hydrogeological types	0.2	0.2	0.6	0.4	0.4	0.6	0.6	0.6	0.6	0.4	0.4	0.8	0.2	0.2	0.2	0.6	0.5
A18 Soil subtypes	0.8	0.8	0.6	0.6	0.8	0.6	0.8	0.6	0.2	0.6	0.8	0	0.2	0.2	0.2	0.2	0.1
A19 Depth of soils	0.6	0.6	1	1	1	1	0.5	0.5	0.6	0.7	0.5	0.6	1	1	0.6	0.6	0.8
A20 Skeletonization of soils	0.6	0.6	1	1	1	1	1	1	1	0.8	1	0.6	1	1	0.8	0.8	1
A21 Granularity of soils	0.2	0.2	0.6	0.2	0.4	0.8	0.4	0.6	0.8	0.6	0.6	0.6	0.3	0.3	0.3	0.5	0.2
B06 Possible biota	1	1	0.2	0.5	0.4	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.4	0.4	0.,2	0.5	0.1

(Voderady, Boleráz, Smolenice, Jaslovské Bohunice), high traffic routes, and areas influenced by traffic routes. Low spatial ecological stability is found in the central part of the district, which is characterized by a homogeneous agricultural landscape.

Discussion

Landscape potential is the ability of a landscape to support a certain activity based on signs of the assets in the primary, secondary, and tertiary structures of geosystems. The limits of the current land cover, as well as the limits of stress determinants and other socio-economic drivers, modify the primary suitability. Human dependence on natural resources and geosystem services is increasing due to population growth, although the natural assets are limited. The traditional development models have failed to bring about conservation solutions to this contradiction, and the successful implementation of natural capital assessment is still in its early stages [47, 48]. The United Nations Millennium Ecosystem Assessment concluded that about 60% of the world's ecosystem services are used unsustainably [7]. Poorly managed natural capital therefore becomes not only an ecological liability but a social and economic liability too. Overexploiting natural capital can lead to serious biodiversity loss and discomfort to human well-being, as ecosystem productivity and resilience decline over time and some regions become more susceptible to extreme events like floods and droughts. Trnava LTSER is such a region, with a wide range of opportunities to exploit natural capital, but often with overexploitation for economic development to the detriment of the most fertile soils and suppression of eco-stabilization potential.

To ensure efficient use of natural capital, an integrated approach has to be applied at all levels of governance and practical implementation, including horizontal and sectoral integration, vertical integration, environmental integration, supply and demand integration, and integration over time [34]. It involves aligning land use with activities promoting health, education, recreation, and biodiversity conservation, integrating supply and demand, and considering long-term development forecasts with a strategic horizon of at least 25 years. Integration of natural capital into policy [49] can help protect and restore natural resources and biodiversity, reduce the risks of environmental degradation and natural hazards, improve water quality, mitigate the effects of climate change, and also support the achievement of economic and social development objectives [30, 50]. Optimal measures for landscape organization and land use should protect the entire landscape and its natural assets simultaneously. Efforts to restore natural capital for ecosystem services and stimulate multifunctionality in landscapes often involve identifying cost-effective geographic priorities or hotspots that provide multiple ecosystem goods and services. This requires integrated spatial modeling, clear goals, and performance indicators guiding targeted land use change and increasing landscape multifunctionality [51].

For sustainable use of natural assets, it is important to recognize that each territory represents an integration of diverse natural capital assets. Our methodological approach brings a new systematic interdisciplinary approach for assessment of landscape capital in the form of comprehensive methodology for sustainable landscape utilization based on geosystem approach. While the ecosystem approach focuses on the assessment of the services provided by ecosystems, mainly based on current land cover and habitats, the geosystem approach takes more account of the abiotic complex of the area. This integrated, geosystem approach eliminates the component-sector approach in landscape use and management. The assessment is focused on several groups of potential natural capital activities, including

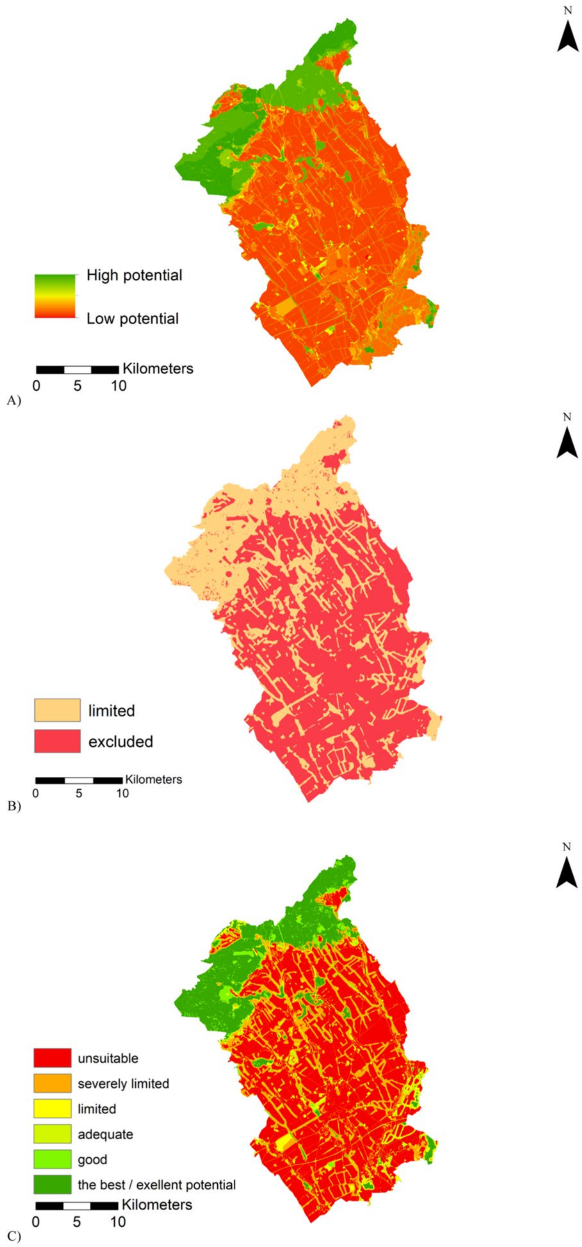

Fig. 3 Eco-stabilizing natural capital in Trnava LTSER **A** Potential natural capital assets for eco-stabilization; **B** Limits to eco-stabilizing natural capital; **C** Total eco-stabilizing natural capital, including the limits

bioproduction, forestry, agricultural, construction, development of industries, urbanization, energy, recreation, water management, and ecosozoological and eco-stabilization potential. This approach is based on the knowledge of the relationships of landscape and natural capital assets to human activities and also the knowledge of the relationships between different landscape indicators, which has not been sufficiently developed in landscape-ecological planning so far. We summarized a set of indicators—basic and derived, reflecting natural capital assets—relating especially to abiotic conditions and natural reconstructed vegetation. Additionally, an important part of our assessment was modeling, using (1) current land use that helps us resolve problems with inappropriate utilization of natural capital and (2) other socio-economic phenomena that may support or limit socio-economic activities in the use of natural capital. By collecting and classifying data sources, their parameterization, and clarifying definitions and underlying concepts for the assessment of natural capital, we fulfill four important functions in planning, particularly where group deliberative processes are involved [52]: 1. Make values and underlying concepts transparent; 2. Provide a sound basis for assessing synergies and trade-offs; 3. Clarify ethical constraints, including aspects of governance and legitimate power; and 4. Provide a framework for cross-cultural analysis and planning.

Several studies indicated that the concept of geosystem services has not yet been fully integrated into planning processes, despite the increasing need for its inclusion under the emerging development agenda of energy services, needs for mitigation climate change, hydrological and hydrogeological cycles management, and the rational use of landscape space [33, 53]. Other review highlights that the under-representation of geosystem services in the scientific literature negatively affects integrated decision-making in spatial planning, environmental policy-making, and long-term ecosystem management [54]. Although the number of studies has increased in recent years, most of them deal only with some aspect of geosystem services assessment [9, 33, 55, 56]. Our approach to complex inclusion of geosystem services into landscape planning by development methodology for the assessment natural capital of landscape planning activities would constitute an important step forward to sustainable urbanization.

The development of our methodological approach has resulted in a more detailed elaboration of the theoretical-methodological basis with the use of modern technologies offered by GIS, Remote Sensing (RS), and computer modeling of the dynamics of individual natural and anthropogenic processes and their impacts on various activities. Our results are available in the dedicated web portal (https://map.iesprit.sk/enviroapp/application), and we will make them available also in the LTER information system DEIMS-SDR (Dynamic Ecological Information Management System-Site and Dataset Registry; [57]). DEIMS-SDR contains each site's location, ecosystems, facilities, observed properties, or research themes [27]. Part of the LTSER platform is also a socio-economic set of data that can be used in the future to assess the realistic use of natural capital in space and time.

The creation of a web application is one way to promote natural capital and efficiently make spatial information accessible, providing information and mapping options to different communities for spatial decision-making purposes [58, 59]. This way, our research results can be can be utilized in spatial planning processes at regional level.

Conclusion

In this paper, we develop an algorithm for a methodological approach to the assessment of natural capital assets, which leads to a proposal for the efficient use of natural capital. It defines the basic methodological steps that need to be carried out to express the value of natural capital and to optimize the use of natural resources in the study area. On the basis of the natural capital assets and their indicators, the landscape capacity for the selected activity—active or passive, "idle" function—is expressed. A comprehensive holistic approach to landscape is applied in the suitability assessment. The novelty of our approach lies in the extension of the geosystem approach and suitability for potential activities determined on the basis of not only indicators of abiotic conditions and land cover but also identification of socio-economic determinants, either supporting or limiting the assessed activities. Natural capital assets are modified by the limits of current land use as well as by the limits resulting from the action of socio-economic indicators arising from the need to protect the precious landscape values as well as from the action of stress factors associated with the implementation of human activities in the landscape. On the basis of their synthesis, the realistic landscape natural capital for a given activity or function was determined.

The methodological approach can be applicable to any territory on the basis of a modification. This approach defines the basic parameters that enter into the assessment of the natural capital for the development of the various activities and forms of land use. When applying a methodological approach to another region, it is crucial to select relevant activities for the target region and propose appropriate indicators to evaluate the territory's suitability for the activity's implementation. For natural capital valuation models, it is also important to determine the functional values of indicators for the selected potential assets and determine weighting coefficients, which was the most labor-intensive phase of data collection for modeling. The experts selected were all actors in the LTSER platform, with different scientific background and therefore had hands on experience of the area.

As an output of this methodological approach, a comprehensive digital spatial database of landscape-ecological data for the assessment of natural capital and the suitability of its use for socio-economic activities has been created in Slovakia. The database represents a set of consistent spatial information on natural capital assets and other indicators, including land cover and socio-ecological indicators. Until now, the lack of spatial data and understanding of interrelationships hindered effective environmental protection, including the protection of nature, natural resources, and biodiversity. The created database is the data and knowledge base for web-based geoprocessing services.

Both the database and the methodology are suitable tools and landscape-ecological basis for the development of landscape planning processes and are of course also applicable in sectoral policies (landscape and species protection, protection of natural resources including water, soils, and forests, flood protection, spatial planning, sustainable development, etc.). Its implementation in practice will contribute to the elimination of existing and new environmental problems and will help ensure the efficient use of the natural capital of the study area.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12302-024-00894-w.

Additional file 1. Table A1. Weighting coefficients of the indicators vxi for the natural capital of specific activities and functions (II.) (EN1 – Wind energy; EN2 – Solar energy; EN3 – Geothermal energy; EN4 – Hydropower energy; R1 – Winter/Snow-related sports; R2 – Summer hiking; R3 - Holiday resorts (cottages); R4 – Sightseeing and scientific tourism; R5 – Water sports; R6 – Hunting; R7 – Fishing; W1 – Surface water supply to the population; W1 – Groundwater supply to the population; E1 – Air quality regulation; E2 – Climate change mitigation; E3 – Water retention; E4 – Natural heritage; E5 – Eco-stabilization; E6 – Biodiversity and pollination support).

Additional file 2: Figure S1. Workflow of GIS modeling for natural capital assessment of total eco-stabilizing natural capital. **Table S1.** The functional capacity of indicators (fxi) for the activity: E5 Eco-stabilization (6—the best or excellent potential assets; 5—good; 4—adequate; 3—limited; 2—severely limited; 1—unsuitable, excluded capacity for activity or service. **Table S2.** The functional capacity of current land cover (B01) for the activity: E5 Eco-stabilization (6—the best or excellent potential assets; 5—good; 4—adequate; 3—limited; 2—severely limited; 1—unsuitable, excluded capacity for activity or service. **Table S3.** The functional capacity of EUNIS habitats (B04) for the activity: E5 Eco-stabilization (6—the best or excellent potential assets; 5—good; 4—adequate; 3—limited; 2—severely limited; 1—unsuitable, excluded capacity for activity or service. **Table S4.** Limits and constraints—from the current land cover (0—no limits; 1—limited; and 2—excluded). **Table S5.** Limits and constraints—from limiting stress determinants (0—no limits; 1—limited; and 2—excluded). **Table S6.** Limits and constraints—from indicators of humans' appreciation of socio-economic protected areas of nature and natural resources (0—no limits; 1—limited; and 2—excluded).

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Author contributions
Zita Izakovicova (AAI-4466-2021) and Laszlo Miklos contributed to the study conception and design; Jan Dick performs supervision of the methodological approach. Material preparation, and data collection and analysis were performed by Jana Spulerova (J-5483-2019), Marta Dobrovodská, and Ľuboš Halada (A-9068-2016). Modeling and GIS tasks were performed by Andrej Raniak (AAD-9176-2020). The first draft of the manuscript was written by Zita Izakovičova and Jana Spulerova and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability
The datasets generated and analyzed during the current study are available in the Institute of Landscape Ecology of the Slovak Academy of Sciences. Analytical data collected for LTSER Trnava will be stored at Dynamic Ecological Information Management System-Site and Dataset Registry [57]. The final maps of the national natural capital assessment are available in the dedicated web portal (https://map.iesprit.sk/enviroapp/application).

Competing interests
There are no competing interests.

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