






Systematic Review

Monitoring Soil Fertility Trends Linked to Arable Land-Use Change in Hungary, 2000–2020: A Systematic Review Integrating Field and Remote Sensing Data

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Abstract

Quantifying the effects of land-use changes on soil fertility is essential for agricultural planning, yet long-term analyses combining field and remote sensing data remain scarce in Hungary. This systematic review followed PRISMA 2020 guidelines to assess arable land fertility trends between 2000 and 2020. A comprehensive search of WoS, Scopus, and Google Scholar identified 202 records, with 106 studies meeting inclusion criteria. Eligibility required empirical soil data collected from Hungarian arable lands. Among these, 17% reported declines in SOC, 13% indicated nutrient depletion, 36% observed stable or lost fertility, and 34% documented improvements. Regarding monitoring methods, 41% relied solely on field sampling, 44% applied GIS or spatial analyses, and 15% incorporated remote sensing indices such as NDVI. Evidence revealed spatial–temporal heterogeneity: fertility declines occurred in intensively cultivated regions, while western Transdanubia showed stability. Trends were linked to land-use intensification and intermittent reductions in agricultural area. Integration of remote sensing indices, such as NDVI, with field observations enhanced detection of spatial and temporal patterns. These findings underscore the need for harmonised monitoring frameworks, precision agriculture tools, and predictive modelling to support sustainable soil management. Identifying fertility-decline zones informs policy aligned with the EU Soil Strategy 2030 and supports Hungary’s agricultural resilience.

Keywords: soil fertility; arable land; land use; remote sensing; Hungary



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1. Introduction

1.1. Introduction and Importance of Soil Fertility

Soil fertility is a key determinant of agricultural productivity and environmental sustainability. It influences land management practices, crop yields, and overall ecosystem resilience [1,2]. Soil fertility is determined by key physicochemical properties, including soil organic carbon (SOC), nutrient availability (nitrogen, phosphorus, and potassium), soil pH, and cation exchange capacity (CEC). These factors collectively influence plant growth and soil productivity [3–8].

Concerns over declining soil quality have increased globally due to intensive agricultural practices, climate change, and land-use changes in recent decades [9]. Any change in land use significantly impacts the fertility of soil, often leading to a decline in soil fertility [10]. Conversion of land cover, particularly forests, into arable land disrupts natural nutrient cycles. This process increases erosion and reduces soil organic matter [11]. Intensive farming practices, such as monoculture, and urbanisation can reduce land productivity through soil sealing and nutrient depletion [12]. These pressures are particularly evident in regions undergoing rapid agricultural and socio-economic transitions. Central and Eastern Europe represents one such region, where historical land management systems have evolved significantly over the past decades.

In parts of Central and Eastern Europe, where Hungary lies, these changes pose significant shifts in the use of land as economies transition from their original plans to market-oriented agriculture [13]. However, sustainable land management, like crop rotation, can improve soil fertility. Thus, the long-term land use impacts depend on how the land is managed after conversion. Consequently, stakeholders such as agronomists and policymakers monitor soil fertility trends and integrate them into land-use planning to ensure food security with minimal land exploitation. The growing body of research on soil fertility dynamics and land-use change necessitates the synthesis of existing evidence through a systematic review approach. Ultimately, this can provide a comprehensive understanding of long-term soil fertility trends and monitoring practices.

1.2. Soil Fertility Monitoring and Regional Context

In most Hungarian and European Union (EU) soil monitoring programmes, soil fertility is characterised using laboratory-derived indicators such as SOC, total N, available P, exchangeable K, and soil pH. These indicators are analysed using standardised national (*Magyar Szabvány, MSZ*; e.g., MSZ 08 0205: Determination of soil pH) [14] and International Organisation for Standardisation (ISO-based) protocols (ISO/TC 190 [15]; Food and Agriculture Organisation, FAO [16]), following standard operating procedures of the Global Soil Laboratory Network (GLOSOLAN). These metrics provide the basis for evaluating long-term soil fertility trends and linking land use to soil conditions [17,18].

Studies indicate that there is a direct relationship between land-use shifts and the corresponding level of soil fertility [19–22]. In Hungary, it is essential to examine the interaction between the use of arable land and soil fertility. Hungary's agricultural sector accounts for approximately 55.6% of land use and 4.7% of gross domestic product (GDP) [23]. Since its accession to EU in 2004, Hungary has undergone structural changes triggered by land ownership patterns, increased adoption of precision farming, and shifts in agricultural subsidies [24–26]. These changes have had a direct impact on the management of arable land through tillage activities, crop rotation models, and fertiliser dosage levels.

Significant soil fertility loss has been reported, particularly due to low phosphorus availability in Hungarian soils [27]. This reflects nutrient mismanagement related to crop selection, farming intensity, and land management policies. Phosphorus deficiency directly affects soil fertility; therefore, identifying nutrient-related fertility loss over time aligns with the goal of monitoring trends. The mismanagement of nutrients suggests a human-driven factor behind fertility decline which is a precursor to land-use change [28]. According to a region-specific study that was conducted, the observation on phosphorus deficiency provides a local context that supports the need for long-term monitoring [27]. Accordingly, it is important to understand the influence of such changes on soil fertility, which can inform planning for sustainable land use.

1.3. Challenges and Integration of Remote Sensing

Traditional field-based assessment approaches, such as soil sampling and laboratory analysis, are accurate [29]; however, they have several limitations for large-scale soil fertility monitoring. These include being time-consuming, labour-intensive, and limited in spatial coverage [30], which complicates gathering the trends on landscape-scale at long-term intervals.

Recent studies have demonstrated that remote sensing data can be integrated with predictive modelling techniques to estimate soil chemical properties and related fertility indicators [31]. These approaches often employ machine learning algorithms, such as Random Forest, which integrates satellite spectral bands, vegetation indices, terrain attributes, and ancillary environmental data. Such models enable the prediction of variables, including SOC, nitrogen content, soil moisture, and pH [30]. In addition to data-driven approaches, physics-based spectral models, including radiative transfer models and soil reflectance spectroscopy, have also been applied to analyse the interaction between soil composition and surface reflectance patterns [32]. For instance, satellite observations can provide scalable and temporally consistent datasets suitable for large scale analysis [33]. Similarly, vegetation indices and surface reflectance patterns provided by sensors such as Landsat and Sentinel have been validated for monitoring parameters related to soil fertility such as soil moisture, plant health, and land-use shifts [34]. In this context, Hungary can benefit from the combined application of in situ soil data and remote sensing imagery to improve understanding of the dynamics of soil health in different arable landscapes [35].

Despite the growing number of studies examining soil fertility indicators and land-use dynamics, the available evidence remains fragmented across different spatial scales, methodologies, and data sources. In particular, few studies systematically synthesise findings from both field-based soil measurements and remote sensing observations to evaluate long-term soil fertility trends. A comprehensive synthesis of how these complementary monitoring approaches can jointly inform soil fertility dynamics in Hungary's arable landscapes remains limited.

1.4. Study Purpose, Objectives, and Significance

Between 2000 and 2020, Hungary experienced notable fluctuations in land-use intensity and abandonment (United Nations Framework Convention on Climate Change, 2002). Arable land remained relatively stable between 2000 and 2009, followed by a decline and subsequent stabilisation after 2010 [36]. A further decrease occurred between 2019 and 2020, indicating renewed land-use changes.

This study presents a systematic review of the literature on soil fertility trends in Hungary's arable lands (2000–2020), guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA)-based methodology, 2020, to integrate field measurements and remote sensing observations to evaluate long-term monitoring approaches. The review addresses two main objectives: (1) to evaluate the trends and patterns in soil fertility across Hungary's arable lands between 2000 and 2020, and (2) to assess the integration of field-based measurements and remote sensing technologies in monitoring soil fertility.

This review identifies key drivers influencing soil fertility changes and evaluates monitoring approaches. It also aims to bridge historical soil datasets with modern monitoring technologies to support evidence-based soil fertility management. Although the review focuses on Hungary, the methodological insights derived from integrating field-based soil measurements with remote sensing data provide a framework that may be applicable to broader European agricultural systems [37–39]. Many countries in Central and Eastern Europe share similar agro-ecological conditions, land-use histories, and policy influences under the European Union's agricultural frameworks [40]. Therefore, the syn-

thesis presented in this study supports the application of broader soil monitoring strategies and sustainable land management practices beyond Hungary.

2. Materials and Methods

2.1. Review Framework

This study was conducted as a systematic review in accordance with the PRISMA 2020 guidelines (BMJ Publishing Group, London, UK). A predefined methodology outlining eligibility criteria, search strategy, study selection, and data extraction was established prior to the review to reduce procedural bias. Selective reporting and inconsistent screening were mitigated through dual independent review and structured procedures. The review synthesised the published literature on soil fertility trends in Hungarian arable lands between 2000 and 2020. It focused on studies employing field measurements, laboratory analyses, geospatial methods, and remote sensing techniques. The methodological framework included a structured literature search, screening and eligibility assessment, and qualitative thematic synthesis.

2.2. Literature Search and Study Selection

A systematic search was conducted on 7 August 2025 across three academic databases: Web of Science (WoS), Scopus, and Google Scholar (Table 1). The full search string was: “soil fertility” AND “Hungary” AND “land-use change” AND (“remote sensing” OR “NDVI” OR “spatial trends” OR “temporal trends”). Filters applied included publication years 2000–2020, all languages, and peer-reviewed sources. Reference lists of included studies were also scanned to identify additional relevant publications. All retrieved records were imported into a reference manager (Zotero) for deduplication.

Table 1. Summary of the literature search results and study selection across databases.

Database	Records Identified	Records Screened	Records Synthesised
WoS	59	44	33
Scopus	23	18	14
Google Scholar	120	84	59

Summary of records identified, screened, and included from three academic databases during the systematic review of soil fertility trends in Hungarian arable lands (2000–2020). Screening was conducted in two stages (title/abstract and full-text). *Source* Authors (2025).

Studies were included if they (1) were conducted within Hungary, (2) reported empirical soil fertility data (SOC, total N, available P, exchangeable K, or soil pH), (3) focused on arable land or land-use transitions affecting cultivated areas, (4) covered the 2000–2020 timeframe, and (5) employed field-based measurements, remote sensing, or integrated geospatial methods (GIS, NDVI). Studies were excluded if they were (1) conducted outside Hungary, unless they provided key conceptual insights into soil aggregate stability. (2) Studies were also excluded if they fell outside the 2000–2020 timeframe (except where they addressed trends within this period), (3) lacked empirical soil data, (4) did not address arable land use, or (5) consisted of non-peer-reviewed sources such as opinion articles.

The study selection workflow followed a two-stage screening process: (1) Title and abstract screening to remove clearly irrelevant studies, and (2) full-text screening against the inclusion/exclusion criteria. Two independent reviewers conducted a screening at both stages, with discrepancies resolved through discussion. The study selection process followed a structured workflow summarised in the PRISMA (2020) flow diagram.

2.3. Soil Fertility Indicators Considered

The review focused on soil fertility indicators commonly reported in Hungarian agricultural studies. These indicators included: SOC, total N, available P, exchangeable K, and soil pH. The indicators were used to evaluate soil fertility status and the impacts of land-use change on arable soils [41]. For synthesis, soil fertility outcomes were classified into four categories: SOC decline, nutrient depletion (N, P, K, pH), stability, and fertility improvement. Monitoring approaches were coded as field sampling, GIS/Spatial analysis, or remote sensing

The methodological quality of the 106 studies was assessed using an adapted framework based on the Risk of Bias in Systematic Reviews (ROBIS) guidelines, with a simplified qualitative approach due to the diversity of study types (e.g., field experiments, observational studies, and remote sensing). Each study was evaluated for research design clarity, sampling adequacy and spatial coverage, analytical transparency, overall methodological rigour (Table 2), and relevance to soil fertility monitoring in arable systems.

Table 2. Risk-of-bias assessment of selected studies included in the systematic review. A complete risk-of-bias assessment for all the 106 studies is provided in Supplementary Table S1.

Study	Methodological Approach/Design	Sampling Clarity	Analytical Transparency	Overall Bias Risk
[42]	Field experiment	High	High	Low
[31]	Remote sensing analysis	Moderate	High	Low
[32]	Soil modelling study	Moderate	High	Low
[43]	Spatial analysis	Moderate	Moderate	Moderate
[44]	Machine learning modelling	Moderate	High	Low
[45]	Soil monitoring study	Moderate	Moderate	Moderate

Source Authors (2025).

Studies were categorised as having a low-, moderate-, or high risk of bias based on these criteria. Additional classification considered methodological approaches such as field experiments, soil sampling, GIS analysis, modelling, and literature reviews. Low-risk studies demonstrated strong design clarity and transparency, moderate-risk studies had some methodological limitations, and high-risk studies lacked sufficient detail or relied on indirect evidence.

Overall, this structured assessment ensured consistent evaluation of evidence reliability across the dataset, strengthening conclusions about soil fertility trends and monitoring in Hungarian arable lands. Of the studies, 42% were rated low risk, 47% moderate risk, and 10% high risk of bias, with full details provided in Supplementary Materials Table S1.

2.4. Soil Fertility Assessment Methods in the Reviewed Studies

2.4.1. Field Sampling and Laboratory Analysis

A large proportion of the reviewed studies (Supplementary Materials Tables S2 and S3) relied on field-based soil sampling followed by laboratory analysis to assess soil fertility status. Soil samples were typically collected from the topsoil layer (commonly 0–20 cm depth), where nutrient dynamics and biological activity are most pronounced.

Laboratory analyses were conducted to quantify SOC, total N, available P, exchangeable K, and soil pH. Standard analytical procedures such as wet chemistry nutrient extraction, combustion methods for organic carbon, and pH determination in soil–water suspensions were commonly applied. These measurements provided baseline data for assessing spatial and temporal trends in soil fertility.

Field experiments and controlled soil sampling studies reported in the reviewed literature frequently investigated the effects of agricultural management practices, including tillage systems and fertilisation regimes, on soil fertility indicators. Several studies employed experimental treatments involving farmyard manure (FYM) and mineral fertilisers (NPK) to examine soil nutrient dynamics and carbon processes under cultivated conditions [42].

Farm-level investigations were also conducted across multiple agricultural sites in Hungary, including studies focusing on intensive crop production systems such as maize cultivation in Hajdú-Bihar County, where soil properties were evaluated using field sampling and laboratory analysis methods.

2.4.2. Remote Sensing and Vegetation Indicators

Several studies incorporated satellite-based remote sensing techniques to analyse vegetation dynamics associated with soil fertility conditions. Vegetation indices such as the Normalised Difference Vegetation Index (NDVI) were frequently used as proxies for plant vigour and productivity.

Satellite imagery from platforms such as Landsat and Sentinel-2 enabled the detection of spatial patterns in vegetation health across agricultural landscapes. Changes in NDVI values over time were used as indicators of variations in soil productivity, land management practices, and land-use change.

2.4.3. Geospatial Analysis and Monitoring Systems

In addition to conventional Geographic Information System (GIS) techniques, several studies incorporated spatial modelling and machine-learning techniques for analysing soil variability and agricultural sustainability. Approaches such as Random Forest and Artificial Neural Networks were used with spatial datasets to model soil property distributions and assess soil fertility patterns [31,32,43–45].

National soil monitoring programmes also provided important contextual data. In particular, the TIM offers long-term soil quality observations across Hungary. The Hungarian Central Statistical Office (HCSO) dataset, along with Hungarian Soil Information and Monitoring System (Talajvédelmi Információs és Monitoring rendszer, TIM), provided statistical data on annual agricultural land-use changes and soil fertility potential over a 20-year period.

2.4.4. Other Soil Data Sources and Monitoring Systems Used in Hungary

Several databases and monitoring systems were used as sources of soil and land-use data in Hungary. The National Pedological and Crop Production Database (NPCPD) provides historical soil and crop production data, including soil pH and nutrient levels collected since the 1970s [9]. Soil data from NPCPD are currently integrated into the Agrochemical Management and Information System (AIIR), supporting soil mapping, nutrient monitoring, and crop yield estimation [46]. The database includes field-based observations linking land-use types with soil quality indicators, such as dissolved organic matter. It contains sampling records from approximately four million hectares of arable land. Additional datasets include chernozem soil sampling conducted during 2018–2019 [47].

The Soil Conservation Information and Monitoring System (SIMS) was also used as a soil data source for land-use analysis in Hungary [48]. SIMS functions as a centralised soil monitoring database containing long-term measurements of soil physical properties [49]. The system incorporates remote sensing data that allow the identification of soil conservation practices, including agroforestry and trenching [50]. SIMS datasets were integrated with geostatistical tools and GIS-based approaches for mapping and spatial analysis of soil properties [51].

Field-based sampling and laboratory analyses were used to obtain additional soil property data. Sampling was conducted on cultivated land, including sloped terrain, with soil depths reaching up to three metres to capture vertical variation in soil characteristics [52]. SOC was measured as an indicator of soil condition and land-use influence. Laboratory analyses were used to determine physical and chemical soil properties, including pH and soil texture, using conventional analytical methods [29].

Long-term experimental datasets were also used as supporting sources of soil information. Data from the Látókép Experimental Station include long-term measurements on representative chernozem soils, where soil parameters such as humus content, porosity, pH, and nutrient concentrations (nitrogen, phosphorus, and potassium) are routinely recorded [53]. Environmental monitoring data collected at the station include air and soil temperature, relative humidity, precipitation, and incoming solar radiation [54].

Additional ecological data were obtained from the Síkfőkút DIRT (Detritus Input and Removal Treatments) long-term experiment located in the North Central Mountains. The experiment includes measurements of soil respiration, SOC, and soil moisture under six litter manipulation treatments [55]. Data from this experimental setup were used to represent soil properties under different organic matter input conditions [56].

2.5. Geospatial and Remote Sensing Approaches for Soil Fertility Assessment

Geospatial and remote sensing methods were applied to support the assessment and mapping of soil fertility. Spatial interpolation using Inverse Distance Weighting (IDW) in ArcGIS 10.6.1 was applied to map soil parameters and analyse their spatial distribution in Hajdú-Bihar County [57,58]. Grid-based mapping and spatial hotspot analysis were also applied to identify spatial patterns of soil fertility within arable land. GIS-based spatial interpolation was further incorporated into remote sensing workflows to support site-specific analysis of arable land conditions [59].

Additional analytical techniques have been applied in combination with field measurements to support soil property assessment. For example, Diffuse Reflectance Spectroscopy (DRS) has been used as a non-destructive method for estimating soil properties such as SOC through analysis of spectral signatures obtained from soil surfaces [52,60]. Laboratory simulations and erosion experiments have also been applied to examine soil processes influencing the redistribution of SOC and nutrients within agricultural landscapes [52,55,60].

Field measurements were also linked with climate data, including the Pálfaí Drought Index (PaDI), to incorporate drought-related variables into soil and crop analyses. Soil data obtained from the NPCPD were used to associate spatial soil properties with maize yield data [61]. These datasets were used to generate spatial yield maps of arable land.

Laboratory simulations were conducted using rainfall simulators and controlled slope conditions to replicate erosion processes and examine their influence on soil properties, including SOC, total N, and soil organic matter (SOM) [55]. Additional analytical techniques, including spectrophotometry and diffractometry, were applied to characterise chemical and mineral properties of soil and sediment samples collected from arable land. Spectral data were also analysed in relation to soil colour variations associated with mineral composition changes.

2.6. Soil Monitoring Networks and Integrated Soil Data Frameworks

The Hungarian Soil Monitoring System (TIM/SIMS) provides long-term soil monitoring data from 1236 sites, including 865 located on arable land and agricultural land (Figure 1). The system records baseline soil conditions and periodically measures physical, chemical, and biological soil parameters, including organic matter content, salinity, acidification, and toxic elements [62].

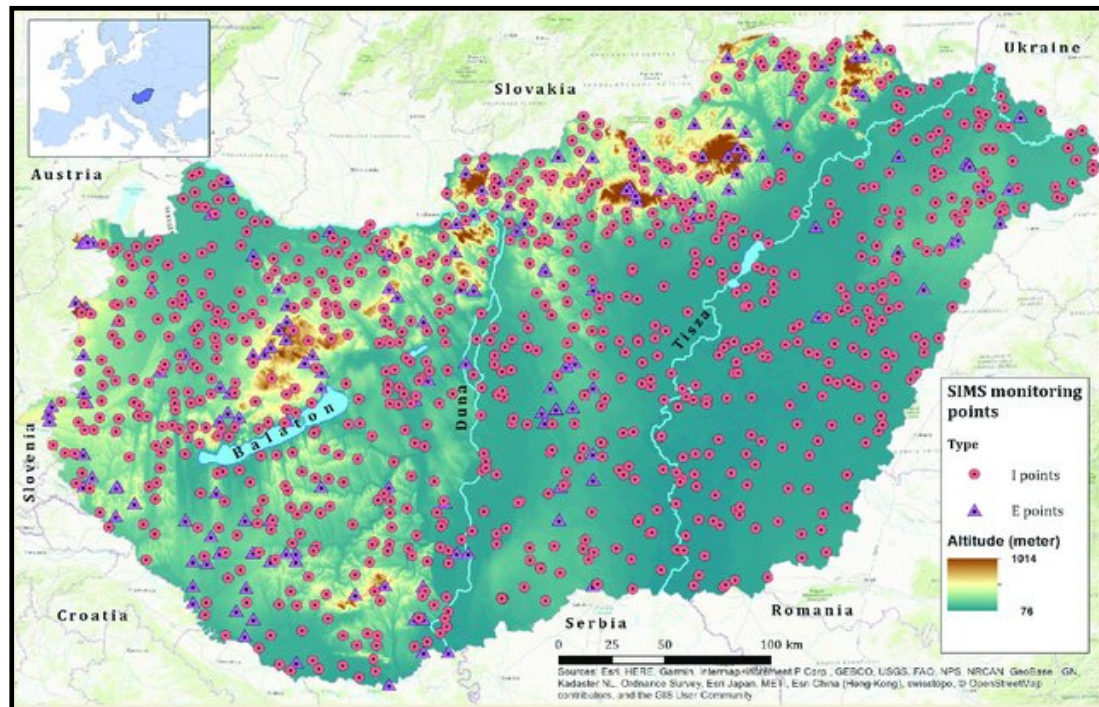


Figure 1. Location of the Hungarian Soil Information and Monitoring System (SIMS) points for soil fertility assessment. *Source* [62].

TIM datasets were integrated with geospatial modelling approaches based on the SCORPAN (soil, climate, organisms, relief, parent material, age, and spatial location) framework. Predictive mapping techniques, such as Random Forest Kriging (RFK) implemented within the European Joint Programme (EJP) SERENA Project, were applied to combine monitoring data with remote sensing and land-cover datasets for spatial soil analysis and mapping of soil fertility trends between 2000 and 2020 [63].

In addition to the national monitoring network, the Land Use/Cover Area Frame Survey (LUCAS) soil dataset of the European Commission was used as a complementary data source. LUCAS provides harmonised soil sampling and laboratory analyses across Europe, including Hungary, with measurements of topsoil properties such as SOC, pH, texture, and nutrient content collected during several campaigns (2009, 2015, 2018) [64]. Together, TIM and LUCAS datasets were used to support multi-scale soil fertility assessment by combining national monitoring data from long-term field experiments and soil management [65]. They also incorporate harmonised European-scale soil observations from the LUCAS programme. These observations provide broad spatial coverage for assessing environmental variability and ecological potential across regions [66].

2.7. Data Extraction and Synthesis

Extracted information included bibliographic details, study location, soil fertility indicators assessed, analytical methods, and key findings, with emphasis on soil quality dynamics, microbial activity, and the effects of land use and management practices [67,68]. Due to heterogeneity in study designs, spatial scales, and reporting formats, a qualitative thematic synthesis approach was adopted [68,69]. Quantitative summaries of land-use change were generated using Microsoft Excel and Past4.11 Software, including box plots and trend graphs. Remote sensing datasets (e.g., NDVI) were used to analyse vegetative vigour and spatial patterns of land-use change [66,69], supported by spatial interpolation techniques commonly applied in soil studies [70].

To contextualise trends from 2000 onwards, data from 1996 to 1999 were analysed to capture baseline conditions and immediate pre-conditions influencing arable land use in Hungary [65]. This pre-analysis period supports objective 1 by highlighting environmental and anthropogenic factors shaping soil conditions prior to the observed fertility trends, consistent with documented landscape transformation processes in Hungary [71]. Detailed evidence tables summarising the characteristics and key findings of all included studies were compiled and are provided in Tables S2 and S3 in the Supplementary Materials.

2.8. PRISMA 2020 Flow Diagram

The detailed study selection workflow is illustrated in Figure 2.

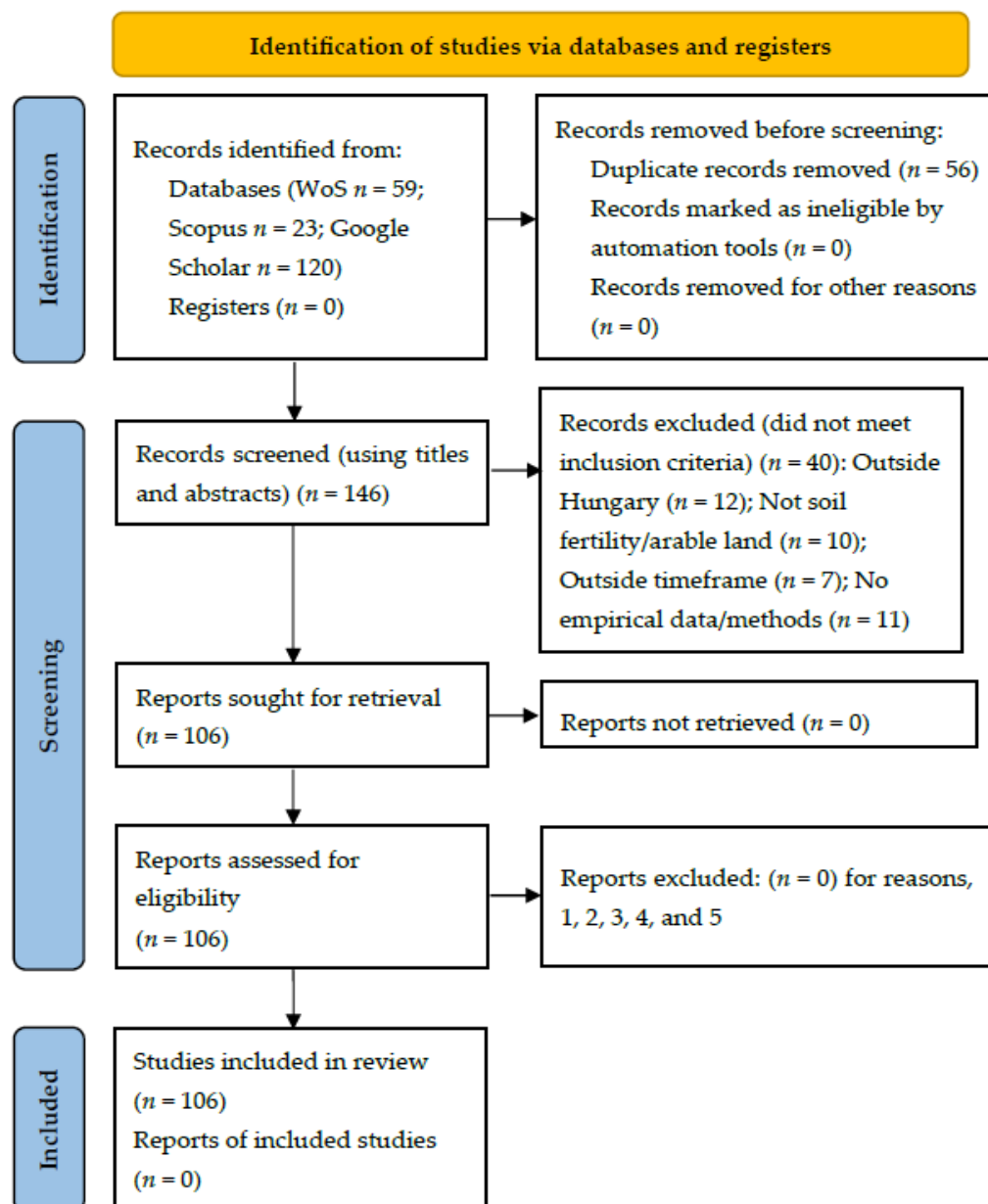


Figure 2. PRISMA 2020 flow diagram of study identification, screening, eligibility, and inclusion for the systematic review on soil fertility trends in Hungary (2000–2020), including detailed categorisation of excluded records by reason. Source [37].

1. Identification: 202 records retrieved across three databases (WoS: 59; Scopus: 23; Google Scholar: 120).

2. **Screening:** After removing 56 duplicate records, a total of 146 publications remained for title and abstract screening (WoS: 44; Scopus: 18; Google Scholar: 84). At this stage, 40 records were excluded based on the predefined exclusion criteria described in Section 2.2. Exclusions included studies conducted outside Hungary, unless they provided key conceptual insights into applicable soil aggregate stability; publications unrelated to soil fertility or arable land use; articles outside the 2000–2020 timeframe, except those addressing soil fertility trends of that period; and studies lacking empirical soil data or relevant field-based or remote sensing methods.
3. **Eligibility:** Full-text assessment resulted in 106 studies meeting inclusion criteria (WoS: 33; Scopus: 14; Google Scholar: 59) and being included in the final synthesis.
4. **Inclusion:** All included studies were synthesised for thematic analysis and integration of field and remote sensing methods.

2.9. Thematic Summary of Evidence

To improve transparency in the synthesis of the 106 included studies, Table 3 summarises the key thematic categories, methodological approaches, soil fertility indicators, and major observations reported in the literature. Particular emphasis was placed on the integration of field-based measurements and remote sensing techniques, which have been widely recognised as effective tools for monitoring agricultural systems and soil conditions at multiple spatial and temporal scales [72]. Many studies, especially [9,71,73–80], contributed to multiple thematic categories.

Table 3. Thematic categorisation of studies analysing soil fertility trends and land-use change in Hungarian arable lands (2000–2020). Some studies appear in more than one thematic category due to interconnectedness and relevance. Direction of Change is indicated by symbols: ↑ = increase; ↓ = decrease; and → = stable.

Thematic Category	No. of Studies	Methods Used	Soil Fertility/Land Indicators	Direction of Change (Key Findings)	Main Observations/Patterns	Representative References
Field-based soil studies	47	Soil sampling, laboratory chemical analysis, long-term field experiments, soil aggregate analysis	SOC, N, P, K, pH, dissolved organic matter, soil moisture	SOC: ↑/↓ (mixed); N: ↑; P, K: ↓; pH: →	Trends in nutrient depletion, SOC decline, fertilisation impacts, soil organic matter changes under agricultural development	[9,27,42,47,48,54,56,71,73–76,79,81–114]
Land use/Land cover change analyses	31	Statistical analysis, national datasets (HCSO), landscape mapping, land cover surveys	Cropland area, land cover types, landscape patterns, arable land extent	Cropland: ↑/↓ (region-specific); landscape heterogeneity: ↑	Historical land-use trends, cropland expansion or abandonment, landscape mosaic changes	[46,58,77,78,80,97,115–139]
Soil degradation and erosion studies	25	Field experiments, erosion modelling, soil degradation monitoring, aggregate stability analysis	SOC redistribution, total N, topsoil loss, soil structure, erosion rates	SOC: ↓ in eroded areas/↑ in depositional zones; topsoil: ↓	Identification of erosion-prone areas, SOC redistribution processes, land-use impacts on soil structure	[54,71,73–75,79,83,87,93,94,96,100–102,109,112,114,119,123,140–145]

Table 3. Cont.

Thematic Category	No. of Studies	Methods Used	Soil Fertility/Land Indicators	Direction of Change (Key Findings)	Main Observations/Patterns	Representative References
National soil databases/monitoring systems	18	NPCPD, TIM/SIMS monitoring systems, digital soil maps, national soil inventories	SOC, N, P, pH, soil texture, nutrient balances	SOC: →/slight ↑; nutrients: mixed trends	Long-term soil property monitoring, baseline soil quality mapping, nutrient management evaluation	[9,78,79,92,99,127,131,139,146–155]
Modelling and predictive approaches	18	Random Forest, ANN, crop yield modelling, drought sensitivity modelling, land quality, index modelling	SOC, N, P, K, crop yield, land productivity indices	SOC and nutrients: predicted ↑/↓ (scenario-dependent)	Prediction of soil nutrient trends, drought sensitivity of soils, spatial variability in agricultural productivity	[9,56,73,76–80,105,107,156–163]
Climate and environmental impact studies	15	NDVI-based climate analysis, statistical correlation with yield data, ecological modelling	Crop yield, soil moisture, SOC	SOC: ↓ under drought; yield: ↓ with climate variability	Impacts of drought, climate variability, and ecosystem processes on soil fertility and productivity	[35,71,77,108,109,119,126,161,164–170]
Water management and irrigation studies	5	Irrigation infrastructure assessment, agricultural water management evaluation	Irrigation coverage, water availability, crop productivity	Productivity: ↑ with irrigation; soil moisture: ↑	Role of irrigation and water management in sustaining agricultural productivity	[48,74,75,91,171]
Land evaluation and ecosystem service studies	17	Integrated land evaluation modelling, ecosystem service assessment	Land suitability, soil productivity indices	Productivity: ↑ with sustainable management	Improved land evaluation frameworks for sustainable agricultural planning	[46,76,79,80,137,138,170,172–181]

Source Authors (2025).

3. Results

3.1. Soil Fertility Dynamics and Monitoring in Hungarian Arable Lands (2000–2020)

3.1.1. Integrated Evidence of Soil Fertility Change in Hungarian Arable Systems

The methodological assessment of the 106 included studies indicated that 45 studies (42%) were classified as having a low risk of bias, demonstrating high clarity in research design and analytical transparency. A total of 50 studies (47%) were assigned moderate risk, reflecting some limitations in sampling procedures or methodological reporting. Eleven studies (10%) were rated high risk of bias, primarily due to limited methodological detail or reliance on indirect evidence. Overall, the majority of studies provided reliable evidence supporting trends in soil fertility and the integration of field and remote sensing approaches in Hungary's arable lands (Supplementary Materials Table S1).

Land management practices influence the results in variations in SOC and nutrient levels across arable lands (Table 3). Long-term precipitation variability influences the yields of corn, sunflower, and winter wheat [9]. This effect is particularly evident in regions such as the Dorozsma-Majsa Sand Ridge, Kerka Riverscape, and Dévaványa Plain. These trends

highlight the need for continuous soil fertility monitoring to assess the impacts of climate variability and land-use change on agricultural productivity [46].

Between 2000 and 2010, SOC increased significantly ($p = 0.0033$). Nitrate (NO_3^-) levels also rose from 15.2 to 19.9 ppm ($p = 0.0000$), likely due to high nitrogen fertilisation in central and northern Hungary [48,50,51,110]. Soil pH and zinc (Zn) showed minor, statistically insignificant increases, whereas phosphorus, potassium, magnesium, and manganese decreased slightly. Spatially, SOC accumulation was higher in western regions, while reductions in phosphorus and manganese may be linked to leaching or soil chemistry interactions [52,53].

Soil erosion, particularly under intensive cultivation, has redistributed SOC within soil profiles up to 3 metres deep, creating localised fertility loss in eroded zones and uneven carbon accumulation elsewhere [54]. Reduced tillage and precision agriculture techniques have been proposed to mitigate these effects [55]. The combination of drought frequency and soil type has further influenced crop yields: chernozem soils showed the highest productivity, while sandy and heavy clay soils were more drought-sensitive [56,57]. Long-term organic matter manipulations, such as those in the Síkfőkút DIRT plots, also revealed impacts on SOC dynamics and CO_2 emissions [58,59].

3.1.2. Observed Soil Fertility Trends in Hungary (2000–2020)

Studies conducted between 2000 and 2020 indicate mixed soil fertility trends. Short-term management practices influence soil fertility, particularly through dissolved organic matter dynamics [47,66]. Overall, SOC, NO_3^- , pH, and zinc increased. In contrast, phosphorus, potassium, and manganese declined, although they generally remained within optimal ranges for crop production [48,67].

Spatial variations were notable: Hajdú-Bihar showed greater variability in NO_3^- and Mn levels, western regions accumulated more SOC, and northern and southern areas showed higher magnesium levels [67]. SOC redistribution remains a key driver of fertility differentiation, with erosion and deposition shaping nutrient distribution [54,68].

Soil type and drought sensitivity continue to influence crop productivity. Regions with loess chernozem and loam soils maintained higher yields, whereas sandy and clayey soils consistently showed low productivity [56]. These findings suggest persistent spatial heterogeneity in soil fertility across Hungarian arable lands.

3.2. Trends and Patterns in Soil Fertility Across Arable Lands in Hungary Between 2000 and 2020

Table 4 summarises the observed soil fertility trends and the monitoring approaches across the 106 included studies. A detailed summary of all studies is provided in Supplementary Materials Table S2. It highlights the proportion of studies reporting declines, stability, or improvements in soil fertility, as well as the relative use of field sampling, GIS/Spatial analyses, and remote sensing methods.

Table 4. Summary of soil fertility trends and monitoring methods in Hungarian arable lands (2000–2020).

Category	Indicator/Method	Number of Studies ($n = 106$)	Percentage (%)
Soil fertility trends	SOC decline	18	17
	Nutrient depletion (N, P, K, pH)	14	13
	Stable fertility/No significant change	38	36
	Fertility improvement	36	34
Total		106	100

Table 4. Cont.

Category	Indicator/Method	Number of Studies ($n = 106$)	Percentage (%)
Monitoring methods	Field sampling only	43	41
	GIS/Spatial analysis	47	44
	Remote sensing (e.g., NDVI)	16	15
Total		106	100

Source Authors (2025).

3.2.1. Soil Fertility Trends in Hungary's Arable Lands (2000–2020)

Table 4 presents the observed trends in SOC, nutrient levels, and pH across 106 studies, as well as the monitoring approaches employed (field sampling, GIS/spatial analysis, and remote sensing). It highlights the proportion of studies reporting declines, stability, or improvements in soil fertility.

Across 106 studies, soil fertility indicators commonly included SOC, N, P, K, and pH. Approximately 17% reported SOC decline, 13% observed nutrient depletion, 36% indicated stability, and 34% reported fertility improvements. Declines were mainly observed in intensively cultivated regions, whereas rotation or organic amendment practices supported soil fertility stability or recovery [55].

Regional contrasts were evident: the lowland Great Plain showed SOC and nutrient decreases, whereas western Transdanubia displayed recovery or stability [149]. Baseline data from 1996 to 1999 (Figure 3) indicate relatively stable soil fertility, supporting the use of 2000 as a starting reference point for subsequent analysis.

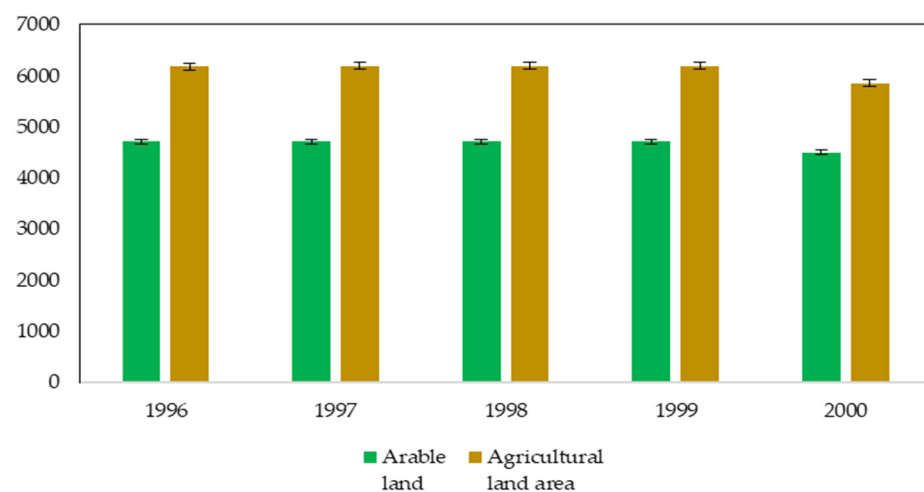


Figure 3. Spatial patterns of soil fertility indicators in Hungary during the pre-study period (1996–1999), showing baseline conditions prior to 2000. Source Author data.

Bars represent soil fertility indices in arable and total agricultural land categories. Non-overlapping error bars indicate statistically significant differences between arable and total agricultural land, while overlapping year-to-year error bars (1996–1999) indicate no significant short-term variation.

Arable land (Figure 4) remained relatively stable between 1996 and 1999, while total agricultural land was consistently higher. Both categories declined after 2000, with a more pronounced decrease by 2020. Specifically, arable land declined by 114.64 ('000 ha) per year according to the slope of the trend line (Figure 4). Trend analysis indicates a consistent decline in arable land over the study period, supported by a moderate downward trend ($R^2 = 0.6262$).

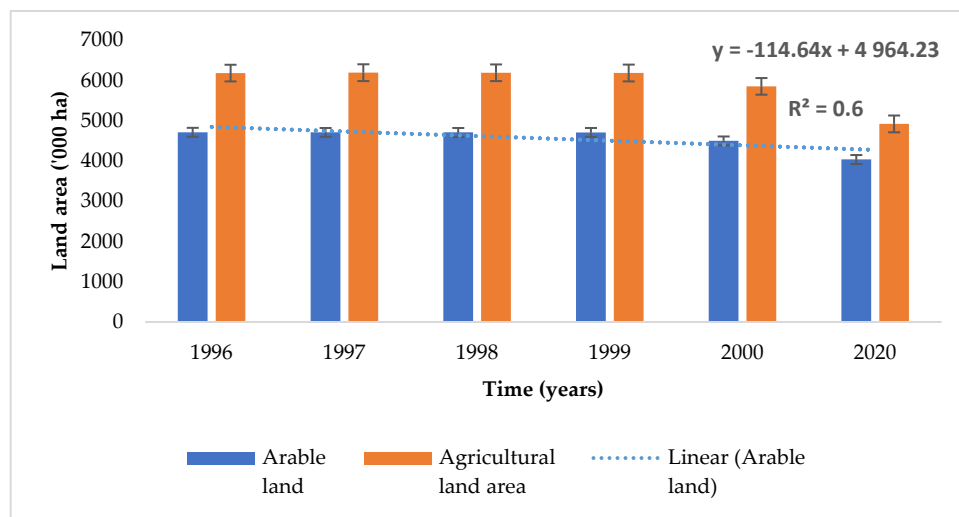


Figure 4. Comparison of soil fertility between 1996 and 1999, 2000, and 2020. Source Author data.

3.2.2. Land-Use Change Patterns

This table presents annual data for arable land and total agricultural land areas (in thousand hectares), demonstrating gradual decline over the study period and highlighting the increasing proportion of arable land within agricultural land.

During the study period, Hungary maintained a higher proportion of arable land than the EU average. According to Eurostat statistics (2022) [115] and the World Bank (2023) [116], cropland represented approximately 47% of the total land area in Hungary, whereas the EU average remained closer to 25% during the same period.

Descriptive statistics of arable and agricultural land show stable land-use patterns prior to 2000, providing a baseline for comparison.

The box plot shows the distribution and variability of arable land compared with total agricultural land. Narrower ranges for arable land reflect less variability in actively cultivated areas.

The correlation plot demonstrates a strong positive relationship between arable and total agricultural land, confirming that arable land consistently constitutes the dominant portion of agricultural land in Hungary.

Arable land declined from 4499.8 to 4037.1 thousand ha between 2000 and 2020, reflecting a gradual reduction over time (Table 5). Total agricultural land also decreased from 5853.9 to 4921.8 thousand ha, although it remained relatively stable in the early 2000s before declining more noticeably in the 2010s. The proportion of arable land increased over time from 76.9% to 82%, indicating a shift towards more intensive crop production [116]. Summary statistics (Table 6) confirm a stable but declining trend, with low variability across years. This is supported by mean values of 4397.3 and 5582.2 thousand ha for arable and total agricultural land. The low coefficients of variation also indicate limited annual fluctuation (Figure 5). Figures 6 and 7 further demonstrate limited variation and a strong positive relationship between arable and total agricultural land, which reinforces the link between land-use intensity and soil fertility pressures [170].

Table 5. Dynamics of use of arable land relative to total agricultural land, 2000–2020.

Year	Arable Land ('000 ha)	Agricultural Land Area ('000 ha)
2000	4499.8	5853.9
2001	4516.1	5865.3
2002	4515.5	5867.3

Table 5. *Cont.*

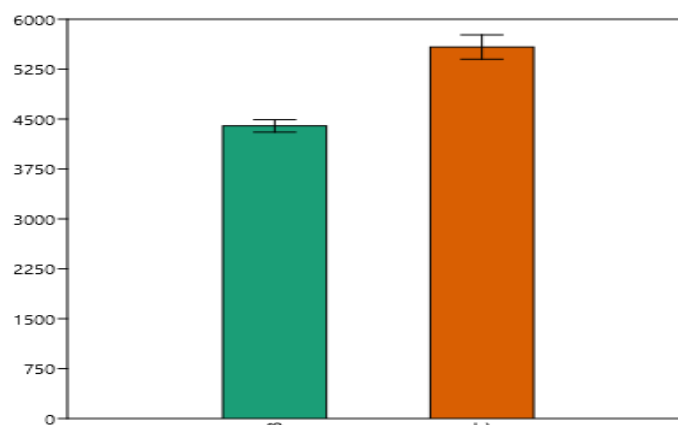
Year	Arable Land ('000 ha)	Agricultural Land Area ('000 ha)
2003	4515.5	5864.7
2004	4510.3	5863.8
2005	4513.1	5854.8
2006	4509.6	5808.9
2007	4506.1	5807.1
2008	4502.8	5789.7
2009	4501.6	5783.3
2010	4322.1	5342.7
2011	4322.3	5337.2
2012	4323.6	5338.0
2013	4325.7	5340.0
2014	4331.3	5346.3
2015	4331.7	5346.4
2016	4332.4	5349.0
2017	4334.3	5352.3
2018	4333.7	5343.8
2019	4317.7	5309.5
2020	4037.1	4921.8

Source HCSO national dataset.

Table 6. Summary statistics of arable and agricultural land including the four-year window (1996–1999).

Parameter	Arable Land	Agricultural Land
N	10	10
Min	4037.1	4921.8
Max	4712.7	6194.6
Mean	4397.3	5582.19
Coefficient of variation	6.693071	10.38977

N = Number of years for the land use recorded in Hungary. Source Author analysis based on HCSO national dataset.

**Figure 5.** Box plot of arable versus agricultural land (2000–2020). B = Arable land; C = Agricultural land. Source Author analysis based on HCSO national dataset.

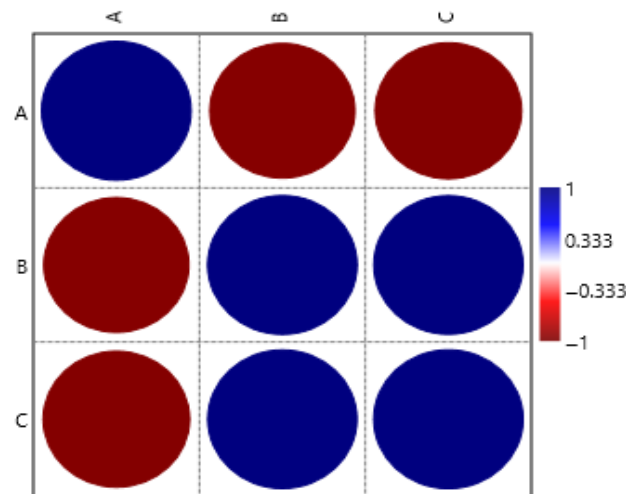


Figure 6. Correlation between arable land and total agricultural land (2000–2020). A = Correlation descriptor; B = Arable land; C = Agricultural land. *Source* Author analysis based on HCSO national dataset.

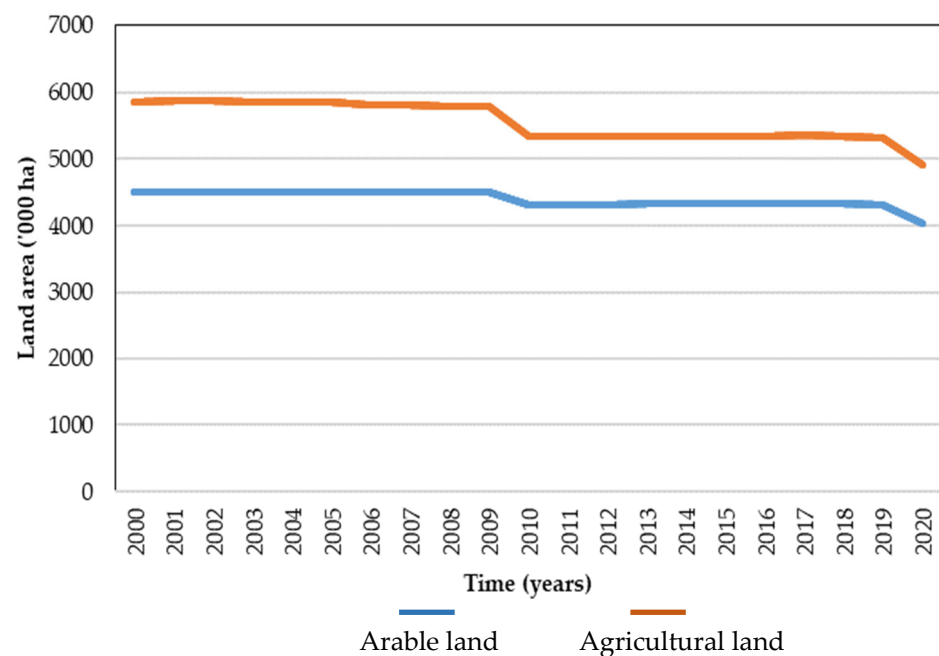


Figure 7. Trends in arable and total agricultural land areas in Hungary (2000–2020). *Source* Author data.

This line chart shows the annual changes in arable and total agricultural land areas ('000 ha). Two major declines are observed: 2009–2010 and 2019–2020. The narrowing gap between the two categories indicates an increasing proportion of arable land, which has implications for soil fertility and land-use management.

3.3. Remote Sensing and Soil Monitoring

3.3.1. Combining Soil Monitoring Networks and Remote Sensing for Fertility Evaluation

Field-based measurements from the Hungarian Soil Monitoring System (TIM), including SOC, pH, and nutrient concentrations, were georeferenced and integrated with satellite-derived datasets such as NDVI and Enhanced Vegetation Index (EVI) obtained from MODIS, Sentinel imagery, and Coordination of Information on the Environment (CORINE) Land Cover database.

Field-based data from the Hungarian Soil Information and Monitoring System (Tajlajvédelmi Információs és Monitoring rendszer, TIM) combined with satellite datasets (e.g., Moderate Resolution Imaging Spectroradiometer—MODIS and Sentinel) and predictive models (e.g., SCORPAN and Soil Ecosystem Services and soil threats modelling and mapping—SERENA) has enhanced soil fertility assessment across Hungary [81,149]. Remote sensing complements field observations by providing continuous spatial coverage and enabling detection of localised changes and degradation hotspots [81,148].

During the period 2000–2020, Hungary maintained a notably high proportion (about 47%) of cropland compared to EU's average of approximately 24% [115,156], making it one of the most intensively cultivated EU member states. SOC stocks showed a generally stable to slightly increasing national trend, rising from approximately 50 to 52.3 t ha⁻¹, although local declines were observed in intensively cultivated lowland areas [149].

3.3.2. Integration of CORINE Land Cover and MODIS Remote Sensing

The integration of CORINE land cover datasets with MODIS-derived productivity indicators such as net primary productivity (NPP) enables high-resolution assessment of land-use transitions and soil biomass productivity [157]. Studies assessing erosion risk using CORINE data demonstrated that conversion from natural vegetation to arable land increased soil degradation susceptibility [142].

SOC mapping initiatives provided baseline spatial datasets for Hungary's soils, which have been extended using recent monitoring and remote sensing approaches to assess long-term changes [172].

3.3.3. Linking Land-Use Change and Soil Fertility

Despite progress, several methodological challenges remain. Key challenges include spatial scale mismatches between point-based surveys (TIM, LUCAS) and satellite data, temporal inconsistencies between sampling intervals, and metadata harmonisation issues [81,148].

Time-series reconstruction approaches, such as Harmonic Analysis of Time Series (HANTS), have been used to address temporal gaps, improving the comparability between remote sensing outputs and field measurements [61]. However, uncertainty in model calibration and validation persists due to indirect relationships between vegetation indices and soil properties [149,157].

3.3.4. Implications for Sustainable Land Management

The increasing proportion of arable land, despite overall agricultural land decline (Table 5), reflects intensification of crop farming, which may pose risks to soil fertility if not properly managed. Sustainable practices include crop rotation, cover cropping, conservation tillage, organic amendments, Integrated Nutrient Management (INM), erosion control, and soil testing [55].

The integration of field-based monitoring and remote sensing provides a robust framework for sustainable land management and aligns with European soil protection strategies.

4. Discussion

Overall, the reviewed studies show that soil fertility dynamics in Hungarian arable lands between 2000 and 2020 are shaped by interactions among land-use change, management intensity, climatic variability, and intrinsic soil properties. While national-scale assessments frequently indicate relative stability in key indicators such as SOC, nutrient levels, and pH, this apparent stability masks significant regional variability and localised degradation processes. These findings highlight the need to move beyond aggregated indicators towards a more spatially explicit and integrated understanding of soil fertility dynamics.

4.1. Soil Fertility Trends and Management Implications in Hungarian Arable Lands (2000–2020)

The overall stability or modest improvement in soil fertility indicators reflects, in part, the effectiveness of management practices such as fertilisation, crop residue incorporation, and conservation approaches [47,48,139]. Increases in SOC and NO_3^- in certain regions have been associated with intensified maize cultivation and nutrient inputs [50,51,114], suggesting that management interventions can offset potential fertility losses under intensive production systems.

However, this interpretation requires careful qualification. Several studies simultaneously report declines in P, K, and micronutrients [52,53], indicating that nutrient balances are uneven and may not be sustainable in the long term. Moreover, observed SOC increases may not always reflect genuine soil carbon sequestration but could instead result from redistribution processes such as erosion and deposition, or differences in sampling depth and methodology [54]. These findings suggest that conclusions about “stable fertility” depend on the indicators, spatial scale, and methods used.

Spatial heterogeneity emerges as a defining characteristic of Hungarian soils. Intensively cultivated areas, particularly in the Great Plain, frequently exhibit localised declines in SOC and nutrient availability, whereas regions practising crop rotation or organic amendments tend to maintain or improve fertility [42,54,111]. This highlights the combined role of management practices and soil properties in determining fertility outcomes [158]. Consequently, national averages can mask critical degradation hotspots, leading to an overly optimistic interpretation of soil health trends.

Climatic variability further complicates these dynamics. Drought conditions, especially in sandy and heavy clay soils, have been shown to reduce crop productivity and influence nutrient cycling [56,57]. While chernozem and loess soils demonstrate greater resilience, their apparent stability may also reflect favourable baseline conditions rather than universally effective management. The interaction between climate stress and soil type therefore introduces additional uncertainty into the interpretation of long-term fertility trends [46,47]. These findings highlight the need for site-specific monitoring frameworks that explicitly account for both environmental variability and management intensity [117,173].

4.2. Land-Use Change as a Driver of Soil Fertility Dynamics

The decline in arable land (slope value of $-114.64 \text{ '000 ha per year}$ in Figure 4) and the concurrent increase in its proportion within total agricultural land indicates agricultural intensification rather than simple land contraction. This structural shift has important implications for soil fertility. Intensification may promote advanced management practices, including precision fertilisation and improved input efficiency. However, it can also increase pressure on soil systems, particularly where crop rotation is limited or monocropping dominates [56,148].

The literature suggests that land-use change is not a uniform process but reflects multiple interacting drivers, including policy reforms under the Common Agricultural Policy (CAP), economic restructuring, and urban expansion [59]. While some studies attribute declining arable land primarily to urbanisation and infrastructural development [176,177], others emphasise land abandonment linked to declining soil productivity and profitability [112]. These findings indicate that land-use change is both a cause and a consequence of soil fertility dynamics, making causal relationships difficult to disentangle.

Importantly, the increasing dominance of arable land within a shrinking agricultural base may amplify soil degradation risks. Reduced diversity in land use, particularly the decline of pastures and mixed systems, can limit opportunities for nutrient cycling and soil recovery. This aligns with findings that continuous cropping without

adequate soil management accelerates nutrient depletion, structural degradation, and erosion [112,141,145,175]. However, some studies also suggest that intensification can stabilise yields and maintain fertility when supported by appropriate technological and agronomic interventions [55,57,62,140,164]. These contrasting perspectives highlight the need for a more nuanced interpretation of intensification, recognising both its potential benefit and risks.

4.3. Integration of Field-Based Measurements and Remote Sensing Technologies in Monitoring Soil Fertility

The extracted material on LUCAS highlights that during 2000–2020, Hungary maintained a high proportion of cropland (approximately 47%), exceeding the EU average of about 25% [115,156].

Therefore, the integration of field-based monitoring systems (e.g., TIM, LUCAS) with remote sensing datasets (e.g., MODIS, Sentinel, CORINE) represents an important advancement in soil fertility assessment. These combined approaches enable multi-scale analysis by linking local soil measurements with broader spatial patterns of land use and vegetation dynamics [82,142,147,157]. The reviewed studies demonstrate that such integration improves the detection of spatial heterogeneity and supports long-term monitoring of soil condition.

Nevertheless, the effectiveness of these approaches is constrained by several methodological challenges. Spatial scale mismatches between field data and satellite imagery can obscure fine-scale variability, especially in heterogeneous landscapes [81,148]. Temporal inconsistencies between intermittent soil sampling and continuous remote sensing observations further complicate trend analysis, potentially leading to misinterpretation of short-term fluctuations as long-term changes.

Additionally, remote sensing indicators such as NDVI and NPP provide indirect proxies for soil fertility, reflecting vegetation response rather than soil properties themselves. This introduces uncertainty in model calibration and limits causal interpretation between land-use change and soil condition [149,157]. While techniques such as time-series reconstruction (e.g., HANTS) help address temporal gaps [61], uncertainties in data integration and interpretation remain significant.

Despite these limitations, the combination of field observations, geospatial analysis, and predictive modelling (e.g., SERENA, RFK) offers a robust framework for soil fertility monitoring. However, the reliability of such frameworks depends on improved data harmonisation, co-temporal sampling strategies, and standardised metadata protocols [83,118,165]. Without these improvements, integrated monitoring systems may continue to produce inconsistent or scale-dependent results.

4.4. Regional Variability and Contrasting Evidence

A consistent finding is strong regional variation in soil fertility trends. The Great Plain is frequently associated with declines in SOC and nutrient stocks, attributed to intensive cereal production and limited conservation practices [146]. In contrast, western Transdanubia and other regions with diversified land use show more stable or improving fertility indicators, reflecting lower cultivation intensity and more sustainable management.

However, not all studies fully agree on the extent or drivers of these regional differences. Some report stable SOC levels even in intensively farmed regions, suggesting that fertilisation and residue management may offset degradation processes. Others highlight significant localised declines, indicating that such compensatory mechanisms are not universally effective [159,160]. These differences may result from variations in sampling design, temporal coverage, and analytical methods, as well as from genuine spatial variability.

This variability underscores the importance of adopting a multi-scale perspective in soil fertility assessment. National-level conclusions, while useful for policy framing,

may overlook critical local dynamics that are essential for effective land management. Consequently, future research should prioritise high-resolution spatial analysis and cross-validation of datasets to better capture regional heterogeneity [174].

4.5. Uncertainties, Limitations, and Knowledge Gaps

Several sources of uncertainty influence the interpretation of soil fertility trends in this review.

Data limitations: These include uneven spatial coverage of monitoring networks, with point-based systems such as TIM and LUCAS, which may underrepresent local variability and small-scale land-use changes. Differences in sampling depth, laboratory methods, and indicator selection across studies further complicate direct comparison.

Methodological constraints: These arise from the integration of heterogeneous datasets. Scale mismatches between field measurements and satellite observations, temporal misalignment of data collection, and reliance on indirect remote sensing proxies introduce uncertainty into trend analysis [81,148,149]. These factors limit the precision of spatial and temporal assessments of soil fertility.

Systematic review limitations: The included studies exhibit substantial heterogeneity in terms of study design, indicators, and analytical approaches, which may influence the synthesis of findings [182]. Potential publication bias towards studies reporting significant changes, as well as inconsistencies in reported metrics, may affect the overall interpretation of trends.

In addition to these limitations, important knowledge gaps remain. These include limited long-term datasets linking soil fertility directly to specific management practices, insufficient integration of socio-economic drivers into soil studies, and a lack of standardised frameworks for combining field and remote sensing data. Addressing these gaps will be essential for improving the reliability and applicability of future soil fertility assessments.

4.6. Implications for Sustainable Soil Management

The findings suggest that maintaining soil fertility in Hungary requires a shift from national-scale strategies to targeted, site-specific management. Evidence from the reviewed studies indicates that regions experiencing nutrient depletion and SOC decline are typically associated with intensive cultivation and limited crop rotation [55,157]. In these contexts, practices such as crop rotation, reduced tillage, and organic amendments are important for mitigating degradation.

The increasing role of precision agriculture technologies, including GPS-guided systems, soil sensors, and remote sensing tools, can optimise input use and improve soil management efficiency [30,164]. However, their effectiveness depends on integration with reliable field data and appropriate calibration to local conditions.

Importantly, the apparent stability of soil fertility at the national scale should not lead to complacency. Localised degradation, combined with ongoing land-use intensification and climate variability, poses a significant risk to long-term soil health [80]. Therefore, sustainable soil management strategies must be informed by high-resolution monitoring systems and supported by policies that promote both technological innovation and conservation practices.

The integration of multi-source data, including TIM, LUCAS, and satellite observations, provides a promising foundation for such strategies. However, achieving their full potential will require coordinated efforts to improve data harmonisation, enhance temporal alignment, and ensure accessibility of monitoring datasets. These steps are essential for evidence-based policy development and long-term agricultural resilience.

5. Conclusions

5.1. Key Findings on Soil Fertility Dynamics

The reviewed evidence indicates that soil fertility in Hungary's arable lands between 2000 and 2020 remained relatively stable at the national scale, particularly for SOC, N, P, K, and pH. However, this apparent stability masks significant heterogeneity, with localised declines in intensively cultivated regions, especially in the lowland Great Plain, and more stable or improving conditions in regions characterised by diversified land use and organic management practices. These patterns show that soil fertility is shaped by interactions among land management intensity, soil type, and climatic variability.

5.2. Effectiveness of Integrated Field and Remote Sensing Approaches

The synthesis indicates that integrating field-based monitoring systems (e.g., TIM and LUCAS) with remote sensing datasets (e.g., CORINE and MODIS) provides a useful multi-scale framework for assessing soil fertility trends and land-use change. This approach improves the detection of spatial patterns and long-term dynamics. These may not be captured through field observations alone. However, the reviewed studies highlight key limitations, including spatial scale mismatches, temporal inconsistencies, and uncertainties associated with indirect remote sensing proxies for soil properties. These constraints indicate that, although integrated monitoring is promising, improved methodological harmonisation and co-temporal data collection are needed to enhance reliability and comparability.

5.3. Land-Use Dynamics and Implications for Soil Fertility

The evidence indicates that declining agricultural land and the increasing proportion of arable land reflect agricultural intensification in Hungary during the study period. This shift has dual implications. Intensification may support targeted soil management practices. However, it is also associated with increased risks of nutrient depletion, soil degradation, and erosion in areas with limited conservation measures. These findings suggest that land-use change remains a central driver of soil fertility dynamics, highlighting the need for site-specific and adaptive management.

5.4. Implications for Policy, Monitoring, and Future Research

These findings support the use of integrated soil monitoring frameworks for sustainable land management and policy development, including alignment with broader European initiatives such as the EU Soil Strategy 2030. However, their effectiveness depends on addressing key evidence gaps, particularly in data harmonisation, spatial-temporal integration, and model validation. Strengthening these aspects would improve evidence-based decision-making. It would also support targeted soil conservation interventions.

Future research should prioritise harmonised monitoring protocols, improved integration of high-resolution remote sensing with field data, and the use of advanced modelling approaches. Greater emphasis is needed on region-specific analyses to understand local degradation patterns and support targeted management strategies.

5.5. Limitations

These conclusions should be interpreted with caution due to methodological variability among the reviewed studies, including differences in spatial and temporal scales, soil indicators, and methods. In addition, uncertainties associated with indirect remote sensing proxies (e.g., NDVI and NPP) and potential publication bias may influence the findings. Despite these limitations, integrating multiple data sources provides a robust basis for understanding soil fertility trends and their links to land-use change in Hungary.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/agriculture16080876/s1>, Table S1: Detailed Risk-of-Bias Assessment for all 106 Studies Included in the Systematic Review; Table S2: Summary of Findings of Included Studies on Soil Fertility, Land Use, and Monitoring in Hungary (2000–2020); Table S3: Summary of soil quality assessment studies and findings.

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Abbreviations

The following abbreviations are used in this manuscript:

EU	European Union
N	Nitrogen
P	Phosphorus
K	Potassium
SOC	Soil organic carbon
CEC	Cation exchange capacity
MSZ	<i>Magyar Szabvány</i>
ISO	International Organisation for Standardisation
TC	Technical Committee
FAO	Food and Agriculture Organisation
GLOSOLAN	Global Soil Laboratory Network
EEA	European Environment Agency
GDP	Gross domestic product
WoS	Web of Science
GIS	Geographic Information System
NDVI	Normalised Difference Vegetation Index
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analysis (2020)
HCSO	Hungarian Central Statistical Office
TIM	<i>Talajvédelmi Információs és Monitoring rendszer</i> (Hungarian).
FYM	Farmyard manure
NPK	Nitrogen-Phosphorus-Potassium
DOM	Dissolved organic matter
NPCPD	National Pedological and Crop Production Database
DIRT	Detritus Input and Removal Treatments (DIRT)
AIIR	Agrochemical Management and Information System
SIMS	Soil Conservation Information and Monitoring System
IDW	Inverse Distance Weighting
DRS	Diffuse Reflectance Spectroscopy
PaDI	Pálfai Drought Index (PaDI)
SERENA	Soil Ecosystem Services and soil threats modelling and mapping

EVI	Enhanced Vegetation Index
RFK	Random Forest Kriging
EJP	European Joint Programme
LUCAS	Land Use/Cover Area Frame Survey)
CORINE	Coordination of Information on the Environment (CORINE)
MODIS	Moderate Resolution Imaging Spectroradiometer
NPP	Net primary productivity
UNISECO	Understanding and Improving the Sustainability of Agro-Ecological Farming Systems
INM	Integrated Nutrient Management
CAP	Common Agricultural Policy
LULCC	Land Use and Land Cover Change
GPS	Global Positioning System
SDG	Sustainable Development Goals

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