

Soil Monitoring Legislation and Environmental Justice: A Comparative International Assessment of Soil Governance and Unequal Environmental Risks

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Abstract: Soil contamination, sealing and degradation are unevenly distributed across territories, yet soil governance and environmental-justice assessment have largely developed through separate regulatory and scientific pathways. This study develops a comparative legal-spatial framework that integrates soil monitoring, Earth observation, geographic information systems (GIS) and environmental justice. The analysis centres on Directive (EU) 2025/2360 on soil monitoring and resilience and examines its interaction with the INSPIRE Directive, the Environmental Information Directive, the Environmental Liability Directive and the Industrial Emissions Directive. Soil-governance approaches in the European Union, the United Kingdom, the United States, Australia and New Zealand are compared with respect to soil monitoring, contaminated-land identification, spatial information, public participation and risk management. Three Greek contexts, the Asopos-Thiva basin, the Thriasio Plain and metropolitan Attica, are examined through published geochemical and land-use evidence to show how Sentinel-2, Landsat and Copernicus imperviousness products can be embedded in a legally traceable monitoring architecture. The study proposes a Soil Environmental Justice Observatory (SEJO) that links soil measurements, contaminated-site records, Earth-observation products, census data and information-access indicators through a legal-provenance layer distinguishing observed, modelled, screened, legally determined and community-reported evidence. A transparent Soil Environmental Justice Index (SEJI), accompanied by a weight-sensitivity protocol, is formulated as a screening instrument rather than a diagnostic or legal determination. The framework offers Member States, and Greece in particular, a reproducible pathway for transposing the Soil Monitoring Law in a manner that is interoperable, spatially explicit and socially contextualised.

Keywords: Environmental justice, Geographic information systems, Greece, Land take, Remote sensing, Soil contamination, Soil governance, Soil monitoring, Soil sealing, Spatial inequality, Sustainable land management, Territorial planning.

I. INTRODUCTION

Soil is a fundamental component of terrestrial ecosystems and underpins food production, biodiversity, water regulation, carbon cycling, climate adaptation and human well-being. Nevertheless, soil has historically occupied a fragmented position within environmental governance. Whereas air and water have progressively acquired dedicated monitoring networks and binding quality standards, soil protection in most European jurisdictions has been addressed indirectly through agricultural, industrial, waste, planning, groundwater and environmental-liability instruments [1].

This fragmentation becomes consequential when soil degradation is examined from an environmental-justice perspective. Contamination, sealing, erosion, compaction, salinisation and loss of organic matter do not occur independently of settlement patterns, industrial geography, transport infrastructure, land markets or socioeconomic conditions. Environmental burdens may therefore concentrate in particular territories, while the capacity of affected communities to obtain information, participate in decisions and influence remediation varies considerably [2, 3]. The environmental-justice dimension of soil governance consequently requires more than the measurement of contaminant concentrations: it requires the spatial integration of environmental condition, exposure opportunity, social vulnerability, regulatory responsibility and access to environmental information.

The European Union has recently entered a new phase in this respect. Directive (EU) 2025/2360 on soil monitoring and resilience (the Soil Monitoring Law) establishes a Union framework for soil monitoring and assessment, soil resilience and the management of contaminated sites, with the objective of achieving healthy soils by 2050 [4]. The Directive entered into force on 16 December 2025 and addresses erosion, loss of soil organic carbon, salinisation, contamination, compaction, soil sealing and loss of soil biodiversity; Member States must transpose it by 17 December 2028 [4]. Its significance for the Earth sciences extends beyond conventional soil sampling. The Directive requires the delineation of soil districts and soil units, the monitoring of common soil descriptors, the assessment of soil health, the identification of potentially contaminated sites and the maintenance of georeferenced public registers, and it provides for the use of Copernicus services and other remote-sensing data together with a Union digital soil-health data portal [4]. This creates a concrete opportunity to connect environmental law with Earth-observation science.

Satellite remote sensing cannot, in general, replace laboratory analysis for determining the concentrations of specific contaminants. It can, however, provide repeated, spatially continuous observations of land-cover change, imperviousness, vegetation condition and landscape transformation [5, 6]. When integrated with field observations and administrative records in a GIS, remote sensing can support sampling design, risk screening, monitoring prioritisation and temporal analysis.

The Soil Monitoring Law operates within an existing body of EU environmental law. Directive 2007/2/EC (INSPIRE) establishes rules on metadata, spatial datasets and network services to ensure the interoperability of environmental spatial information [7]. Directive 2003/4/EC guarantees public access to environmental information and requires its progressive electronic dissemination [8], giving effect to the first pillar of the Aarhus Convention [9]. Directive 2004/35/EC establishes environmental liability based on the polluter-pays principle and includes land damage that creates a significant risk to human health [10]. Directive 2010/75/EU requires baseline reports on soil and groundwater for installations involving relevant hazardous substances [11]. The legal architecture therefore increasingly connects soil condition, industrial activity, spatial information and public access; the scientific challenge is to make these connections operational.

Greece provides an appropriate case for such an investigation. Greek soil governance has developed through several environmental, industrial, planning and water-related instruments rather than through a single soil-protection statute. Law 1650/1986 constitutes the foundational environmental-protection instrument, while Law 4014/2011 established the contemporary environmental-licensing framework [12, 13]. Recent research has identified significant gaps in Greek contaminated-land governance, including the absence of comprehensive national soil screening values and of a systematic contaminated-site management mechanism [14]. At the same time, Greece contains well-documented areas in which soil contamination, industrial activity, agriculture, residential development and land-use change intersect: the Asopos-Thiva basin is a reference case of chromium contamination, the Thriasio Plain is a complex industrial-agricultural-residential environment, and Attica is a prominent example of metropolitan soil sealing and land consumption.

Despite a growing literature on each of these elements, no framework currently connects the obligations of the Soil Monitoring Law to Earth-observation workflows and to an explicit environmental-justice assessment. The present study addresses this gap through the following research question: *how can soil legislation, Earth-observation technologies, digital spatial infrastructure and environmental-justice analysis be integrated into a legally traceable framework capable of identifying spatially unequal soil-related environmental risks?* Four objectives are pursued: (i) to compare major international approaches to soil governance and contaminated-land management; (ii) to analyse the implications of Directive (EU) 2025/2360 and related EU legislation for spatial soil governance; (iii) to demonstrate how documented Greek soil and land-use evidence can be integrated with remote sensing and GIS; and (iv) to develop a reproducible Soil Environmental Justice Observatory (SEJO) that connects environmental measurements, legal obligations and socially differentiated exposure.

The central proposition is that contemporary soil governance should evolve from fragmented, predominantly site-based regulation towards an integrated system combining soil science, Earth observation, spatial information, environmental law and environmental justice.

II. MATERIALS AND METHODS

A. Research design

The research follows a comparative, mixed-method design comprising (i) comparative environmental-law analysis; (ii) a review of international soil-governance systems; (iii) a synthesis of published Greek soil-contamination and land-use evidence; (iv) an analysis of remote-sensing and spatial-data opportunities; (v) the formulation of a GIS-based environmental-justice screening model; and (vi) the design of a legally traceable digital governance architecture. The methodology distinguishes four analytical levels (Fig. 1). Level I (*legal exposure*) identifies statutory obligations concerning monitoring, contamination, liability, soil sealing, public information and participation. Level II (*environmental condition*) identifies measurable soil and land-system pressures, including contamination, sealing, land-use transformation and degradation. Level III (*exposure and vulnerability*) examines the spatial relationship between environmental burdens and population, land use and sensitive receptors. Level IV (*governance accessibility*) examines whether relevant information is available, spatially explicit, interoperable, current, understandable and accessible to affected communities. The four levels are integrated in the proposed SEJO.

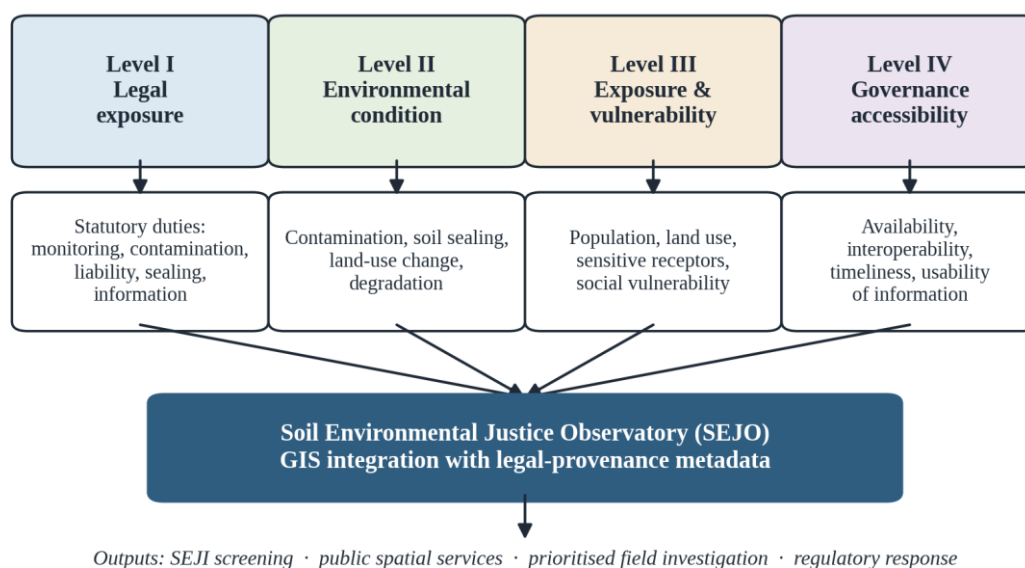


Fig. 1: Four-level analytical framework of the Soil Environmental Justice Observatory (SEJO)

B. Comparative legal framework

Five governance contexts were examined: the European Union, the United Kingdom, the United States, Australia and New Zealand. The objective was not to rank jurisdictions but to identify complementary regulatory mechanisms relevant to soil governance (Table I). The United Kingdom's contaminated-land regime under Part 2A of the Environmental Protection Act 1990 adopts a risk-based approach to determination, based on significant harm and significant pollution of controlled waters [15]. Australia's National Soil Action Plan and associated national soil-monitoring programme provide a framework for measuring, mapping and reporting soil condition [16]. New Zealand's National Environmental Standard for Assessing and Managing Contaminants in Soil to Protect Human Health establishes nationally consistent planning requirements and soil-contaminant standards [17]. In the United States, the Environmental Protection Agency's EJScreen tool demonstrated the value of combining environmental and demographic indicators spatially, while explicitly recognising that screening tools do not substitute for detailed risk assessment [18].

Table I: Comparative characteristics of selected soil-governance systems

Jurisdiction	Principal regulatory characteristic	Spatial / digital component	Relevance to environmental justice
European Union	Harmonised soil monitoring and contaminated-site framework (Directive (EU) 2025/2360)	Soil districts, digital soil-health data portal, Copernicus and INSPIRE data	Public information and harmonised monitoring
United Kingdom	Risk-based contaminated-land regime (EPA 1990, Part 2A)	Planning and contaminated-land registers	Risk-based protection and remediation
United States	Federal and state contaminated-land programmes with environmental-justice screening	Integrated environmental and demographic mapping	Cumulative-burden screening
Australia	National soil strategy and monitoring architecture	National soil information and monitoring system	National-scale soil-condition assessment
New Zealand	National contaminated-soil environmental standard	National soil-contaminant standards and planning controls	Consistent identification and management

The comparison identifies four transferable governance characteristics: harmonised soil indicators; risk-based contaminated-site management; interoperable spatial information; and explicit consideration of population vulnerability and public participation.

C. European Union soil legislation

Directive (EU) 2025/2360 constitutes the principal legal basis of the proposed framework. It requires Member States to delineate soil districts and soil units, establish soil-monitoring systems based on common soil descriptors and criteria for soil-health assessment, and set up a risk-based approach to the identification, investigation and management of potentially contaminated sites [4]. The Directive is particularly significant for Earth observation because it explicitly incorporates soil sealing and soil removal (land take) into the monitoring framework and provides for the use of Copernicus services and other remote-sensing data [4]. Its implementation timetable (Table II) defines a clear policy window within which Greece can develop a national digital soil-monitoring infrastructure.

Table II: Implementation timetable of Directive (EU) 2025/2360

Date	Milestone
16 December 2025	Entry into force
17 December 2027	Establishment of the Union digital soil-health data portal
17 December 2028	Transposition deadline for Member States
17 December 2029	Systems for identification, investigation and management of contaminated sites, including public registers
17 December 2030	First soil measurements under the Directive
17 December 2031	First soil-health assessment
17 December 2035	Identification and recording of potentially contaminated sites completed
2050	Objective of healthy soils across the Union

Source: compiled from Directive (EU) 2025/2360 [4].

D. Spatial-information and access-to-information legislation

Directive 2007/2/EC provides the technical and legal basis for the interoperability of spatial environmental information [7]. An INSPIRE-compatible soil-monitoring system should therefore include standardised metadata, common coordinate reference systems, interoperable discovery, view and download services, harmonised feature definitions, documented provenance, and explicit temporal and uncertainty information. Directive 2003/4/EC complements this architecture by establishing a right of public access to environmental information [8]. Taken together, these instruments imply that digital soil governance should be designed not as an internal administrative database but as an interoperable public environmental-information infrastructure.

E. Greek legislative framework

Law 1650/1986 established a foundational framework for environmental protection and the prevention of environmental degradation [12]. Law 4014/2011 subsequently restructured the environmental licensing of projects and activities, including procedures for environmental-impact assessment and the approval of environmental terms [13]; the licensing system has since become increasingly digital through the Electronic Environmental Registry. Law 3937/2011 on biodiversity conservation further contributes to spatial environmental governance [19]. However, recent analysis has identified the absence of comprehensive national soil screening values and of a systematic contaminated-site management framework as significant limitations [14]. Directive (EU) 2025/2360 therefore represents not merely an additional obligation but an opportunity to reorganise fragmented datasets within a coherent national soil-governance architecture.

F. Earth-observation data

The proposed implementation relies on three Earth-observation sources. Sentinel-2 multispectral imagery offers 10-60 m spatial resolution and a revisit time of five days, which is suitable for monitoring land cover, vegetation condition and surface characteristics [5]. The Landsat archive, continuous since 1972 and with 30 m multispectral data since the 1980s, supports the reconstruction of long-term land-use and urbanisation trajectories [6]. The Copernicus High Resolution Layer Imperviousness provides pan-European imperviousness-density and built-up information with a time series beginning in 2006 and 10 m resolution for recent reference years, forming an operational basis for monitoring soil sealing and land take [20].

G. Soil datasets

The framework integrates national laboratory measurements, LUCAS Soil observations, published Greek soil studies, contaminated-site records, industrial environmental-monitoring data and, where available, groundwater observations. The LUCAS Soil survey, distributed through the European Soil Data Centre, provides harmonised topsoil observations of pH, organic carbon, nitrogen, phosphorus, potassium, carbonates, electrical conductivity and other properties, and includes sampling points in Greece [21, 22]. LUCAS data are valuable for harmonisation and broad-scale comparison but should not be interpreted as field-scale contamination maps, because sampling density and spatial representativeness vary.

H. Population and vulnerability data

Population and socioeconomic information should be integrated at the smallest legally and statistically appropriate spatial unit. The 2021 Population and Housing Census of the Hellenic Statistical Authority provides population information at regional, municipal and settlement levels [23]. Candidate vulnerability variables include population density, age structure, socioeconomic deprivation, employment characteristics, housing conditions, proximity to schools and healthcare facilities, agricultural dependence and access to green space. Their selection must be transparent, because aggregated socioeconomic datasets are subject to the modifiable areal unit problem and to measurement limitations.

I. Soil Environmental Justice Index

The proposed Soil Environmental Justice Index (SEJI) is a screening instrument; it is not a measure of disease risk and does not constitute a determination of legal environmental injustice. For each spatial unit i , every indicator x is first rescaled to a normalised score z in the interval $[0, 1]$ by min-max normalisation, Eq. (1), and the index is computed as a weighted linear combination of five normalised components, Eq. (2):

$$z_i = \frac{x_i - \min(x)}{\max(x) - \min(x)} \quad (1)$$

$$SEJI_i = w_E E_i + w_V V_i + w_X X_i + w_G G_i + w_P P_i, \sum_k w_k = 1, w_k \geq 0 \quad (2)$$

where E_i denotes environmental burden, V_i social vulnerability, X_i exposure opportunity, G_i the governance and information deficit, P_i the procedural-access deficit and w_k the transparent weighting coefficients. Environmental burden is itself a composite of contamination (C_i), soil sealing (S_i), soil degradation (D_i) and cumulative environmental pressure (R_i), Eq. (3):

$$E_i = f(C_i, S_i, D_i, R_i) \quad (3)$$

Weights should not be fixed arbitrarily. The protocol therefore requires a sensitivity analysis in which weight vectors are sampled repeatedly (for example, from a uniform Dirichlet distribution) and the stability of spatial rankings is evaluated by rank-correlation and rank-shift statistics; only units that remain highly ranked under most weighting scenarios should be flagged as priority areas. Each input is additionally tagged with its evidential status (Table V), which prevents the index from conveying false precision. Table III summarises the proposed operationalisation of the five components.

Table III: Proposed operationalisation of the Soil Environmental Justice Index

Component	Example indicators	Candidate data sources
Environmental burden (E)	Contaminant concentrations; imperviousness and its change; erosion and organic-carbon loss; density of permitted installations	National monitoring, LUCAS, published studies, Copernicus HRL, permit records
Social vulnerability (V)	Age structure, deprivation, housing conditions, agricultural dependence	ELSTAT 2021 census and related statistics
Exposure opportunity (X)	Residential population, schools and healthcare facilities within defined distances of burdens; groundwater use	Census, facility registers, hydrogeological data
Governance deficit (G)	Monitoring frequency; age of last measurement; availability of metadata and uncertainty	SEJO-GR provenance layer, INSPIRE metadata
Procedural-access deficit (P)	Downloadability and currency of data; availability of participation channels	Audit of public portals and consultation records

J. Remote-sensing indicators

Vegetation condition is characterised with the Normalised Difference Vegetation Index [24], Eq. (4), and built-up surfaces with the Normalised Difference Built-up Index [25], Eq. (5), where NIR , Red and $SWIR$ denote surface reflectance in the near-infrared, red and short-wave infrared bands:

$$NDVI = \frac{NIR - Red}{NIR + Red} \quad (4)$$

$$NDBI = \frac{SWIR - NIR}{SWIR + NIR} \quad (5)$$

Additional indicators include imperviousness percentage, built-up expansion, agricultural-to-artificial land conversion, vegetation-cover change, landscape fragmentation and Euclidean distance to industrial installations, waste-management facilities, transport corridors and water bodies. The remote-sensing workflow is intended primarily for spatial screening and temporal change detection; laboratory measurements remain necessary for regulatory determinations of soil contamination.

K. Spatial statistics

Where sufficient observations are available, global spatial autocorrelation is evaluated with Moran's I [26], Eq. (6):

$$I = \frac{n}{W} \cdot \frac{\sum_i \sum_j w_{ij} (x_i - \bar{x})(x_j - \bar{x})}{\sum_i (x_i - \bar{x})^2}, \quad W = \sum_i \sum_j w_{ij} \quad (6)$$

where n is the number of spatial units, x_i the value at unit i , $\bar{x}$ the mean, w_{ij} the spatial weight between units i and j , and W the sum of all weights. Local indicators of spatial association [27] can subsequently identify statistically significant clusters and spatial outliers. Statistical significance, however, must not be confused with environmental causation: clustering describes spatial structure, whereas causal interpretation requires additional environmental, geological and exposure evidence.

III. RESULTS

A. Comparative governance results

The comparative analysis shows that the principal challenge in contemporary soil governance is not whether soil contamination is regulated but whether information can be transferred through a complete governance chain, from measurement through spatialisation, legal responsibility and public information to remediation and verification (Fig. 2). Directive (EU) 2025/2360 offers an important opportunity to establish this chain because it combines soil monitoring, contaminated-site management, soil sealing, digital information and public access within a single regulatory architecture [4]. The United Kingdom provides an established model of risk-based contaminated-land determination [15]; New Zealand demonstrates the value of nationally consistent contaminated-soil standards [17]; Australia illustrates the importance of a national soil-information and monitoring framework [16]; and the United States provides a model of spatial environmental-justice screening that integrates environmental and demographic indicators [18]. An effective soil-governance architecture should therefore combine, rather than reproduce, these separate approaches.

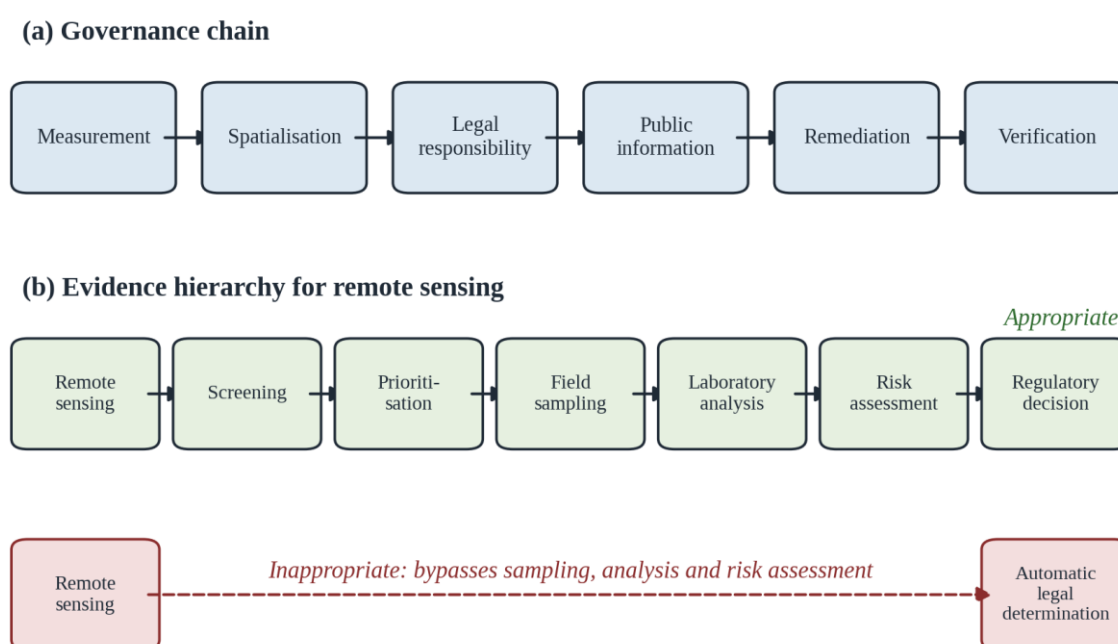


Fig. 2: (a) Governance chain required for effective soil governance; (b) appropriate and inappropriate evidence hierarchies for the use of remote sensing

B. Case Study I: Asopos–Thiva basin

The Asopos–Thiva basin is one of the most extensively studied Greek examples of combined soil and groundwater contamination. Megremi et al. investigated the spatial distribution of chromium in soil and groundwater in relation to land-use management in Central Evia and the Asopos-Thiva basin and emphasised the need to distinguish anthropogenic from geogenic contributions, given the presence of ultramafic lithologies in the wider region [28]. This distinction is critical: a map of elevated chromium concentrations cannot by itself establish the industrial origin of every observation, and geological background, mineralogy, groundwater pathways and industrial sources must be considered jointly.

Within the SEJO framework, the Asopos-Thiva problem is therefore represented through four layers: (i) measured soil and groundwater concentrations; (ii) geological and hydrogeological conditions; (iii) industrial and land-use history reconstructed from Landsat and Sentinel-2 imagery; and (iv) population and sensitive receptors. The overlay identifies locations in which environmental burden and exposure opportunity coincide. The methodology does not interpret such coincidence as evidence of adverse health effects; rather, it identifies locations that warrant further investigation. This caution is central to environmental-justice research, because spatial proximity is not equivalent to exposure, and exposure is not equivalent to health causation.

C. Case Study II: Thriasio Plain

The Thriasio Plain presents a different but complementary problem. Massas et al. analysed soils from 90 sampling sites for total and available concentrations of potentially toxic elements, including Cr, Zn, Ni, Pb, Co, Mn, Ba, Cu and Fe, and applied several soil-pollution indices that revealed spatially variable enrichment [29]. A subsequent study examined soil and plant samples from 31 locations and assessed bioavailability and potential human-health implications for elements including As, Cd, Cr, Cu, Ni, Pb and Zn [30]. These studies demonstrate that the Thriasio Plain cannot be represented adequately by a single contaminant or a single land-use category: the relevant system links industrial sources, soil, agriculture, groundwater and residential areas.

Remote sensing adds a temporal dimension to this system. Historical Landsat imagery can reconstruct changes in agricultural, industrial and residential land use, while Sentinel-2 and Copernicus products provide recent spatial detail. A parcel that was historically industrial but has since been redeveloped for housing can thus be distinguished from a continuously industrial parcel. The screening-level risk context is therefore dynamic and is expressed as Eq. (7), rather than as a static function of contamination alone:

$$Risk_t = f(C, LU_t, Pop_t, EP_t) \quad (7)$$

where LU_t , Pop_t and EP_t denote land use, population and exposure pathways at time t . This temporal formulation is a distinctive feature of the proposed methodology.

D. Case Study III: Metropolitan Attica

Attica represents a third form of soil-related pressure: extensive urbanisation and soil sealing. Nickayin et al. overlaid diachronic settlement maps (1948-2018) with soil-property geodatabases for the Athens metropolitan region and showed that peri-urban expansion progressively consumed soils of differing quality [31]. Gounaridis et al. mapped land-use and land-cover change in Attica between 1991 and 2016 from Landsat imagery with a Random Forest classifier, distinguishing urban fabric by density, and documented urban expansion predominantly at the expense of agricultural land [32]. These studies establish a scientific basis for integrating Earth observation into the monitoring framework of the Soil Monitoring Law. The principal indicator is the change in sealed-soil share between two reference years, Eq. (8):

$$\Delta S = S_{t_2} - S_{t_1} \quad (8)$$

where S is the percentage of sealed soil in a spatial unit. Three spatial conditions should be differentiated: high existing sealing; rapidly increasing sealing; and rapid sealing in environmentally sensitive or agriculturally valuable areas. The distinction matters because sealing alters infiltration, runoff, heat storage, ecological connectivity and the availability of agricultural soil. The Copernicus imperviousness layers provide an appropriate operational dataset for this purpose [20].

E. Legal-to-spatial traceability

A central result of the analysis is that environmental datasets should be linked directly to the legal obligations that motivate their collection. Table IV operationalises this principle by mapping each legal instrument to its principal requirement, its spatial representation and its potential data source. The table demonstrates that soil governance can be converted into a coherent spatial data architecture rather than remaining a collection of independent legal obligations.

Table IV: Legal-to-spatial traceability framework

Legal instrument	Principal requirement	Spatial representation	Potential data source
Directive (EU) 2025/2360	Soil monitoring	Soil-health indicators	LUCAS / national monitoring
Directive (EU) 2025/2360	Soil sealing	Imperviousness and change	Copernicus HRL
Directive (EU) 2025/2360	Soil removal	Land-cover transitions	Sentinel-2 / Landsat
Directive (EU) 2025/2360	Contaminated sites	Georeferenced site register	National administrative data
Directive (EU) 2025/2360	Public information	Open spatial services	Digital soil-health data portal
Directive 2007/2/EC	Interoperability	INSPIRE network services	Spatial-data infrastructure
Directive 2003/4/EC	Public access	Information portal	Public environmental data
Directive 2004/35/EC	Environmental liability	Land-damage sites	Regulatory records
Directive 2010/75/EU	Soil and groundwater baseline	Installation footprints and buffers	Permit records
Law 1650/1986	Environmental protection	Protected and affected areas	Greek environmental GIS
Law 4014/2011	Environmental licensing	Licensed installations	Electronic Environmental Registry

IV. DISCUSSION

A. From soil monitoring to environmental justice

Soil monitoring and environmental-justice assessment answer different questions. Soil monitoring asks what the condition of the soil is: whether contamination is present, whether organic matter is changing, and whether soil is being sealed or eroded. Environmental-justice assessment additionally asks where burdens are located, who lives, works or depends on affected resources nearby, which populations are more vulnerable, which areas are monitored regularly, who has access to environmental information and who participates in remediation and land-use decisions. The two systems should therefore be connected rather than treated as independent, following a chain from soil condition through spatial evidence, exposure context and vulnerability to governance response. This approach is consistent with cumulative-impact research, which recognises that communities experience combinations of environmental and socioeconomic pressures rather than isolated pollutants [33].

B. The role and limits of remote sensing

Remote sensing offers three major advantages: spatial coverage, temporal repetition and historical reconstruction. It also has an important limitation: most soil contaminants cannot be reliably quantified at regulatory concentrations directly from conventional multispectral satellite observations. The scientifically appropriate hierarchy therefore proceeds from remote sensing to screening, prioritisation, field sampling, laboratory analysis, risk assessment and, finally, regulatory decision (Fig. 2). An inappropriate hierarchy would pass directly from satellite observation to legal determination. Maintaining this distinction is essential to the scientific and regulatory credibility of any soil-monitoring system.

C. Digitalisation as an environmental-justice mechanism

Digitalisation should not be understood simply as a technical improvement. A publicly accessible spatial database can alter the relationship between environmental authorities and communities by making environmental information visible and geographically interpretable. INSPIRE establishes the interoperability framework and Directive 2003/4/EC the right of access [7, 8], while Directive (EU) 2025/2360 strengthens this architecture through the digital soil-health data portal and the public availability of monitoring results and contaminated-site registers [4]. Digital information does not, however, automatically produce environmental justice. A map can remain effectively inaccessible if the interface is technically complex, data cannot be downloaded, uncertainty is omitted, data are overly aggregated, local knowledge is excluded, information is not updated or legal status is unclear. Data accessibility should therefore itself become a soil-governance indicator, which is the rationale for the G_i and P_i components of the SEJI.

D. Distribution, procedure and recognition

Environmental justice comprises at least three interconnected dimensions [2, 3]. Distributive justice concerns the geographical distribution of environmental burdens and benefits; procedural justice concerns participation, access to information and access to justice, as codified in the Aarhus Convention [9]; and recognition justice concerns whether affected communities, local knowledge and historically marginalised territories are adequately represented in decision-making. Remote sensing and GIS are particularly effective for distributive analysis but are insufficient for the procedural and recognition dimensions. Participatory GIS can complement conventional spatial analysis by allowing communities to identify historical pollution sites, abandoned industrial areas, local flooding, agricultural concerns, suspected exposure pathways and inaccessible environmental information. Such inputs should be classified as community-reported evidence until independently verified.

E. A Soil Environmental Justice Observatory for Greece

The central institutional proposal is the establishment of a Greek Soil Environmental Justice Observatory (SEJO-GR). The Observatory would integrate five groups of information (Fig. 3): soil and environmental observations (soil monitoring, groundwater vulnerability, erosion indicators); Earth-observation products (soil-sealing maps and land-use-change time series); regulatory records (contaminated-site registers, industrial installations, environmental permits, remediation status and monitoring frequency); socio-demographic data (population, socioeconomic vulnerability, schools and healthcare facilities); and participatory inputs (public and community observations). A cross-cutting metadata layer would record uncertainty and legal provenance. Such an architecture is compatible with both the Soil Monitoring Law and the INSPIRE infrastructure.

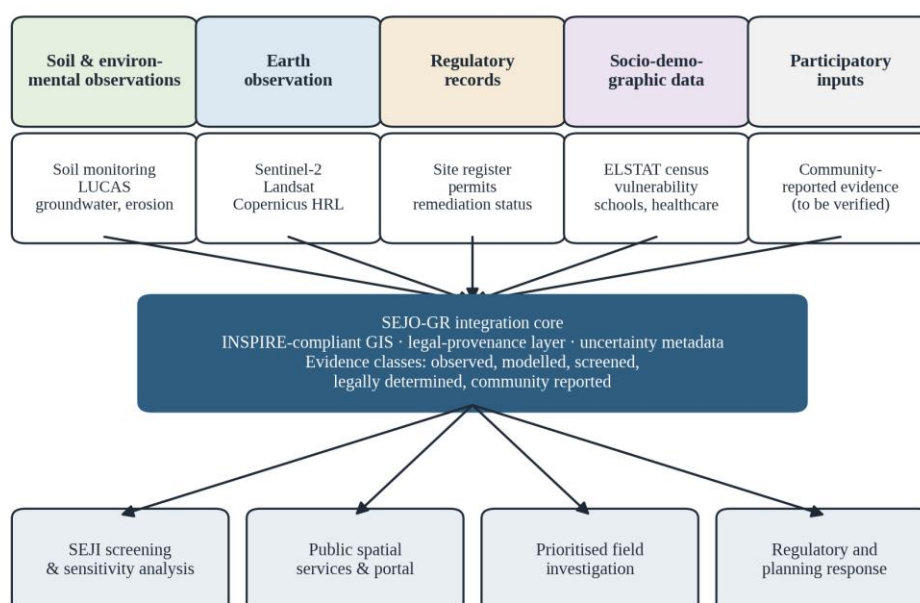


Fig. 3: Proposed architecture of the Greek Soil Environmental Justice Observatory (SEJO-GR)

F. Legal provenance

An important methodological innovation of the framework is the introduction of a legal-provenance layer. Every environmental data product should document the measurement date, analytical method, responsible institution, spatial accuracy, data source, applicable legal instrument, relevant threshold where applicable, uncertainty, monitoring status and remediation status. Evidence is thus defined not merely as a measurement but as a measurement situated in its method, date, authority, legal context and uncertainty. The database should further distinguish explicitly between five classes of evidential status (Table V). This classification reduces the risk that digital maps acquire an unjustified appearance of legal or scientific certainty.

Table V: Evidential-status classes of the legal-provenance layer

Class	Definition	Illustrative example
Observed	Obtained directly through measurement	Laboratory Cr concentration at a sampling point
Modelled	Estimated through a mathematical or geostatistical model	Kriged topsoil Pb surface
Screened	Used to identify potential priority areas	SEJI rank of a municipal unit
Legally determined	Associated with a formal regulatory determination	Site entered in the contaminated-site register
Community reported	Originating from residents or local stakeholders; requires verification	Participatory-GIS record of a former dumping site

V. POLICY AND GOVERNANCE IMPLICATIONS

The analysis yields seven recommendations for the transposition and implementation of Directive (EU) 2025/2360 in Greece.

National soil-monitoring architecture. Greece should develop an integrated national soil-monitoring system compatible with Directive (EU) 2025/2360 and INSPIRE, connecting national sampling programmes with LUCAS observations, Copernicus products and Greek administrative datasets.

National contaminated-site register. Potentially contaminated sites should be georeferenced and recorded with their location, historical use, responsible operator where legally established, contaminants of concern, sampling history, regulatory status, remediation status and monitoring frequency.

Earth observation in statutory monitoring. Satellite products should be incorporated into monitoring workflows for soil sealing, land take, land-use conversion, industrial expansion, vegetation change and landscape fragmentation, consistent with the explicit recognition of remote-sensing data in the Directive [4].

National soil screening values. The incomplete development of national soil screening mechanisms represents a significant institutional gap [14]. Scientifically justified screening values should be developed for residential, agricultural and industrial land, ecological receptors, groundwater protection and sensitive land uses.

Cumulative environmental-risk screening. Environmental permitting should progressively incorporate spatial cumulative-burden analysis, so that a new installation is not assessed solely on its individual emissions when it is located in a territory already subject to multiple pressures. Such screening should remain transparent and should not replace project-specific impact assessment.

Public access. Environmental information should be provided through interoperable digital services offering downloadable datasets, metadata, uncertainty estimates, timestamps, source institutions, legal provenance and visualisation tools.

Participatory GIS. Communities should be given structured opportunities to contribute environmental information and identify local concerns; participation should supplement rather than replace scientific measurement.

VI. LIMITATIONS

Several limitations must be acknowledged. First, no new laboratory soil sampling was performed in the three Greek case-study areas; published measurements are treated as documented empirical evidence rather than as newly generated observations. Second, remote sensing cannot replace laboratory analysis where specific contaminant concentrations must be established. Third, demographic information is spatially aggregated and can conceal inequalities within statistical units. Fourth, socioeconomic indicators embed methodological assumptions and should be interpreted cautiously. Fifth, composite indices can create false precision, which is why the SEJI must always be accompanied by sensitivity analysis. Sixth, historical contamination measurements may not represent current conditions. Seventh, geogenic and anthropogenic sources may overlap; the Asopos-Thiva case demonstrates the importance of geological and geochemical interpretation before

contamination is attributed to industrial sources [28]. Eighth, proximity to a contaminant source is not equivalent to exposure, which depends on transport mechanisms, environmental media, behaviour and duration. Ninth, environmental justice cannot be represented fully by numerical indices; its procedural and recognition dimensions require qualitative and participatory investigation. Finally, the SEJO framework requires validation through an operational Greek pilot study involving satellite processing, field measurement, statistical testing and stakeholder participation.

VII. CONCLUSION

Soil governance in Europe is undergoing a fundamental transformation. By establishing a common framework for soil monitoring, soil health, soil resilience and contaminated-site management, Directive (EU) 2025/2360 creates, for the first time, an explicit legal connection between soil science, spatial information, remote sensing and digital environmental governance.

The comparative analysis shows that the examined jurisdictions contribute complementary institutional mechanisms. The European Union contributes harmonised soil monitoring and digital spatial governance; the United Kingdom a mature risk-based contaminated-land model; New Zealand nationally consistent contaminated-soil standards; Australia an integrated national soil-monitoring architecture; and the United States extensive experience in environmental-justice screening and cumulative-burden mapping. None of these systems, taken alone, links soil condition to social vulnerability and to procedural access in a legally traceable manner.

The Greek case studies illustrate why such integration is needed. The Asopos-Thiva basin shows the complexity of spatial soil and groundwater contamination and the necessity of separating anthropogenic from geogenic sources. The Thriasio Plain shows the interaction of industrial activity, agricultural land, residential development and multi-element contamination over time. Attica shows a different dimension of degradation, in which urbanisation and sealing progressively remove soil functions. Each case calls for a different combination of laboratory, geological, Earth-observation and demographic evidence, and none can be governed adequately through site-by-site regulation alone.

The principal contribution of the study is the Soil Environmental Justice Observatory framework. Its central principle is that environmental monitoring is not in itself environmental justice; environmental-justice governance emerges only when monitoring is combined with spatial exposure analysis, social vulnerability, legal accountability and public participation. The framework therefore proposes a shift from a linear sequence of sampling, analysis and reporting towards a cycle of observation, spatialisation, validation, exposure assessment, justice screening, legal response and public verification.

Within this architecture, remote sensing occupies an important but bounded position. Satellite observations can identify land-use change, soil sealing, vegetation dynamics and environmental patterns, whereas field and laboratory measurements remain indispensable for establishing contamination. Correspondingly, the SEJI is a screening instrument rather than a health-risk model or legal determination: its purpose is to identify areas in which environmental burden, exposure opportunity, vulnerability and governance deficits coincide, and where further scientific or regulatory investigation may be warranted. The legal-provenance layer and the five-class evidential taxonomy are intended to ensure that every mapped condition carries information on its source, method, date, uncertainty, legal relevance and regulatory status, so that the resulting system constitutes a legally traceable digital evidence infrastructure rather than simply another environmental map.

For Greece, the period leading to the December 2028 transposition deadline represents a strategic opportunity. A national SEJO-GR could transform fragmented soil information into an interoperable spatial infrastructure that incorporates soil monitoring, contaminated sites, Copernicus Earth observation, census data, environmental licensing, groundwater information and public participation. The same architecture is transferable to other Member States facing similar combinations of legacy contamination, industrial–agricultural interfaces and metropolitan land take.

The scientific value of the approach must ultimately be established empirically. Future research should implement the methodology in the Asopos-Thiva basin, the Thriasio Plain and Attica using Sentinel-2 and Landsat time series, Copernicus imperviousness data, LUCAS observations, national soil measurements, environmental permits and census information, and should apply spatial autocorrelation analysis, weight-sensitivity testing and field validation to determine whether the framework adds measurable value over conventional soil monitoring. More broadly, the study advances the proposition that

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soil should be understood simultaneously as an Earth-system component, an environmental resource, a regulatory object and a geographically distributed determinant of environmental inequality—a perspective on which a new generation of socially contextualised soil monitoring can be built.

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Data availability: No new data were generated in this study. All sources used are publicly accessible European and national legal texts, published scientific literature and open Earth-observation products, as cited in the reference list. Spatial datasets generated in future implementations of the framework should be deposited in an open repository, subject to licensing, privacy and national-security restrictions.

Ethical statement: The study did not involve human participants or individual-level data. Demographic information should be analysed at appropriately aggregated spatial scales to prevent disclosure or re-identification of individuals.

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