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RESEARCH ARTICLE

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The LANDSUPPORT geospatial decision support system (S-DSS) vision: Operational tools to implement sustainability policies in land planning and management

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Abstract

Nowadays, there is contrasting evidence between the ongoing continuing and widespread environmental degradation and the many means to implement environmental sustainability actions starting from good policies (e.g. EU New Green Deal, CAP), powerful technologies (e.g. new satellites, drones, IoT sensors), large databases and large stakeholder engagement (e.g. EIP-AGRI, living labs). Here, we argue that to tackle the above contrasting issues dealing with land degradation, it is very much required to develop and use friendly and freely available web-based operational tools to support both the implementation of environmental and agriculture policies and enable to take positive environmental sustainability actions by all stakeholders. Our solution is the S-DSS LANDSUPPORT platform, consisting of a free web-based smart

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Geospatial CyberInfrastructure containing 15 macro-tools (and more than 100 elementary tools), co-designed with different types of stakeholders and their different needs, dealing with sustainability in agriculture, forestry and spatial planning. LANDSUPPORT condenses many features into one system, the main ones of which were (i) Web-GIS facilities, connection with (ii) satellite data, (iii) Earth Critical Zone data and (iv) climate datasets including climate change and weather forecast data, (v) data cube technology enabling us to read/write when dealing with very large datasets (e.g. daily climatic data obtained in real time for any region in Europe), (vi) a large set of static and dynamic modelling engines (e.g. crop growth, water balance, rural integrity, etc.) allowing uncertainty analysis and what if modelling and (vii) HPC (both CPU and GPU) to run simulation modelling 'on-the-fly' in real time. Two case studies (a third case is reported in the Supplementary materials), with their results and stats, covering different regions and spatial extents and using three distinct operational tools all connected to lower land degradation processes (Crop growth, Machine Learning Forest Simulator and GeOC), are featured in this paper to highlight the platform's functioning. Landsupport is used by a large community of stakeholders and will remain operational, open and free long after the project ends. This position is rooted in the evidence showing that we need to leave these tools as open as possible and engage as much as possible with a large community of users to protect soils and land.

KEYWORDS
land degradation, land management, soil, spatial decision support system, sustainability

1 | INTRODUCTION

1.1 | Background

There are numerous means available nowadays to challenge land degradation and implement environmental sustainability, both in the European Union (EU) and elsewhere. Amongst these are as follows

1. Everyday satellites (e.g. USGS-NASA, ESA Copernicus), sensors on board drones and in-field, which produce hundreds of terabytes of data that can support monitoring and management systems and models for sustainable land use.
2. A large availability of precision farming techniques, robotics, omics, biopesticides and nanoparticles which support sustainable farming.
3. Stakeholders engaged in research and innovation that lead to better-orientated land planning and management. A classic example is the EU's investment of great resources in implementing European Innovation Partnerships (EIP) for agriculture and sustainability and, more recently, in Soil Mission Living Labs and Lighthouses.

Most importantly, there is an increasing number of legislation and policy frameworks aimed at achieving a better environment and agriculture that preserves natural resources and adapts to climate change (e.g. 7th EAP, FAO Agenda, 17 Sustainable Development Goal [SDGs] of 2030 UN Agenda, EU directives). Some of this legislation, along with its implementation actions, such as the Nitrate Directive (year 1990) and Water Framework Directive (year 2000), has been in place for at least 2 decades.

It is clear that policies, data and stakeholder engagement are in place, but it is also dramatically clear that land degradation is increasing and our natural resources are under increasing pressure (Gowdy, 2020, UN, 2022-SDG Report) from climate change and land degradation processes.

It is also well-known that these degradation processes in turn induce biotic stresses, including augmenting the population of insects/pests and disease, increasing weed growth, threatening pollinators and increasing drought, waterlogging, salinity/alkalinity and abrupt rainfall patterns affecting agriculture in a series of ways (Shahzad et al., 2021). So how do we tackle all the contrasting issues mentioned above?

We argue that all the measures in place are simply not enough to produce a change. There is still something missing, something that would turn the above three elements (good policy, effective data and engaged communities) into operational tools – easy to use and freely available to everyone – that would support both (i) the many good environmental and agriculture policies that still face huge problems in their full implementation (e.g. reports on policies implementation: EU COM2015/120;

EU COM2013/683) and (ii) positive environmental sustainability actions on the part of stakeholders and local communities.

1.2 | Aim

Here, we aim to demonstrate that a free web-based, smart, geospatial decision support system (S-DSS), based on GeoSpatial CyberInfrastructure (GCI), could make the difference in connecting data, policy and communities engagement. This is in line with this LDD special issue which requires the '*implementation of S-DSS to address the various sustainable land uses in different sectors such as in agriculture and forestry*'.

In the LANDSUPPORT S-DSS (www.landsupport.eu), more than 100 operational tools are ready to support the implementation of sustainability policies and to assist a wide range of end-users for more sustainable land planning and management in agriculture, forestry, spatial planning, environmental protection, biodiversity and eco-tourism. This S-DSS brings together diverse sources of data (e.g. the EU's Copernicus satellite and not satellite data, climate change data, soil maps, etc.), a large set of models simulating reality (e.g. crop growth and pesticide leaching) and a user-friendly graphical user interface, with the aim of enabling end-users to access and work on the platform easily.

We do not aim to provide a literature review of geoSpatial DSSs here, but we do wish to highlight the fact that, in recent years, there has been great progress towards the development of operational S-DSS tools using similar GCI infrastructure applied to for example:

1. Agriculture and forestry applications: including irrigation (Bonfante et al., 2019; Zhao et al., 2022), olive growing (Manna et al., 2020), viticulture (Terribile et al., 2017), forest planning and management (Marano et al., 2019; Povak et al., 2020) and crop planning and management (Kim & Kisekka, 2021).
2. Environmental protection: including soil conservation (Terribile et al., 2015), water contamination (Lan et al., 2020), risk assessment (Kijewski-Correa et al., 2020), land take (Langella et al., 2020; Manna et al., 2017) and pesticide leaching (Bancheri et al., 2022) and, finally, ecotourism (Mileti et al., 2022).
3. A large set of other multidisciplinary studies (S. Wang et al., 2019).

The specific development illustrated in this paper was carried out as a part of the EU-funded LANDSUPPORT project, which brought together 19 partners from 10 different countries across Europe, the Middle East and Asia.

Following similar approaches of many DSS-based papers, we have avoided the usual separation in this specific contribution's 'Materials & Methods, Results, Discussion' sections. This choice aims to enable easy reading since – due to the complexity and interconnection of platform implementation, modelling development and user requirements – each section contains some elements overlapping (these may be methods and results) of a specific step which are a prerequisite to the next step. Thus – sequentially – we treated:

1. Implementing the aim: key issues
2. The Landsupport platform. This includes (1) the requirements (including conceptual needs, required content of each tool and need to optimise tools), (2) the architecture of the system (IT infrastructure, dashboard, data and model) to implement the tools and (3) test of tools by end users.
3. Three case studies (one is given in the Supplementary materials), with their results and stats, highlight the platform's functioning.

1.3 | Implementing the aim: Challenging key issues

To produce operational tools which successfully support sustainability in agriculture, environmental protection and their connected policies, a necessary prerequisite is to acknowledge, analyse and solve the following key issues, often ignored, five specific issues:

1. The embedded, often overlooked, high physical and socio-economic multifaceted complexity of the landscape

This requires having a system that, for any type of landscape, addresses the following:

- The physical, socio-economic, cultural variables and, thus, the trans-disciplinarity context of the landscape.
- Spatial variability and spatial uncertainty of influential geospatial variables (e.g. soil and hydrology).
- Multi-functionalities: the system must deliver useful operational results by capturing the deeply diverse multifunctionality of any landscape. For instance, this requires having, within one system, outputs for agriculture, environment, spatial planning, biodiversity, cultural heritage and environmental awareness. Basically, it is fundamental to capture as many dimensions of the very same landscape as possible.
- Site-specific dynamic nature of selected key geospatial variables change continuously in time and space. For instance, if the system seeks to address dynamic processes such as crop growth and nitrate leaching, then it is self-evident that monthly climate data are of little use since rainfall varies continuously over time and space. Therefore, it is necessary to capture at least the spatial and temporal 'daily-based' climate (e.g. rainfall) variations. This also applies to many other agriculture and environmental processes. Unfortunately, many operational tools dealing with agriculture and environment issues still employ highly aggregated datasets (e.g. Himics et al., 2020). For instance, Zwetsloot et al. (2021) in identifying synergies and trade-offs when choosing different land uses employ climate data obtained from rather coarse scale European climatic zones, and in addition they have failed to use soil data (they highlight the coarse nature of currently available soil mapping).

2. The lack of a truly integrated physical approach to many agricultural/environmental problems. Here, there are at least two issues to be considered:

- The lack of a true integrated Earth Critical Zone (ECZ) vision. Even when claiming interdisciplinarity, most operational approaches give priority to just one or two of the aspects (climate, plant, soil and bedrock) instead of developing a truly integrated ECZ approach. This is very unfortunate when dealing with environmental issues since many processes (e.g. nitrate leaching) affect the entire ECZ. In addition, soil information is often acknowledged in a very simplified way (e.g. no layering, great oversimplification of processes, etc.).
- The need for process-based modelling approaches: in the last decades there have been many efforts at modelling to address agriculture and environmental issues. These may be schematically separated into empirical versus process-based approaches with pros and cons. When dealing with operational tools (e.g. DSS) for agriculture and environment, empirical models are by far the most widely employed. This is the case when using simple empirical multicriteria models or overlapping (as in a typical GIS system) data layers/knowledge about environmental variables (vegetation, soil, climate, etc.) to address complex agriculture and environmental issues depending on the 'Earth Critical Zone' (e.g. primary productivity or groundwater vulnerability). Here, we claim that an adaptive approach is required since empirical models are indeed essential in many cases (e.g. erosion at landscape scale), but process-based models are much more appropriate and powerful when dealing with interlinked biophysical processes and ecosystem services, at different temporal and spatial scales. In addition, one of the many drawbacks when using empirical models of this type of process (e.g. crop growth, water balance) is the very high cost of calibration and validation when transferring these models to new areas (Manna et al., 2009). To this end, process-based models, being based on superior general physical rules, are more replicable to new areas, decreasing the effort of new calibrations and validations and, thus, giving much better value for money.

3. The lack of factual scientific support (science-based solutions) to both farmers and regional governments for achieving both a realistic and performant sustainable management of agriculture, forest lands and many other environmental issues. Indeed, after many years in which both agriculture and environmental issues have benefited from the large availability of data, sensors and supposed tools, most farmers and regional governments have acknowledged a lack of support for sustainable management and planning activities. For instance, Lundström and Lindblom (2018) highlight the fact that most DSS applied to agriculture '*have not been used appropriately in practice*' (Aubert et al., 2012; Eastwood et al., 2017; Rossi et al., 2014). Important reasons for this include the fact that developers '*normally consider only technology while the farmer must consider the technology in the whole complex situation of practice*'. Such a lack of factual sound scientific support also applies to the guidance Research and Innovation (R&I) offers to policy makers in the designing or increasing the effectiveness of good land management practices (e.g. best practices, restoring carbon stocks, etc.)
4. The fragmentation of current approaches, models and DSS tools. A large variety of models and DSSs has emerged over recent decades (Geertmanand & Stillwell, 2009; Amelung et al. 2020; Manna et al., 2020) but typically these have been developed to address specific problems for specific end-user groups. Thus, they are of little use for delivering an integrated approach. Figure 1 aims to show this critical issue. Here, a number of cars are depicted, each representing an example of the many currently available specialised model/DSS systems designed to achieve a specific goal (e.g. climate change impact assessment, state of land degradation, crop productivity, etc.).

It should be extremely important that each of these models/DSSs be related to the others, but, unfortunately, this is not the case (the grey roads are not interconnected). Indeed, the current scenario is very fragmented and the many available models/DSSs systems do not interact with each other. This is not surprising considering the great fragmentation of disciplines around landscape analysis. Moreover, the majority of already existing models and DSSs is typically limited within a specific scale.

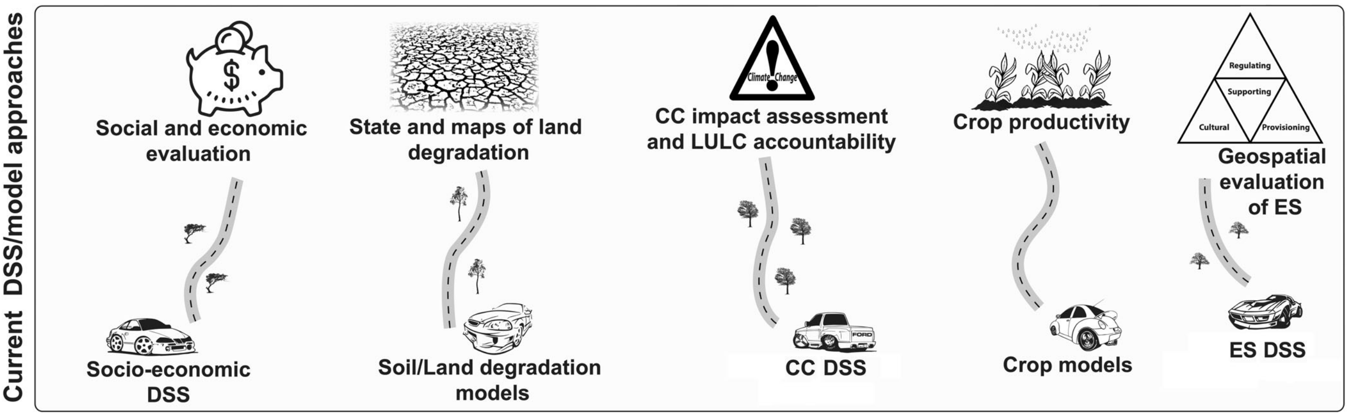

FIGURE 1 The figure depicts current fragmentation of models and decision support systems (DSSs) approaches. CC, climate change; ES, ecosystem services; LULC, land use and land change.

5. The difficulties in the implementation of the many good policies to improve both the environment and agriculture so that they better preserve natural resources and adapt to climate change (e.g. 7th EAP, FAO Agenda, 17 SDG of 2030 UN Agenda, EU directives). The evidence of difficulties in the full implementation of these policies is reported in many official documents (e.g. reports about the implementation of a water framework Dir. COM2015/120 & Nitrate Dir. COM2013/683, UN, 2022).

It is believed that these difficulties arise from the fact that the implementation of much environmental and agriculture legislation requires, as a 'must', answers which vary in space (over the landscape) and time (dynamic). Here, it is necessary to underline the fact that the cause of this complexity is often the soils, whose properties vary in space and time (i.e. after soil tillage). In Table 1, some requirements, often overlooked, are reported that apply when implementing prominent agri-environmental legislation in the EU and beyond.

Thus, this hidden embedded complexity makes things rather difficult when considering points 1, 2, 3 and 4 above. The general problem is that what is required is a full implementation of many environmental policies which often require positive actions at a very detailed local scale and over very large areas (regions, countries, EU). From our understanding, current approaches are not challenging this complexity when addressing policy implementation as they offer either a simplistic aggregated view of the problem (e.g. NUT aggregation in CAPRI model, Himics et al., 2020) or address the complexity through the plethora of Agent-Based Modelling (WoS reports over 80 papers per year in only field of agriculture), which indeed produces interesting results (e.g. Bestmap https://cordis.europa.eu/project/id/817501, Agricore https://cordis.europa.eu/project/id/816078 projects), but, as yet, not enough quantitative, farm-level rooted evidence (Shang et al., 2021). In our view, their view of soil-land complexity is very simplistic (Brown et al., 2022; Ziv et al., 2020), especially with respect to policy implementation which often requires quantitative, spatially-explicit soil-based approaches (e.g. EU Nitrate and Water Framework Directives, new CAP).

2 | THE LANDSUPPORT PLATFORM

2.1 | Requirements

2.1.1 | The need for a novel concept

Here, an attempt is made to deal with the above issues, 1, 2, 3, 4 and 5, by overcoming the fragmented approach reported in Figure 1 and developing the S-DSS approach (LANDSUPPORT GCI), described in Figure 2 as a powerful 4-wheel car which, thanks to its unique engines, is able to address (black road) various objectives simultaneously, thus, overcoming the current fragmentation of tools and land policy implementation. In this way, with very limited investment and using the same infrastructure, it is feasible to reach new important additional objectives (e.g. socio-economy evaluation, spatial planning, what if modelling, water use efficiency, etc.) on a number of spatial scales. All the above is indeed feasible if intrinsic optimisations are achieved where the marginal cost of developing each new single engine is low because each engine is used for multiple purposes.

For instance, the high cost of developing the 'soil-plant-atmosphere (SPA) agro-hydrologic simulation modelling working on high-performance computing (HPC) parallel processing' is counterbalanced by the fact that this model is used for many different issues such as evaluating (i) ecosystem services, (ii) farm management, (iii) soil compaction, (iv, v) nitrate and pollutant leaching, (vi) food security, (vii) impact of climate change and (viii) spatial planning. The same may apply to other modelling engines and, thus, the outcome of this approach might represent extraordinarily good value for money. Of course, data, model and HPC resources must work in accordance with the geographic scales, enabling actions to be tackled on the local scale where the largest multi-beneficial agriculture and 2030 SDGs deliveries will be produced while still delivering on very large spatial scales.

More specifically, our system should enable us to retain the following aspects, as depicted in Figure 3: (i) standard Web-GIS features, such as easy data updates and a user-friendly graphical user interface (GUI) and (ii) new additional features to be added to standard Web-GIS to enable a GUI to deliver multiscale, multi-stakeholder and multi-functionality outputs and permit upload of thematic maps by end-users and stakeholders. The latter is the case when the user is entering a new data layer (e.g. his/her own Region Of Interest-ROI as the focus of the analysis). Eventually, the system must include (iii) a third set of features well beyond Web-GIS architectures and philosophy. These refer to the use of dynamic databases (e.g. daily update of geospatial satellite or climate data) and the demand for 'on-the-fly' simulation modelling, as required by most dynamic environmental and/or agriculture applications (e.g. primary productivity, water balance, pollutant leaching, etc.).

Moreover, for specific applications (on the scale of the farm), the system must enable the uploading of soil analysis data produced by the farmer (e.g. soil textures) to ameliorate the performance of crop growth simulation modelling. In addition, the system requires computing codes to be easily updated; this is a crucial issue to ensure system flexibility and modularity. Here, we argue that current scientific and technological advances, the excellent availability of databases and, most importantly, the vision of the responsibility of scientists in leading sustainability (Bouma, 2015, 2020) make it possible to move down a new road.

These advances are made possible by (i) the large availability of geospatial data (maps, satellite, drone, etc.); (ii) progress in environmental sciences and adjacent sciences, including digital soil mapping (e.g. Chen et al., 2022; Huang et al., 2022; Piikki et al., 2021) and simulation modelling of the soil–plant–atmosphere system (Coppola et al., 2019; Penuelas & Sardans, 2021; see https://soil-modeling.org/ for a deeper insight); (iii) advances in open-source Web-GIS (Tavra & Škara, 2020); (iv) high performance computing and, especially, CPU and GPU processing (Badia et al., 2022; Goodman et al., 2019);(v) recent developments in building Geospatial-DSS for agriculture and the environment built on web-based 'geospatial

TABLE 1 Some important European Union (EU) regulations concerning the management of agricultural/forestry and environmental issues (a more detailed version of this table is provided in the Supplementary material).

SDG and EU regulation/ directive	Key sustainability topics addressed by the selected legislation	Required answer to implement the policy	
		In time	In space
Climate and Environmental Policy	Kyoto Protocol (UNFCCC), COP 15, COP21 (Paris) about legally binding commitments to greenhouse gases reduction. Reduction GHG emission and adapt to climate change by agriculture.	Static	Varying across the terrain (landscape)
Sustainable Development Goals: 2, 3, 6, 12, 15	Target 2.3 double agricultural productivity and incomes Target 2.4 resilient agricultural practices Target 3.9 reduce water and soil pollution Target 6.3 improve water quality by reducing pollution Target 6.4 increase water-use efficiency Target 12.4 reduction of chemicals in water and soil Target 15.3 land degradation-neutral world	Dynamic	
EU Common Agriculture Policy	Conditionality (Art. 12) EU Member States shall define minimum standards and good practices (GAEC and SMR, ANNEX III) considering characteristics of the areas concerned, including soil and climatic conditions, existing farming system, land use, crop rotation, farming practices and farm structures. Schemes for the climate and the environment (Art.28) Elements common to several interventions (Art. 98).	Static	
EU Soil Strategy for 2030	Soil for climate change mitigation and adaptation (sect. 3.1)	Static	
	Land takes limitation by circular use of land (sect. 3.2.2)	Dynamic	
	Closing the nutrient and carbon cycles (sect. 3.2.3)	Dynamic	
	Soil for healthy water resources (sect. 3.4)	Static	
	Making sustainable soil management (sect. 4.1)	Dynamic	
	Restoring degraded soils and contaminated sites (sect. 4.4)	Static	
Dir. 91/676 Nitrates Dir.60/00 Water Fram. Dir	Land vulnerability to nitrate pollution and best management practices	Dynamic	
Dir.60/00 Water Framework Dir.	Amelioration of water quality and quantity in river basins in terms of resilience to future climate change	Dynamic	
Dir. 80/68 Groundwater pol. Dir	Soil protective ability against groundwater pollution	Dynamic	
Dir. 86/276 Sewage sludge Dir	Evaluation of the attitude and criteria for the application of sewage sludge	Static/dynamic	
Reg. 510 and 1898/06 Designations origin Reg.	Support for geographical indications and designations of the origin of foods	Static	
COM (2013) 659 (forest strategy)	Best practices to achieve good forest maintenance	Dynamic	
USA EPA (Environmental Protection Agency) (regulatory), USDA (voluntary)	Conservation Reserve Program (CRP): improve water quality, prevent soil erosion and reduce loss of habitat US Farm Programs: land conservation requirements to support and conserve environmentally sensitive lands	Static	

Abbreviations: COM, communication; Dir., directive; Reg., regulation.

cyberinfrastructure', thus enabling the '*acquisition, storage, management, and integration of both advanced and dynamic data (e.g. pedological, daily climatic, and land use), data mining and data visualization, and computer "on-the-fly" applications in order to perform simulation modelling* (e.g. *soil–water balance and crop growth*), *all potentially accessible* via *the Web*'; (vi) new understanding of the key issues of transdisciplinarity (Bouma, 2020; Daliakopoulos & Keesstra, 2020; Terribile et al., 2015) and (vii) the increasing role of

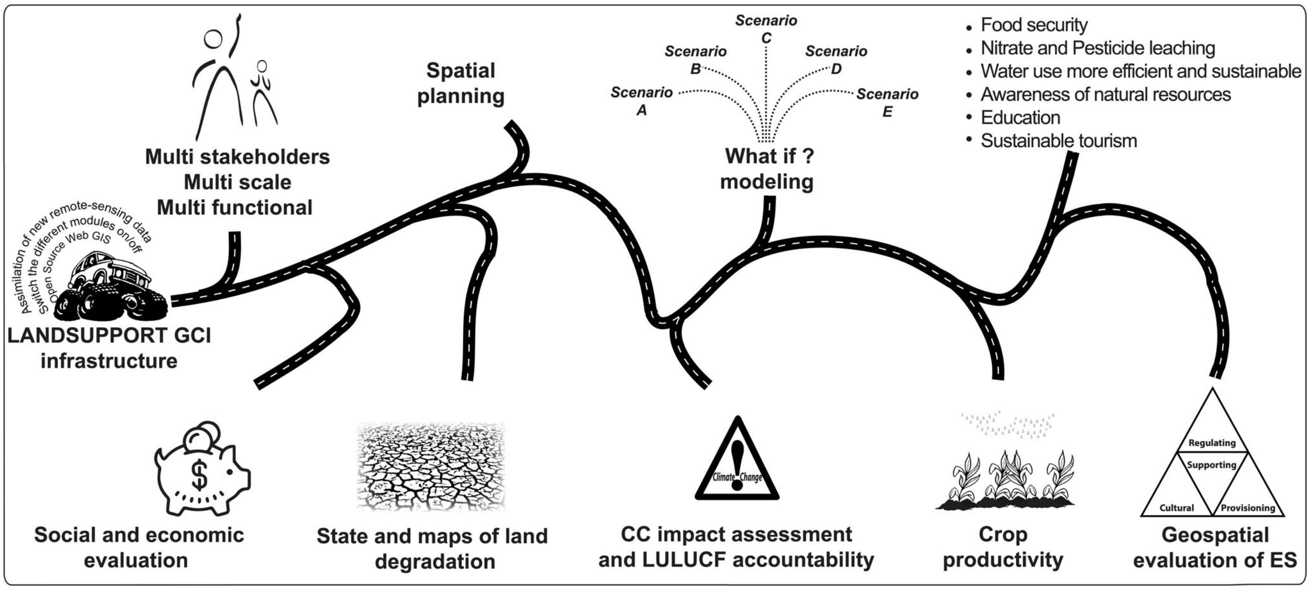

FIGURE 2 Optimisation of the Landsupport geospatial cyber-infrastructure (CGI) approach. CC, climate change; ES, ecosystem services; LULUCF, land use and land change forestry; S-DSS, geospatial decision support system.

multiple stakeholders (Maring et al. 2022; Thompson Klein et al., 2001) in co-designing new approaches (e.g. EIP. Living labs, EIP AGRI, etc).

2.1.2 | The need for operational tools

Here, we seek operational tools to better implement policies and actions dealing with sustainability in agriculture, forestry and spatial planning. In Table 2, we reported the main policies we aim to intercept by use of the LANDSUPPORT GCI system and also (last column) the list of 15 macro-tools we developed from the letter 'a' to 'o' (named macro-tools because each one is composed of many elementary tools). The expected achievements and tangible products produced after the use of the cited tools to fulfil both the implementation of selected policies and actions on various scales are reported in Table 3.

From the analysis of Tables 1–3, it is self-evident that we do not seek generic tools on aggregated scales, but rather tools that enable users to act at the specific scale of implementation of each policy. For instance, the EU Nitrate directive (Dir. 91/676) is indeed pan-European, but its implementation is on a regional scale and not on a broader scale. Basically, each EU administrative region has to develop (i) its own actions at a local level to lower nitrate leaching and (ii) to map (with an update every 4 years) the Nitrate Vulnerable Zones of the region. Therefore, the development of a tool (in this case tool 'j') to handle the Nitrate Directive problems means developing operational tools to support officers as they implement points (i) and (ii) to lower the risk of groundwater pollution through nitrate leaching.

2.1.3 | Co-design the tools

Development, testing and engagement involved different types of users and their different needs due to the multisectoral and multiscale nature of the project.

More specifically, each tool was co-designed with specific communities of users, which of course varied according to the particular tool. This ensured that user requirements were taken on board.

The community of users involved in the development process were the following:

1. Policy makers at local, regional and national levels (e.g. regional administrations, ministries, etc.).
2. Farmers associations, cooperatives and consortia.
3. Environmental agencies.
4. Researchers (e.g. in the fields of soil, agriculture, environment, urban and landscape planning, sustainable development, etc.).
5. Sectoral associations and bodies (e.g. food security agency, Chamber of Agriculture).
6. Small and medium-sized enterprises (SMEs) (agritourism activities, tourism agencies, environmental guides…);
7. Environmental non-governmental organisations (NGOs) and associations.
8. Consultants in several LANDSUPPORT-related topics – for example, soil, agriculture, environment, urban and landscape planning, sustainable development, and so on.

To engage stakeholders and end-users, a knowledge transfer chain, depicted in Figure 4, was developed. More specifically, knowledge transfer from researchers to end-users was ensured using the

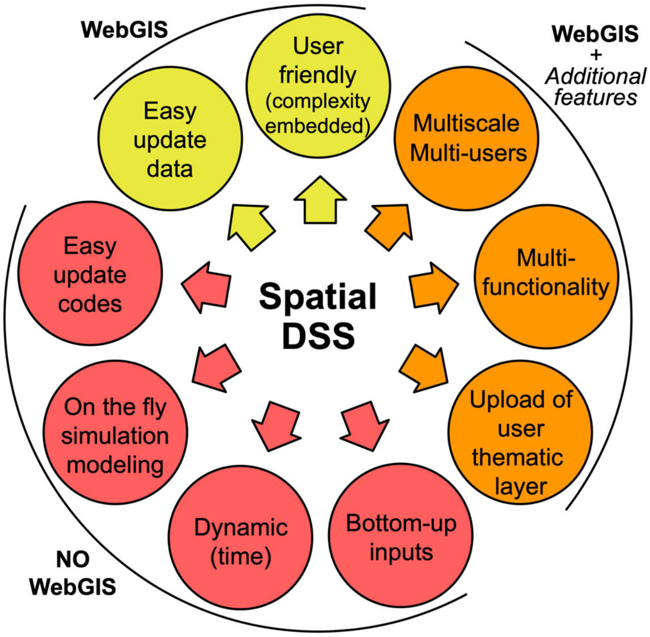

FIGURE 3 Desired features of the Landsupport decision support system system to address current agriculture and environmental sustainability challenges. [Colour figure can be viewed at wileyonlinelibrary.com]

LANDSUPPORT platform (depicted as mode 1 in Figure 4). While a large set of general meetings and face-to-face meetings were organised with many users to ensure knowledge transfer from end-users to researchers (mode 2 in Figure 4). This required complementary types of knowledge (scientific and practical) and needs (challenges, incentives) to be taken into account so as to transform our system into concrete opportunities for end-users.

2.1.4 | The need to optimise tools

To satisfy all very high expectations reported above (Figures 2–4 and Tables 2 and 3), it is required to equip our system (depicted in Figure 5 as an engine to be placed into the LANDSUPPORT 4-wheel car) with a series of special features, the main ones of which were the following: (i) Web-GIS facilities, connection with all (ii) satellite data (e.g. Copernicus Sentinel), (iii) ECZ data (e.g. geology, soil, land use etc.) and (iv) climate datasets including climate change (e.g. COSMO-CLM) and weather forecast data (COSMOLEPS), (v) data cube technology (*rasdaman*) enabling us to read/write when dealing with very large datasets (e.g. daily climatic data to be obtained in real time for any region in Europe), (vi) a large set of modelling engines (e.g. crop growth, water balance, rural integrity, etc.) allowing uncertainty analysis and *what if* modelling, HPC (both CPU and GPU) to run simulation modelling in real time and, finally, (vii) a specific module to allow the user to insert his/her own data (e.g. soil analysis from his/her field) into the system (named as FMIS).

The IT architecture designed to fulfil the above needs is reported below in the IT Landsupport description.

2.2 | The architecture of the system

2.2.1 | The IT infrastructure

Here, we move from a conceptual basis towards the actual implementation of LANDSUPPORT taking on-board all requirements reported in Section 1 and Section 2.1. The system is built on a GCI platform supporting '*acquiring, storage capacity, management and integration of both static (e.g. hydrogeology, soil) and dynamic data (e.g. rainfall, temperature, land use) and "on-the-fly" data elaboration and visualisation*' (Terribile et al., 2015; Yang et al., 2010).

LANDSUPPORT has a 3-tier architecture as depicted in Figure 6: (a) database, (b) application server and (c) GUI; all supporting 15 macrotools (Bancheri et al., 2022; Mileti et al., 2022).

The database includes both vector and raster data (Table 4). Vector data include three main types of geometries: points, lines and polygons, and are stored in PostgreSQL (open-source license database) and managed using the PostGIS extension. Raster data are typically composed of pixel arrays (with continuous or discrete values) and are managed through a data cube technology, in our case the rasdaman database (Baumann et al., 2021), allowing management, storage and recovery of huge multidimensional arrays.

The data can be processed either (or both) by static and dynamic models (see Table 5) which can generate pdf reporting, interactive maps and tables and informative Html popups as outputs. User-tool interaction takes place within the Graphical User Interface.

2.2.2 | The dashboard

The GUI is given in Figure 7, and it includes a variety of graphical devices and processes aiming to combine geospatial data (analysis and visualisation), production of outputs as tables and maps, and easy-to-use navigation. The dashboard includes three sections: the 'data viewer', the 'map' (central box) and the 'analysis tools' (left-hand box).

The 'data viewer' section (left-hand box, Figure 7) includes the 'Layers' sheet (Figure 7a), which enables the user to navigate through the different thematic maps, the 'Legend' sheet viewer (Figure 7b) and the 'Preferences' sheet (Figure 7c), where the user can modify the type of visualisation and obtain metadata. The 'Maps' box (Central box, Figure 7d) displays the maps which have been selected from the 'layers' sheet. In the Analysis Box (right-hand, Figure 7), there are two sections: the 'toolbox' (Figure 7e), which enables the end-user to browse through the many LANDSUPPORT tools, and the 'results' section (Figure 7f), where the user can visualise his own results, which have been produced and stored on the platform (including the applied model, scale, processing status, etc.). Additionally, at the very top of the dashboard, there are some devices (measure distances/areas, point locator and draw polygon) that enable the user to draw the ROI he/she is interested in and save it within a public (or personal) storage space for use it whenever he/she requires. The ROI can also be modified or deleted at a later stage.

TABLE 2 Policies addressed by the Landsupport System and list of 15 macro-tools (a more detailed version of this table is provided in the Supplementary material).

Theme	Policies covered by the S-DSS: European	National (A + H + I: applied to Austria, Hungary and Italy)	Regional	Main features of Landsupport tools impacting over selected land policies
General	CAP; 7th Environmental Action Plan; 2030 Agenda for SDG (N. 2, 3, 15); Dir 2000/60/EC; Dir 2007/2/EC – Inspire; European Decision n. 529/2013; Green Deal; UN Framework Convention on Climate Change (UNFCCC)	A + H + I: European Decision n. 529/2013 on LULUCF reporting and accounting for climate change mitigation and adaptation; National Strategy for Adaptation to Climate Change	REGCAM (Italy), Zala (Hungary), Marchfeld (Austria): PSR2023-2027/ Water Management Plan/ Action plan for zones vulnerable to nitrates. REGCAM: General Forestry Plan 44/2010 Zala County: CAP Regional applications Marchfeld: Nature and landscape Protection Law	a. Support implementation, impact and delivery of current CAP and SDGs policies by developing a smart S-DSS b. Support for developing robust knowledge to help in making informed decisions and improving the climate resilience of agriculture and forestry. c. Alignment of private/ public actors involved in land planning/ management using a harmonised approach
Agriculture Forestry CAP	RDPs (Pillar I and II); CAP; Reg. 2021/2115 (Strategic Plans); Reg. 2021/2116 (ex cross-compliance) Dir 2000/60/EC (WFD) Dir 2006/118/EC (GFD) Green Deal (Zero Pollution Action Plan) COM (2013) 659 final; EU Forest Strategy	A + H + I: CAP Greening Payment Requirements and GAEC Cross-Compliance Standards/ CAP Strategic Plans Austria: Federal Forest law; Austrian Programme of agri-environmental measures Hungary: Act on the Protection of Cultivated Soil Italy: Legislative Decree on Modernisation of the Forestry Sector; Agricultural policy instruments; Regional RDP; dlgs 18/05/01 no. 227		d. Support institutions in Rural Development and designation of origin of specific agrifood/ land use e. Supporting farmers for Cross-Compliance and greening f. Improvement of water status, ecosystem services and resilience to climate change g. Agricultural practices and water h. Support sustainable forestry as required by EU Forestry Strategy and support forest owners in adopting best practices
SDG15, Land Degradation Neutrality, Biodiversity	UN Convention to Combat Desertification (UNCCD); Dir. 91/676/EEC (nitrates directive); Dir 128/2009/ EC (pesticides Dir.); EU Soil Strategy COM (2021) 699 final	A + H + I: Protection of Waters against Nitrates and pesticide pollution Austria: Austrian Fertiliser Act Hungary: Act on soil protection (CXXIX. Of 2007) Italy: Sustainable Use of Pesticides National Plan		*Land degradation* i. Evaluation of soil threats and support the adoption of best management practices. j. Support implementation of Nitrates and Pesticide Directives and adoption of best management practices
	COM (2011) 571 final (roadmap to a Resource Efficient Europe); 2001/42/EC (SEA Dir.) and 85/337/EEC (EIA Dir.); COM (2013) 249 final (green infrastructures); SEC (2006) 16 (urban environment strategy)	Austria: Austrian EIA Act, Spatial Planning Recommendation No. 56 on Land take reduction Hungary: Decree No. 314/2005 for environmental impact assessments. Italy: dlgs 152/06; (Codice Ambiente DDL 2039)		*Land take and Spatial planning* k. Support for stakeholders to achieve Zero Net Land Take by 2050 l. Support towards the implementation of Strategic Environmental Assessment and Environmental Impact Assessment Directives

(Continues)

TABLE 2 (Continued)

Theme	Policies covered by the S-DSS: European	National (A + H + I: applied to Austria, Hungary and Italy)	Regional	Main features of Landsupport tools impacting over selected land policies
				m. Support planning of green infrastructure
	Dir. Habitat 92/43/EEC; Reg. 477/2011 (birds and natural habitats); EU Biodiversity Strategy for 2030	Austria: Austrian Biodiversity Strategy 2020+ Hungary: Strategy for Biodiversity Conservation Italy: National Strategy for Biodiversity (SNBD)		*Biodiversity and ecosystem services* n. Support for decision-making over MAES (Mapping Assessment Ecosystems and Services) action under the EU Biodiversity Strategy
Additional obj.	Dir. Habitat 92/43/UE; 92/43/EEC; Action Plan COM2017/198 final; Agenda for sustainable tourism COM (2007) 621 final			o. Support implementation Natura 2000; Improvement knowledge, online digital technology to support EU Action Plan Nature and tourism

Finally, on the lower right-hand side of the GUI, the user will find the specific tool of interest (Figure 7g).

2.2.3 | Database

The database is connected with the 15 macro-tools and typically consists of geo-referenced data and metadata from different sources (Table 4). Up to now, LANDSUPPORT stored more than 450 layers, equally subdivided between raster and vector data. The data are stored in different folders according to the scale of application and themes. All stored data are reported in the Supplementary material and are available through the project catalogue at www.landsupport.eu.

Some of these data, such as those found in official repositories of a public institution (e.g. ESDAC-JRC, Imperviousness-ISPRA), were already available, some were also interoperable (e.g. EU Copernicus); some others were held within the local repositories of public institutions (e.g. soil type and database of the Marchfeld region, Austria), a few required further processing (e.g. population data from Eurostat) and many new data had still to be created (soil database integration for the Campania region, Italy). Data are organised on the basis of the following: (i) theme area (soil, land use, geology, etc.), (ii) data type (vector data such as Corine CLC or raster data as DEM), (iii) spatial extension/resolution (European, National, Regional or local) and (iv) data details (source and year).

Before being integrated into the LANDSUPPORT database, raster and vector data were tested for quality and, where required, subjected to up-scaling procedures (e.g. coarser resolution data are better for some applications) or checked for spatial coordinates, missing data, outliers, etc. and then uploaded.

Table 4 represents an excerpt from the data layers stored in the database, either already available from existing data repositories or created during the project. They are include data on soil, geology, land use, morphology, meteorology, biodiversity, and so on.

To produce some of the tools, it was necessary to generate and harmonise a large set of these data.

2.2.4 | Models

All tools perform a variety of types and numbers of processing operations on the ROI selected by the user. This processing generates a variety of outputs, ranging from the visualisation of standard maps, through the production of tables and graphs, to geospatial functions that enable the complex processing required by some of our models.

Most of the tools involved writing specific codes aiming to produce new models or recompiling and adapting existing programme code to fit into our LANDSUPPORT system.

Table 5 gives a short description of the implemented models, which are at the basis of the 15 tools. Each of these models refers to a specific theme, a specific functionality and operating mode (e.g. 'on-the-fly' or offline mode), the required input and, finally, the outputs produced.

Models can be organised according to their operating mode in the following two types:

1. Static models employ offline processing: one example is related to climatic data on a regional scale. This operation allows us to evaluate in advance the parameters of linear relationships between temperatures (average, minimum and maximum) and altitude, thus

TABLE 3 Achievements and tangible products produced after the Landsupport tools (a more detailed version of this table is provided in the Supplementary material).

Theme	Landsupport tools, fully listed in Table 2	Landsupport achievement	Landsupport tangible products (list not exhaustive)	Scale
General	a. Support implementation of multilevel land policies b. Climate resilience agriculture c. Alignment actors in land planning/management	An *operational* interactive web *tool supporting public authorities in implementing CAP, SDG*, improving *climate resilience in agriculture/ forestry* and *LULUCF accounting* *One single platform, with a very strong scientific basis, to align the many different actors* involved in land management	• Selected institutions implementing land policies have their tailored digital dashboard designed to *support institutional duties* towards CAP, SDG • A tool enabling the testing of current *LULUCF* country *accountability* • Reports with indicators of climate change anomalies • Simulation of the effects induced by climate change on main agricultural crops	E, N, R, L E, N
Agriculture Forestry CAP	d. Support for institutions in Rural Development and designation of origin of agrifood/land use	Tools to support regions in RDP by: (i) giving *support for a participative approach*; (ii) *support agro-climatic services*; (iii) Identification of *sustainable agri-environmental practices*; (iv) reinforcing designation of origin for specific agrifood/ land use	• Evaluate the site-specific potential performance of crops (e.g. on-the-fly report, maps and tables to support the sustainable production of high-quality wines). • Maps and tables that simulate the potential production of major agricultural crops and connected impacts on soil organic carbon and nitrate leaching	R, L
	e. Support for farmers for Cross-Compliance and greening	Tools to: (i) support farms in *assessing best agricultural practices to meet cross-compliance* and conditionality	• Farmers can modulate different agronomic practices (fertilisation, soil tillage, etc.) and identify the most effective combination (e.g. increasing SOC)	R, L
	f. Improve ecosystem services, g. Agricultural practices and water	*Tools based on quantification of some key soil ecosystem services*	• The user can freely draw his area of interest (e.g. farm and municipality) and obtain maps of some of the major soil Ecosystem Services (e.g. water storage)	R, L
	h. Support for sustainable forestry	Modelling and mapping tools designed to *support sustainable forestry* by providing detailed information to support local forest practitioners (tool based on Forest Inventory Data)	• Maps, tables, reports on the environment, forest species, pedoclimate, forest management plans and support sustainable forest management • The tool simulates harvest, growth, C accumulation and mortality	N, R L
SDG, Land Degradation Neutrality, Preservation of Biodiversity	i. Evaluation of, multilevel land/soil degradation (LD) threats	Reporting, modelling, monitoring and mapping tools designed: (i) for *land degradation mapping*, (ii) to *obtain a list of good practices to challenge land degradation* (GeoC)	• LDN tool supports and calculates target SDG 15.3 • Scale appropriate solutions to land/soil degradation (GeoC) • Geographic analysis and risk assessment of landslides	(G), E, N R

(Continues)

TABLE 3 (Continued)

Theme	Landsupport tools, fully listed in Table 2	Landsupport achievement	Landsupport tangible products (list not exhaustive)	Scale
	j. Nitrates and Pesticide Directives k. Zero Net Land Take by 2050 l. SEA and EIA m. Green infrastructure	*Best management practices to lower nitrate and pesticide leaching in farm systems*	• Simulations of alternative farm management scenarios over nitrate and pesticide leaching, thus obtaining quantification/ reports/maps	(R), L
		Evaluate and quantify land taken and simulate the effects of new urbanisation or new green corridor, support *SEA, EIA*	• Yearly mapping (Copernicus, national data) of soil sealing • Interactive mapping/ reporting/accounting of current or newly simulated land take or new green corridor and impact on ecosystem services/SEA and EIA	E, N E, N, R, L
Additional obj.	n. Biodiversity Strategy o. Natura 2000, Sust. tourism	Tools to exploit the potential of LANDSUPPORT for *education*, land/soil *awareness* and *sustainable tourism*	• Empower natural, cultural and eno-gastronomic heritage of rural territories through specific reports and maps designed according to user requirements	R, L

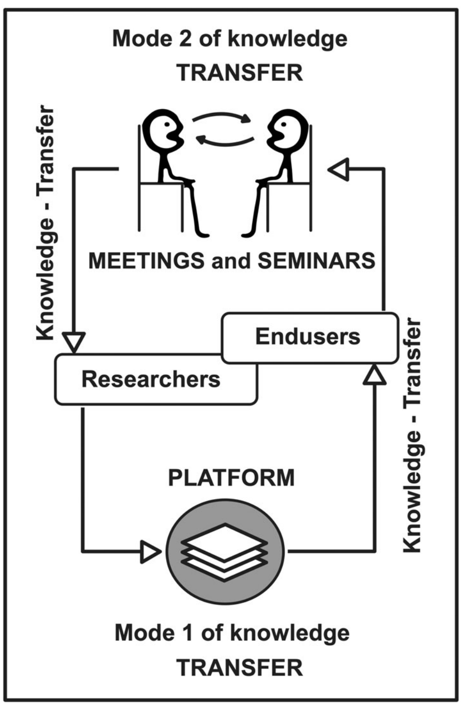

FIGURE 4 Knowledge transfer in Landsupport.

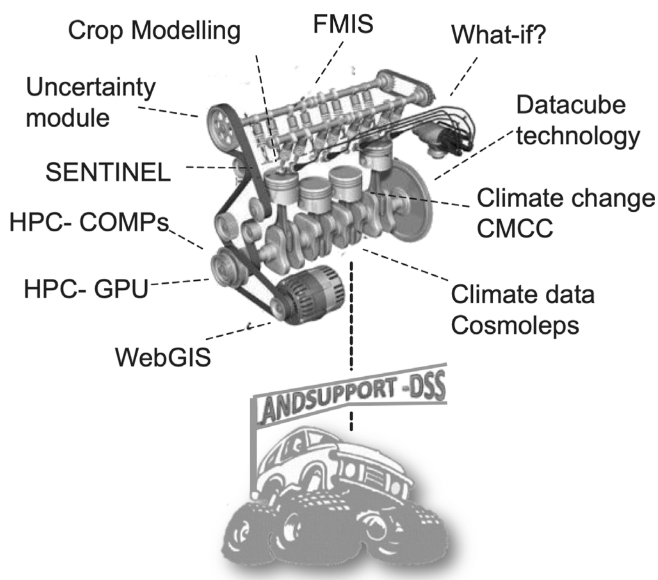

FIGURE 5 Design of the engine to optimise geospatial decision support system tools for sustainability. CMCC, Centro euro Mediterraneo per il Cambio Climatico; FMIS, farm management information systems; GPU, graphic processing unit; HPC, high performance computing.

allowing easier spatial interpolation of temperature (using Postgres/PostGIS table).

2. Dynamic models employ 'on-the-fly' calculations: this is the most commonly used type of model for biophysical processes such as crop growth. Using daily climatic data, these models evaluate the climate-soil plant dynamics for each day and produce output phenology, yield and many other outputs. The latter can be used, for example, to populate PDF reports and graphs describing the basic

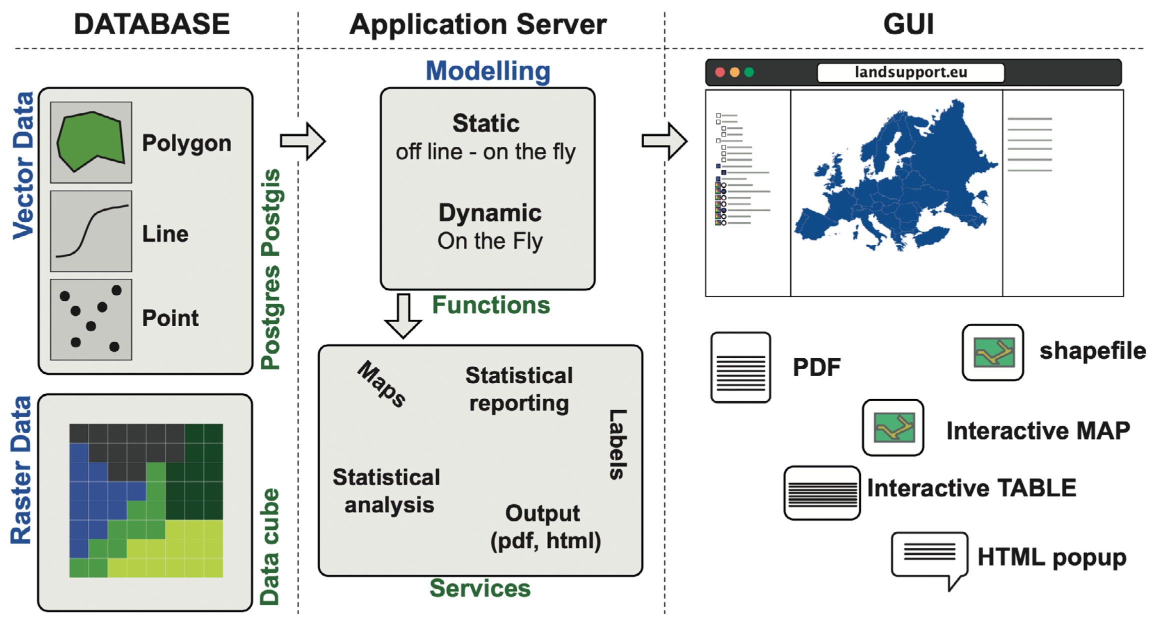

FIGURE 6 Architecture of the Landsupport geospatial cyberinfrastructure. [Colour figure can be viewed at wileyonlinelibrary.com]

statistics of the output parameters. This data cannot be pre-calculated as it depends on the specific ROI designed by the user at the time of the query.

2.3 | Co-development and testing of the LANDSUPPORT platform

Successful S-DSS tools indeed require a continuous process of co-development and testing of tools by end-users both during and after the release of the different tools.

This activity has covered all phases of the DSS development process, namely: (i) the preparatory phase with needs assessment; (ii) the testing phase and (iii) the technical dissemination phase, which was the final step of the process and aimed at making the LANDSUPPORT platform known to its potential users and enabling them to use the platform through targeted hands-on sessions and training.

In our case, co-development included different forms of feedback to the developers, depending on the issues raised, such as (i) semi-structured interviews, including requests and remarks from experts; (ii) e-mails describing problems in using tools and (iii) direct interaction with the developers. The feedback activities contributed to the co-development and co-creation of the S-DSS tools by identifying the main concerns of stakeholders concerning the tools. They also helped to establish a direct link between stakeholders and developers.

Assessment was made of users' judgments that emerged during the interviews regarding performance indicators, including interoperability, reliability, relevance for policy needs and overall satisfaction with the functionalities (usability and operational capacities) of the LANDSUPPORT DSS tools.

Here, we report some results: at the country level, the total number of institutions involved in the testing process in the three pilot countries (Italy, Austria and Hungary) is 55, and 367 people tested the tools. By category, the figures are as follows: 32 public institutions were involved and 127 people tested the tools. Regarding the actors of agriculture, environment and spatial planning, the numbers are 9, 5 and 9 for the institutions and 85, 106 and 49 for the people.

Throughout the duration of the project, 25 workshops were organised, involving 877 potential users and other stakeholders at European, national and regional levels and on tools belonging to different application areas. Throughout the duration of the project, the LANDSUPPORT platform received approximately 910 registrations and more than 4500 log-ins.

3 | CASE STUDIES

Some LANDSUPPORT case findings have already been published on pesticide leaching (Bancheri et al., 2022), groundwater vulnerability to nitrate (Bancheri et al., 2023) and ecotourism (Mileti et al., 2022). To highlight the functioning of the platform, we here report 2 case studies (in addition a third case on Sustainable Land Management [SLM] practices is reported in the Supplementary materials) being put to use aiming towards sustainable practices and lowering land degradation. These have been chosen to cover the different spatial extents: region, country and Europe.

Additional information on all case studies concerning both the environment (e.g. soil, geology, etc.) and local communities (e.g. NUTS4 population trends in the last decade) are available in other Landsupport tools (e.g. environmental report tool not explained in this paper).

TABLE 4 Some of the data layers stored in the Landsupport database (a more detailed version of this table is provided in the Supplementary material).

Scale		European	National: Italy	Regional: Marchfeld
Soil	Soil database/ map	SDGBE2.0 Soil Database (JRC, 1:1M)	Soil Provinces and Soil Regions map (ISPRA, 1:1M)	Soil type map (Marchfeld Region, 1:25k) plus dataset for physical soil properties
	Soil threats	WATEM_SEDEM water erosion map (JRC, 100 m res.)	WATEM_SEDEM water erosion map (JRC, 25 m res.)	
	Ecosystem Services	Mapping and Assessment of Ecosystems and their Services (EEA reference grid 10 km)	Maps of soil carbon stock, potential crop production, potential timber production (ISPRA)	Crop potential productivity map 2018 (Boku University, res. 10 m)[a]; Map of Ecosystem services
Land use	Land use/cover	Corine Land Cover 1990, 2000, 2006, 2012, 2018 (100 m res.)	Land use/land cover maps (CUCS Corine) 2012–2017 res. 10 m	Crop types map 2019; HR land cover map of Austria and Liechtenstein (2016)
	Land take	Imperviousness 2006, 2009, 2012, 2015, 2018 (Copernicus Land Monitoring Service, 20 m)	Imperviousness 2006, 2012, 2015, 2016, 2017, 2018, 2019, 2020 (ISPRA. 10 m res.)	Imperviousness 2006, 2009, 2012, 2015, 2018 (Copernicus Land Monitoring Service, 20 m res.)
Morphology	Elevation morphology	EU-DEM v1.0 (Copernicus Land Monitoring service, 25 m res.)	National DEM (ISPRA, 75 m and 20 m res.)	Regional DEM (Marchfeld, 10 m res.)
Geology	Geology and hydro-geology	European Geological map 1:1M 'OneGeology'	Geological map (ISPRA, 1:100k); Hydrogeological risk: Landslide risk areas (PAI-ISPRA) 2017	Geological map (Marchfeld Region, 1:250k); Groundwater isolines, water permeability
Water	Rivers and lakes	Groundwater bodies/surface water bodies (WF Directive)	Water and wetness 2015, 2018 (Copernicus Land Monitoring Service, 10 m res.)	Water and wetness 2015, 2018 (Copernicus Land Monitoring, 10 m); Rivers, lakes, reservoirs 2015, 1:10K
Meteorology and climatology		COSMOLEPS grib data (5.5 km res.); ERA5-Land from 1950 (9 km res.); COSMO-CLM data for Climate change data and indicators (8 km res.) by CMCC	COSMOLEPS grib data (5.5 km res.); ERA5-Land from 1950 (9 km res.); COSMO-CLM data for Climate change data and indicators (8 km res.) by CMCC	ERA5-Land from 1950 (9 km res.); Meteorological data of 4 measuring stations (1997–2016)
Biodiversity	Bio-diversity	Global Soil Biodiversity Atlas Maps; EU Ecosystems types (100 m res.); Natura 2000 sites (2017)	Natura 2000 sites 2006, 2012, 2018 (Copernicus Land Monitoring Service, 10 m res)	MAES habitat map, 2013 Natura 2000 network (EEA)
Green infrastructures	Landscape elements	Green Linear Elements (Copernicus Land Monitoring)	Street tree layer 2012, 2018 (Copernicus Land Monitoring Service, MMU 500 m^2)	Maps of landscape elements in agricultural land
	Biotypes	Riparian Zones (Copernicus Land Monitoring, MMU 0.5 ha)	Riparian Zones (Copernicus Land Monitoring, MMU 0.5 ha)	Riparian Zones (Copernicus Land Monitoring, MMU 0.5 ha)
Eurostat	Population and agriculture	EU Population data 2012–2018 – LAU2 NUTS2; EU_historical population (1961–2011) LAU2 LAU1	Population data 2012–2018 – LAU2 NUTS2; Historical population (1961–2011) LAU2 LAU1	
Others	Other data	SDG 15.3.1 maps Map of areas degraded, improved and stable (ISPRA, 2020)	GeOC data and maps Contextual Similarity Unit (CSU) maps	Example Ecotourism: Administrative units (ISTAT); Sites of natural and cultural (e.g. monuments) interest (from Open Street Map)[a]

Note: ISPRA: https://www.isprambiente.gov.it/en.
[a]Data are created during the project.

TABLE 5 Selection of models employed in Landsupport (a more detailed version of this table is provided in the Supplementary material).

Main themes	Models	Tools	Main functionalities	Main input	Main output
Crop production	*ARMOSA*: crop growth, H_2O, C and N balance, crop management	• Dynamic crop growth modelling • Dynamic crop growth modelling on your soil • Best practices • Underutilised crop growth	Dynamic on the fly	Meteorological forcing, soil parameters (texture, bulk density, SOC), cropping system (crop sequences, sowing and harvesting dates, residue management), irrigation, nitrogen fertilisation (i.e. mineral or organic, amount, timing, application depth) and tillage operations	Data set and maps on: • Yield • Nitrate leaching • SOC change
		• Best practices	Dynamic on the fly		As above + I_{BP} (Index of Best Practices)
Forest production	*MLFS*: Machine Learning based forest simulator	• Forest development dynamics	Static	Forest inventory data, year of the simulation, yield harvesting, RCP scenarios, mortality rate, thinning rate	pdf with Growing stock, basal area, harvested volume
Land degradation	*GEOCC*: sustainable land management options	• Sustainable land management (SLM) practices (LDN)	Static	Contextual similarity unit maps (describing social-ecological context) and database of sustainable land management practices	List of sustainable land management practices on the base of the selected ROI
	TFM-ext: Spatio-temporal distribution of nonpoint-source solutes along the unsaturated zone and towards the groundwater	• Intrinsic groundwater vulnerability • Groundwater vulnerability to nitrates and pesticides	Dynamic on the fly	Unsaturated hydraulic conductivity, meteorological forcing, solute input concentration (tracers, pesticides, fertilisers), first-order rate coefficient of transformation, water table depth.	Data set and maps on: • Depth arrival in a fixed time span of a solute. • Mean travel times of the input solute to a defined depth
Ecosystem services	*FLOWS-HAGES*: flows of water and solute transport in the soil–plant-atmosphere system	• Food production • Water regulation • Heat containment	Dynamic desktop based	Hydraulic properties, meteorological forcing (rain, ET), crop parameters (root depth, LAI, etc.), solute input concentration (tracers, pesticides, fertilisers), hydrodynamic dispersion and the first-order rate coefficients	Data set and maps on: • Crop water stress index • Groundwater recharge • Water storage • Days of potential runoff • Day of solute peak arrival • Actual evapotranspiration
	ARMOSA	• Biomass potential productivity: equivalent durum wheat production	Dynamic desktop based	As above (first row)	Data set and map of: Durum wheat yield
	Producer surplus (PS) indicator: Gross margins per crop and per unit of utilised agricultural area	• Estimated gross margin	Static	FADN (European Farm Accountancy Data Network)	Data set and map of: • Estimated gross margin of local durum wheat production

(Continues)

TABLE 5 (Continued)

Main themes	Models	Tools	Main functionalities	Main input	Main output
					(€ $year^{-1}$ ha^{-1})

Note: The models used in the 3 case studies reported below are reported with a grey background.
Abbreviation: SOC, soil organic carbon.

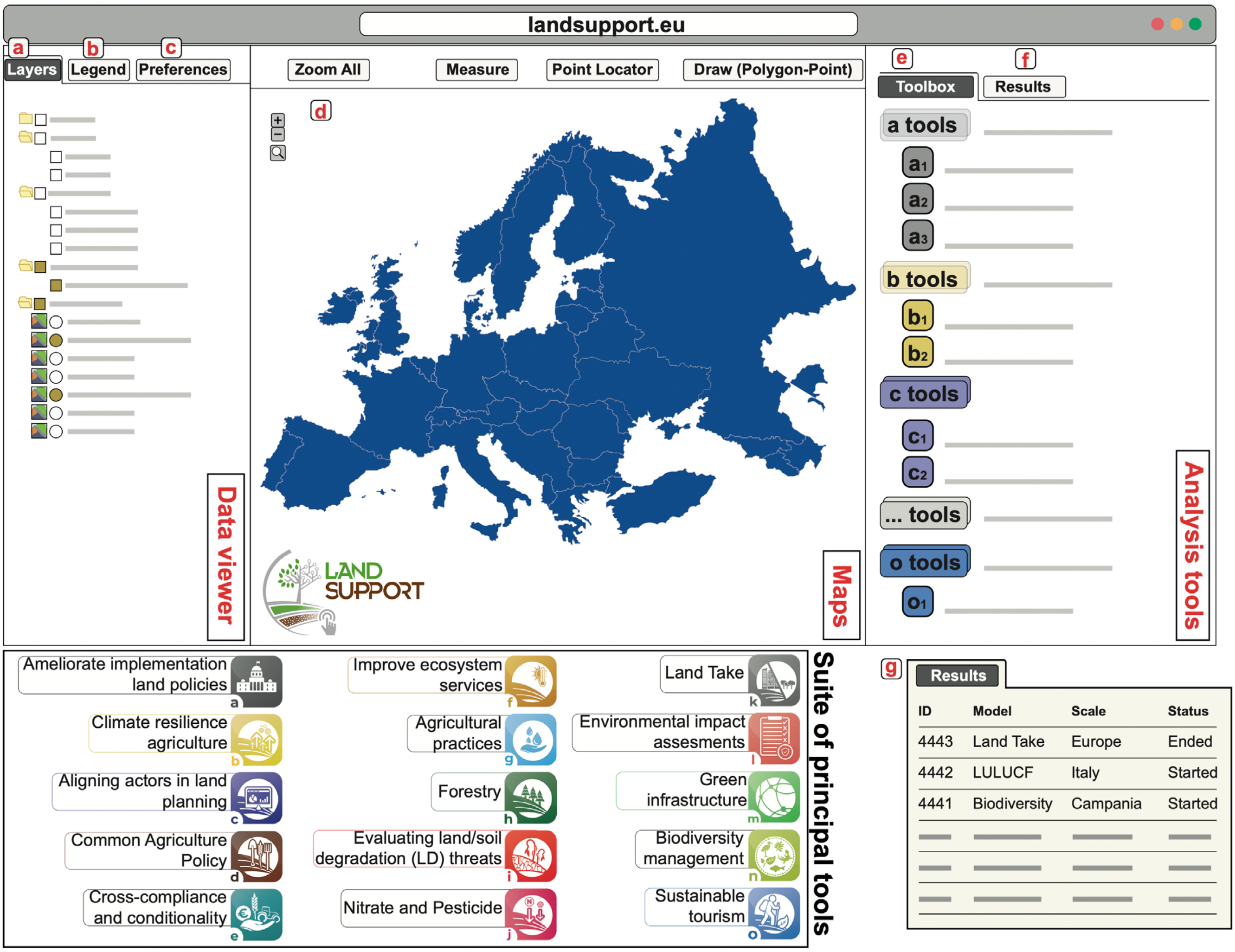

FIGURE 7 Scheme of the graphical user interface and its different panels. [Colour figure can be viewed at wileyonlinelibrary.com]

3.1 | Crop growth case study

3.1.1 | Background

The new fair, green and performance-based EU Common Agricultural Policy (2023–2027) will be a key item in securing a more sustainable future for agriculture and forestry, as well as achieving the objectives of the European Green Deal (e.g. combat land degradation). This Deal requires each EU country to design a national strategic CAP plan which, in addition to many other aspects, has to put into practice enhanced conditionality, eco-schemes and farm advisory services, as well as agri-environmental and climate measures and investments, to address the Green Deal targets (e.g. Farm to Fork Strategy, Biodiversity Strategy 2030).

For the best implementation of the strategic plans, the planned interventions (e.g. GAEC, SMR) should be designed *'considering* *characteristics of the areas concerned, including soil and climatic conditions, existing farming system, land use, crop rotation, farming practices and farm structures*' (territorial scope).

In this specific scenario, this example case addresses the following specific issue: in designing the Strategic Plan in line with the new Common Agricultural Policy (2023–2027), a national administrative authority aims to test, in a specific region, how different land use management scenarios have an impact on three ecosystem services, two of which are critical in terms of lowering land degradation: production, filtering capability and carbon sequestration.

3.1.2 | LANDSUPPORT crop growth tool solution

'Crop Growth' is a Landsupport tool that support the design of the Strategic Plan in line with the new Common Agricultural Policy.

The 'Crop Growth' tool performs crop growth modelling and produces results regarding crop yield, so enabling simulation of management scenarios. The tool runs, 'on the fly', through a model request that allows the user to carry out the simulation. The heart of the tool is ARMOSA (Analysis of cRopping systems for Management Optimisation and Sustainable Agriculture) process-based crop model (Perego et al., 2013; Valkama et al., 2020), which simulates the high level of complexity found in those agroecosystem processes which vary in response to agricultural management (i.e. crop rotation, intercropping, crop residues management, fertilisation, irrigation and tillage) and pedoclimatic conditions.

The user has to select the 'Crop Growth' tool and then he must choose between the following parameters: (i) the ROI; (ii) the date (start and end) of simulation; (iii) the crop rotations (on the basis of the local site); (iv) conventional agriculture versus organic farming (this choice is also associated with type of fertiliser); (v) occurrence of cover crop; (vi) irrigation management (either restoring 100% or 80% of crop requirement) and (vii) tillage (two options: ploughing at 30 cm depth or tillage limited at 15 cm in topsoil with no mixing of soil layers). The user can select also the type of output: (i) production (tons ha^{-1} $year^{-1}$) of each crop included in the rotation (for each simulated year), (ii) mean annual nitrate leaching (NO_3–N kg ha^{-1} $year^{-1}$) at the base of the soil profile and (iii) mean annual change of soil organic carbon stock in the 30 cm topsoil layer (% of changes per year).

Here, we report an example. In a predefined ROI, chosen in the Marchfeld region in Austria, two different land use management strategies were performed in the same 7 years of simulation (2012–2018).

> *Case 1 (organic approach - Table 1)*: Crop rotation = Clover + Wheat + Soybean + Wheat + Clover + Maize.

Irrigation = 100%; Fertilisation = Organic; Tillage = Minimum tillage; Residue = Yes.

In Table 6, we report the main results after using the crop growth too.

> *Case 2 (conventional approach - Table 2)*: Crop rotation = Sunflower + Maize; Irrigation = 100%; Fertilisation = Inorganic; Tillage = Conventional; Residue = No (resutls of this simulation are shown in Table 7).

From the above simulations, the user can obtain a clear quantification of the following ecosystem services: (i) crop production, (ii) soil filtering (Nitrate leaching) and (iii) C sequestration (SOC variation) capabilities, all performed under alternative crop rotations (with vs. without cover crop), fertilisation (mineral vs. organic), tillage (ploughing vs. minimum tillage) and crop residue management (retained vs. removed).

In this specific case, we observe that for the same area of 8.4 ha, in the case of raw soil, maize yield is 8.1 tons ha^{-1} $year^{-1}$ in *case 1* versus 10.4 tons ha^{-1} $year^{-1}$ in *case 2*; but this increase of 2 tons ha^{-1} $year^{-1}$ in annual production yield has a trade-off in terms of both (i) N leaching, which increases from 55.9 kg NO_3–N ha^{-1} $year^{-1}$ (*case 1*) to 129.2 kg NO_3–N ha^{-1} $year^{-1}$ (*case 2*) and (ii) annual SOC, which shows an increase of 0.53% for case 1 and a decrease of – 0.14% for case 2.

This tool was shown to be beneficial for consortia/cooperative of farmers and Public Administrations (e.g. Administrative Regions), and for those interested in quantifying crop production and connected environmental trade-offs. For instance, nitrate leaching and C sequestration in soil maybe be conflicting under diverse field management

TABLE 6 Results after the use of the crop growth tool in the first land use management case in Marchfeld region (Austria).

Crop	Soil type	Area (ha)	Area (%)	Prod (ton ha^{-1} $year^{-1}$)	N-leach (kg NO_3–N ha^{-1} $year^{-1}$)	SOC-change (% $year^{-1}$)
Clover	Chernozem	10.9	5.3	1.4	14.8	1.10
Soybean	Chernozem	10.9	5.3	2.4	14.8	1.10
Wheat	Chernozem	10.9	5.3	8.3	14.8	1.10
Maize	Raw soil	8.4	4.1	8.1	55.9	0.53
Clover	Raw soil	8.4	4.1	1.4	55.9	0.53
Soybean	Raw soil	8.4	4.1	2.3	55.9	0.53
Wheat	Raw soil	8.4	4.1	5.4	55.9	0.53
Maize	Raw soil	24.1	11.7	7.5	2.1	0.08
-	-	-	-	-	-	-

TABLE 7 Results after the use of the crop growth tool in the second land use management case in Marchfeld region (Austria).

Crop	Soil type	Area (ha)	Area (%)	Prod (ton ha^{-1} $year^{-1}$)	N-leach (kg NO_3-–N ha^{-1} $year^{-1}$)	SOC-change (% $year^{-1}$)
Sunflower	Chernozem	10.9	5.3	3.5	100.5	−0.14
Maize	Chernozem	10.9	5.3	9.5	100.5	−0.14
Sunflower	Raw soil	8.4	4.1	3.5	129.2	−0.13
Maize	Raw soil	8.4	4.1	10.4	129.2	−0.13
Sunflower	Raw soil	24.0	11.7	3.5	44.1	0.02
-	-	-	-	-	-	-

TABLE 8 Description of plots captured by the region of interest.

Plot ID	Growing stock (m^3 ha^{-1})	Basal area (m^2 ha^{-1})	Harvested volume (m^3 ha^{-1} $year^{-1}$)
197038	459.74	50.69	9.75
204464	109.32	14.0	3.13
-	-	-	-

scenarios. In addition, through the tool, the farmer can estimate the possible change in the production of currently cultivated crops by moving from conventional agriculture to conservation agriculture, and therefore reduce production costs over time and improve soil fertility.

3.2 | Forestry case study

3.2.1 | Background

Forest ecosystems fulfil and provide crucial functions and services to humanity, among which are biodiversity, protection against natural hazards and carbon sequestration. The new EU Forest Strategy for 2030 is one of the 'flagship initiatives' of the European Green Deal and builds on the EU biodiversity strategy for 2030. The strategy sets out specific actions to: (i) improve the quantity and quality of EU forests and strengthen their protection, restoration and resilience; (ii) adapt Europe's forests to the new conditions (e.g. climate change) and (iii) support the socio-economic functions of forests. To achieve these targets, calibrated interventions, based on a deep understanding of environmental and socioeconomic components, are required.

3.2.2 | LANDSUPPORT MLFS tool solution

Here, we aim to demonstrate the Forest tool named 'MLFS (Machine Learning Forest Simulator)', which is a decision-making tool designed to understand the dynamics of forest development at various scales based on forest inventory data developed in the R environment (https://cran.r-project.org/web/packages/MLFS/index.html). The tool allows, through simulation, to better understand the impact of forest management on forest growth. The latter is quantified through the simulation of 3 parameters: growing stock (m^3 ha^{-1}), basal area (m^2 ha^{-1}) and harvested volume (m^3 ha^{-1} $year^{-1}$).

The user using the 'MLFS tool' will be able, to select between the following parameters to be employed by the simulation process: (i) ROI (freely drawn or selected from administrative NUTS4 – NUTS3 areas); (ii) year of the simulation; (iii) harvesting yield (which represents the simulation of the intensity of forest cutting as a percentage); (iv) RCP scenarios (RCP: 4.5 and 8.5 on the basis of GHG emissions until 2100); (v) mortality rate (which is made on the basis of local conditions) and (vi) thinning rate, affecting future growing dynamics.

Finally, MLFS supports a wide range of plot-designs and data types and can be applied to various forest types, from monocultures to forests with rich species compositions.

The tool produces two tables as outputs. The first table (given here as Table 8) reports for each forest plot captured by the ROI, the three parameters discussed above, namely: groeing stock, basal area and harvested volume.

The tool will then produce a second table (not reported) with the basic statistics (count, mean, min, max, standard deviation, 25% percentile, 50% percentile and 75% percentile) about growing stock, basal area and harvested volume for the entire selected ROI.

To highlight the importance of local pedoclimatic settings over management practices, we performed a sensitivity analysis using the forestry tool.

In Figure 8, a boxplot is reported where the numbers identifying 30 different ROIs (forest plot) of the same size (about 0.1 ha) and circular shape are given on the *x*-axis while the mean of harvested volume (m^3 ha^{-1} $year^{-1}$) estimated for the year 2030, considering all possible combinations of four variables (yield harvesting, thinning, mortality and RCP scenario), is reported on the *y*-axis. The 30 ROIs are randomly located within a 457 km^2 area of Slovenia, between Trebnje (immediately north) and Semič (south-west). For the sake of clarity in reading the figure, the ROI was ranked from the lowest to the highest values of harvested volume.

The horizontal line within the box marks is the median value. The box contains the middle 50% of the data points (IQR) and is a measure of data variability while the vertical bar for each ROI represents the upper and lower fences of the harvested volume based on all combinations of the variables.

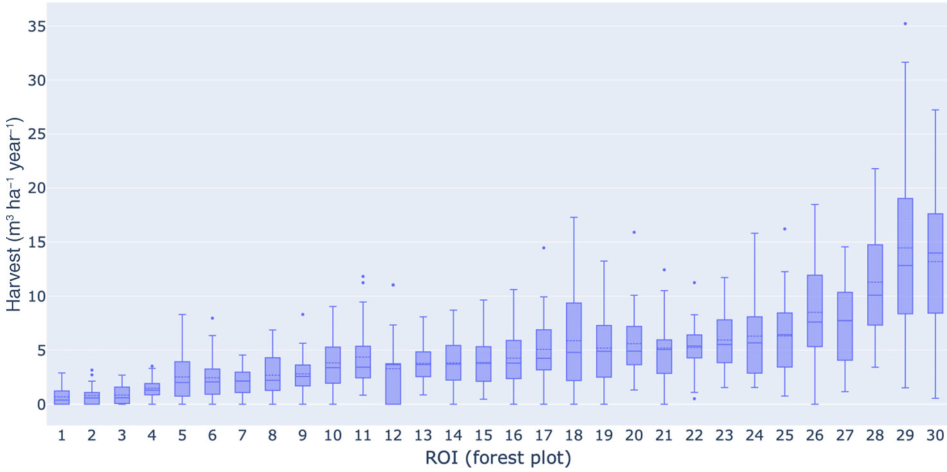

FIGURE 8 Sensitivity analysis of the harvest in the different region of interests (ROIs) (forest plot). [Colour figure can be viewed at wileyonlinelibrary.com]

The sensitivity analysis emphasises the existence of sites (e.g. sites 18, 24 26, 28, 29 and 30) where changes in yield harvesting, thinning rate, mortality rate and RCP scenario have a huge impact on harvest, while there are other sites (e.g. ROI 1, 2, 4, 7, 9 and 22) where the impact of the three management variables and RCP scenarios have a minimum impact on the growing stock.

This tool supports different users such as (i) forestry authorities to carry out scenario analysis and thus better fine-tune management practices on the basis of specific local settings, (ii) scientists interested in the long-term effects of environmental factors and climate on forest development and finally (iii) forest professionals and engineers, who can use the tool as a decision-making support in their forest planning process.

4 | CONCLUSION

This work starts by acknowledging that the vast availability of data (e.g. from satellites, sensors and drones), policies (e.g. SDGs, EU environmental policies) and stakeholder engagements (e.g. EIP-AGRI) are not enough to have a positive impact on sustainable land management, especially considering that land degradation is worsening to a tipping point at which it will be difficult or impossible to reverse it. We assert that agriculture, forestry and environmental protection require something additional to the information at present accessible to address some key shortcomings due to: (i) the great physical and socio-economic multifaceted complexity of the landscape and land degradation processes, (ii) the lack of a truly integrated physical approach to many agriculture/environmental problems, (iii) the lack of factual scientific support for both farmers and regional governments so as to support the adoption of sustainable agriculture practices, (iv) the fragmentation of current approaches, models and DSS tools dealing with agriculture and environmental protection and (v) difficulties in the implementation of the many good policies aimed at improving the environment and agriculture.

Our vision is that robust operational S-DSS are the way forward to translate data availability into positive actions towards sustainability thus challenging land degradation. This was the starting point of the EU-funded LANDSUPPORT project, which brought together 19 partners from 10 different countries across Europe, the Middle East and Asia and developed 15 macro-tools (and more than 100 elementary tools) by establishing a free web-based smart geospatial decision support system. This system is based on Geospatial Cyber-Infrastructure IT architecture applied to the better implementation of a large set of EU, national and regional policies in the field of agriculture, forestry and the environment.

The system brings together diverse sources of data including Sentinel satellites (from the EU's Copernicus programme), advanced climate and ECZ modelling, various technologies (e.g. datacube and parallel processing) and stakeholder engagement to develop and test the tools. All this complexity is 'hidden' behind an easy-to-use graphical user interface that has been created to enable end-users to easily access and work on the LANDSUPPORT platform.

Here, we have shown that it is possible to overcome the current fragmentation of data and models by combining the following features into a single system: (i) a user-friendly GUI where all complexity is hidden; (ii) implementation of the concept of the operational multifunctionality of land and soil; (iii) adaptability to many different needs of end-users; (iv) implementation of 'what-if' modelling, so empowering the choices of the end-users (In this sense, we want to emphasise here that the system does not aim to provide the 'solution', but rather provide a set of 'options' for the user to choose from); (v) low cost of transferability of the approach to new areas and (vi) incorporation of bottom-up contributions from users (e.g. uploading of ROI or local soil data).

The platform has been demonstrated here through three cases dealing with sustainable management practices in agriculture and forestry to lower land degradation processes. In the three case studies (one is reported in Supplementary materials), this is achieved by producing results and stats on sustainable crop growth, forestry and sustainable land management.

In terms of the future and legacy, the LANDSUPPORT platform will remain operational, open and free long after the project ends. This position is rooted in the evidence showing that we need to leave these tools as open as possible and engage as much as possible with a large community of users if we are to protect soils and land. Currently, there is great interest from such stakeholders as public administrators, cooperatives, farmer associations, spatial planner associations, natural parks and metropolitan areas. Actually, members of the Italian Parliament proposed at the Italian Senate a new soil law on the basis of LANDSUPPORT (soil legislative bill n. ddl 2614). In addition, the project has received two awards (EU Success Story and Falling Walls global winner), which makes it hopeful that a widening of use, adoption and scope is welcome and possible.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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