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To cite this article: Francesca Poggi, Selma Pena, Natália Cunha, Ana Müller & Beatriz Romão (2025) Digital land-use decision support tools in Europe: a systematic review using the PRISMA method, *European Planning Studies*, 33:10, 1840-1863, DOI: [10.1080/09654313.2025.2524002](https://doi.org/10.1080/09654313.2025.2524002)

To link to this article: <https://doi.org/10.1080/09654313.2025.2524002>



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Digital land-use decision support tools in Europe: a systematic review using the PRISMA method

Francesca Poggi ^a, Selma Pena ^b, Natália Cunha ^b, Ana Müller ^b and Beatriz Romão ^a

^aCICS.NOVA - Centro Interdisciplinar de Ciências Sociais/Faculdade de Ciências Sociais e Humanas, Universidade Nova de Lisboa, Lisbon, Portugal; ^bLEAF Linking Landscape, Environment, Agriculture and Food Research Center, Associate Laboratory TERRA, Instituto Superior de Agronomia, Universidade de Lisboa

ABSTRACT

Decision-making for sustainable land use transformations is a key driver of society's future development, particularly in addressing complex threats posed by climate change and biodiversity loss. Digital tools represent promising technologies that can support decision-makers in facing these challenges. However, existing literature reveals a gap in studies exploring digital tools within the land-use decision framework. The present study uses the PRISMA methodology to systematically review digital tools in Europe. As a result, 48 digital tools were identified and analysed regarding their functionalities, limitations, and adoption factors. The findings highlight the prevalence of spatially explicit outputs and key functions such as interaction and visualization, scenario modelling, and stakeholder engagement. Despite their potential, challenges remain, including barriers to accessibility, the need to enhance trust in tool outputs, and an overall lack of digital literacy that could further promote the adoption of these tools. This study thus provides co-development recommendations gathered from interviews with five tool developers and systematic review analysis. By addressing the identified barriers and fostering digital literacy, digital tools can provide valuable contributions in supporting sustainable land use decisions, bridging the gap between data-driven insights and real-world complexity.

ARTICLE HISTORY



Received 5 January 2025
Revised 21 March 2025
Accepted 19 June 2025


KEYWORDS

Digitalization; sustainable land-use; decision-making; decision support tools; decision support system; digital literacy

1. Introduction

The transition of our society through a Digital Era undeniably represents the most recent long wave of humanity's socio-economic evolution (Hilbert 2020). This technological paradigm shift represents an upscaling process that has clearly showcased its transformative potential across various sectors, including its economic, social, cultural, and political

CONTACT Francesca Poggi  fpoggi@fcsh.unl.pt  CICS.NOVA - Centro Interdisciplinar de Ciências Sociais/Faculdade de Ciências Sociais e Humanas, Universidade Nova de Lisboa, 1099-085, Lisbon, Portugal

 Supplemental data for this article can be accessed online at <https://doi.org/10.1080/09654313.2025.2524002>.

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organization (Hilbert 2020). This aligns with the demand for efficient and effective solutions associated with rapid economic innovation, social acceleration, and environmental change.

In the social sciences, digital transformation has become a subject that has raised several intriguing questions since the early 1990s, particularly in governance and spatial planning, where it presents new opportunities for enhancing political decision-making, stakeholder engagement (Hafferty et al. 2024), participatory methods (Wagner, Vogt, and Kabst 2016) and influencing advancements in reshaping socio-spatial relation (Ash, Kitchin, and Leszczynski 2018). Within this perspective, scientists have followed the economists' lead, exploring the impact of rapid technological change on public decision-making (van Kersbergen and Vis 2022), demonstrating how digital tools offer new opportunities for participation in international policies (Hafferty et al. 2024) and related decision-making (Noennig 2022). Using digital tools in stakeholder participation, for example, including co-creation, co-design, interaction, engagement, and involvement in innovation and decision-making processes, is one of the most recent and practical fields of application as they improve the value creation in projects in a multidimensional way and at different levels (Toukola and Ahola 2022). Notably, the increasing use of digital tools can also be identified in citizen participation (Hovik et al. 2022), opening new forms of public governance (Shin et al. 2024).

These approaches are particularly relevant when intervention scales shift to the complexity of the regions, cities and local communities, where digital tools support cross-sectoral decision-making processes related to governance, policies and spatial planning. Understanding and managing land use transformations is an urgent and complex domain that must be addressed in light of changing drivers, multiple actors, and significant impacts on climate, biodiversity, and the environment, among many other processes. Furthermore, the recent rapid changes in land use due to substantial societal development and population growth necessitate the consideration of three critical factors, such as time, intensity, and uncertainty, as new driving forces to be controlled. Due to the need to consider complex dimensions for decision-making and the involvement of different stakeholders, it is undeniable that using digital tools can lead to making more informed choices in a shorter time.

Decision-makers worldwide have long used digital tools to address complex topics such as urban planning and development (Hammond et al. 2023), environmental sustainability (Goel, Masurkar, and Pathade 2024), integration of ecosystem services (Grêt-Regamey et al. 2017), spatial planning and land-use planning (Hersperger et al. 2022). At these levels, the digital transition represents an opportunity to address the complexity of decision-making, considering several dimensions, such as space-related processes, interaction among different actors and entities, and resource optimization and management. However, digital tools related to land use decision-making vary significantly in types, functions, and scopes, ranging from 'Mapping and Monitoring Approaches' to 'Planning, Decision Support, and Participation', as highlighted by Hecht, Behnisch, and Herold (2020). Several recent studies have examined the literature on digital tools for land-use decisions. For example, Liu et al. (2024) comprehensively review the development of land-use planning tools from a time evolution perspective. Hong (2024) systematically reviews planning support systems but focuses only on China. Wagner and de Vries (2019) present a comparative review of a selected set of digital tools which support decision-making processes in urban development and land

management. However, they evaluate only three specific technologies: cellular automata, artificial intelligence, and operational research.

Additionally, the scoping review developed by Tefera et al. (2023) discloses that decision support processes in digital formats are still in an emerging phase regarding urban planning. The analysis of the insights derived from these reviews illustrates theoretical frameworks or technology-specific methodologies pertinent to digital tools, highlighting the relevance and novelty of this topic. However, it also identifies a gap, as no review is focused explicitly on systematising and characterizing existing digital tools that support land-use decision-making.

The present study aims to address this gap by reviewing digital tools for land-use decision-making in Europe and providing knowledge for adding substantial value to digital literacy among stakeholders engaged in these processes. The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework (Page et al. 2021) is adopted to ensure a rigorous and transparent systematic review. While this method has been widely applied in medical research to document health protocols, its principles are equally relevant in reviewing the extensive and dispersed information on digital tools. In doing this, the study also aims to provide a methodological contribution to the replicability of this approach.

The study's objectives thus include mapping the current landscape of European digital tools and examining their types, policy domains, scales, functions, and outputs. Additionally, it identifies significant barriers and factors affecting stakeholders' adoption of these tools, seeking to address one of the most significant challenges in the digitalization of decision-making processes.

The research is structured around the following three key research questions (RQs):

RQ1 – What are the common types of digital land-use decision support tools available in Europe?

RQ2 – What key features and functionalities are typically found in them?

RQ3 – What are the main barriers and recommendations for their uptake?

To address these RQs, this study begins with a review of the literature on the definitions and concepts associated with digital tools and their role in land-use decision-making. It then explains the PRISMA methodology and its application in systematically identifying relevant digital tools across Europe. The results present a detailed analysis of 48 digital tools, highlighting trends, functionalities, barriers to adoption, and co-development recommendations to increase their uptake. The discussions and conclusions contribute to the ongoing dialogue on how digital tools can aid complex spatial planning processes and policy frameworks by connecting digitalization with land-use decision-making.

2. Defining digital land-use decision support tools

This section examines how existing literature defines digital tools and their relationships to decision support in land use, highlighting two interconnected key concepts: Decision Support Tools (DST) and Decision Support Systems (DSS).

DST refers to frameworks, methods, guides, techniques, procedures, and analytic approaches targeted at a specific group to inform decision-making (Chazdon and

Guariguata 2018). The DSS is a computer-based system that represents and processes knowledge in ways that allow decision-making to be more productive, agile, innovative, and/or reputable (Power 2008).

Literature on DSTs is extensive and diverse. They have been developed and adopted to aid decision-making across scales and various disciplines for problem-solving, appraising projects and environmental modelling (Mabhaudhi et al. 2023). In particular, over the last few decades, there has been a rise in DSTs intended to help stakeholders make higher-quality decisions to manage environmental risk (Wong-Parodi et al. 2020) and the broader challenge of sustainable development in different contexts, such as agri-food production (Arulnathan et al. 2020) and agroforestry (Ellis, Bentrup, and Schoeneberger 2004), coastal planning (Barzehkar et al. 2021), urban development (Kapelan, Savic, and Walters 2005).

Unlike the DSTs, the DSSs reflect the advancements of the twenty-first century. They are intrinsically associated with the progress of the Internet, the Web, and telecommunications technology within an increasingly more global, complex, and connected society (Shim et al. 2002). Current trends in DSS highlight growing interest in using Big Data and web-based technologies (Talari et al. 2022). In this sense, DSSs are developed to address the overflow of information and knowledge, supporting decision-makers in choosing the best compromise (Razmak and Aouni 2015). One of the most interesting functions of DDS is thus to provide decision-makers with analysis, information, recommendations, and environments to test different scenarios (Elkady, Hernantes, and Labaka 2024).

Introducing the digital dimension associated with land use leads to the focus of the present review on digitalization and the technologies applied to support decision-making in this field. Digital is a crucial concept in defining a digital land-use decision support tool. This definition excludes tools related to methods, instruments, frameworks, or models. It highlights the specific tools that fall under digital planning. These tools encompass a wide range, from online or social media platforms to apps and gaming devices (Wargent 2023).

The relevance of shedding scientific light on this topic revolves around its multi-faced and novel nature. This includes designing, deploying and adopting digital tools to provide innovative ways that assist private and public stakeholder groups in understanding changes in urban and rural areas and support their decisions towards determined development goals. Such digital tools help communicate change to all those interested and undertake pilot activities to support better understanding and involvement in planning decision-making. In this framework, Shin et al. (2024) reveal how self-organizing, community-based, and digital technologies characterize the rapidly changing landscape of citizen participation.

This is the general essence of how and for what digital tools are used, revealing the importance of systematising the knowledge on available technologies to understand which would best suit supporting land-use change decisions and what the potentials and limitations of existing digital tools are to then co-develop recommendations for increasing their uptake in decision-making processes.

In conclusion, a Digital Land-Use Decision Support Tool can be defined as an interactive, computer-based system designed to assist decision-makers in analysing, planning, and managing land-use changes. These tools integrate the functionality of traditional DST, which provides structured methods and frameworks for project assessment and

decision support across various scales and disciplines, with the enhanced data processing, accessibility, and scenario-testing capabilities of DSS.

3. Materials and methods

This section outlines the systematic literature review (SLR) method employed to identify existing digital tools pertinent to the specified topic of supporting land-use decisions in Europe.

Among the different methods and techniques to carry out SRL (García-Holgado, Marcos-Pablos, and García-Peñalvo 2020), the present study adopts the PRISMA method – Preferred Reporting Items for Systematic Reviews and Meta-Analyses (Page et al. 2021). Developed in 2009 to conduct systematic reviews on a broader array of questions for developing clinical practice guidelines, the PRISMA method is used to cover any systematic review, not just those whose objective is to summarize the benefits and harms of a healthcare intervention (Moher et al. 2010). Within this framework, the PRISMA method ensures a high-quality research process to collate and synthesize findings of studies that address the research questions.

The subsections below outline how this study has implemented the PRISMA method, following the checklist published by Page et al. (2021), the Systematic Research Projects Reviews guideline by García-Holgado, Marcos-Pablos, and García-Peñalvo (2020) and the work of Grêt-Regamey et al. (2017), which successfully adopted PRISMA to systematically review decision support tools to operationalize the ecosystem services concept.

Recognizing both the need and opportunity to enhance the adoption of digital tools, this study provides co-developed recommendations based on a systematic review analysis. These recommendations incorporate specific insights from interviews with five developers of the digital tools listed in Table 1. The interviews, conducted via video conference in September 2024, lasted between 45 and 60 min each.

3.1. Information source and search strategy

The first step of the present SRL has been to select the databases, registers, websites, organizations, reference lists, and other sources to identify studies. Due to this

Table 1. References of the five digital tools selected for developers' interviews.

Digital Tool	Developer	Country	Online Link	Interviewed Date
Crafty	KIT – Karlsruher Institut fuer Technologie	Germany	https://landchange.imk-ifu.kit.edu/CRAFTY	September 30, 2024
Dynamic Energy Atlas	VITO – Vlaamse Instelling voor Technologisch Onderzoek	Belgium	https://vito.be/en/news/how-much-renewable-electricity-can-be-generated-within-belgian-borders-dynamic-energy-atlas	September 19, 2024
Swiss SolarWind Explorer	ETH Zurich	Switzerland	https://swiss-solarwind-explorer.ethz.ch/	September 20, 2024
EPICWebGIS	ISA – Instituto Superior de Agronomia	Portugal	http://epic-webgis-portugal.isa.ulisboa.pt/	September 23, 2024
Nature Value Explorer	VITO – Vlaamse Instelling voor Technologisch Onderzoek	Belgium	https://www.natuurwaardeverkenner.be/	September 24, 2024

review's scientific aims and the expected practical outputs' relevance, the primary search database has been the CORDIS platform – Community Research and Development Information Service (<https://cordis.europa.eu>). This database is a rich and structured public repository with all the results from the projects funded by the European Union (EU)'s framework programmes for research and innovation. Including CORDIS in this literature review is relevant for gathering insights from EU projects that have developed digital tools and services collecting data that is not always available in scientific publications.

Then, Web of Science (WOS) and Scopus electronic databases were selected for scientific publications. These databases include documents from different publishers, allowing full-length searches or searches only in specific fields of the works, filtering options such as publication year or publication language and using logical expressions or a similar mechanism (García-Holgado, Marcos-Pablos, and García-Peñalvo 2020).

Secondary sources, such as the grey literature, including governmental, enterprise, and academic reports and websites, were identified using the Google search engine and the predefined query to ensure comprehensive coverage.

Finally, we also conducted a search based on an internal survey of the EU MOSAIC project (<https://www.mosaic-europe.eu/>) from January to February 2024 to enrich the PRISMA workflow by incorporating insights from 19 partners experienced in developing and utilizing digital tools.

The search strategy employed across the three databases, CORDIS, WOS, and Scopus, is founded on a process that utilizes a common query string: 'Digital AND tool AND decision support system AND land-use' for records from 2000 to 2023. Specific filters were applied according to the respective database: in CORDIS, records were filtered based on fields of science such as Society, Climate Change and Environment, Energy, Food, and Natural Resources, whereas in WOS and Scopus, the search was limited to the titles and abstracts of journal articles.

The Boolean operator 'AND' has been adopted to find results with information common to the search terms. This approach narrows the relationship between digital tools, decision support systems, and land use. Other tests were performed using the query string 'digital AND land-use OR land AND use AND tool OR method OR approach AND decision AND support,' but this was excluded as it produced an overwhelming number of results that would be difficult to analyse thoroughly. In this sense, the query integrates 'Digital,' 'tool,' and 'decision support system,' encompassing both DST and DSS related to 'land use'. The period from 2000 to 2023 has been selected as the most representative of progress in the digitalization process.

Using the PRISMA method sequence of steps,, the search led to the identification of **109 registers (journal articles)**, including 44 entries from SCOPUS and 65 from WOS; **90 registers (research projects)** from CORDIS; **29 registers (digital tools)** from the internal survey and **14 registers (digital tools)** from grey literature sources.

While the results from CORDIS and the other sources are ready to proceed to the screening phase, registers from Scopus and WOS need to pass through a preliminary stage that involves removing duplicate records. In this way, 19 journal articles published in both databases have been removed, limiting the number of records for screening to 90 (Figure 1).

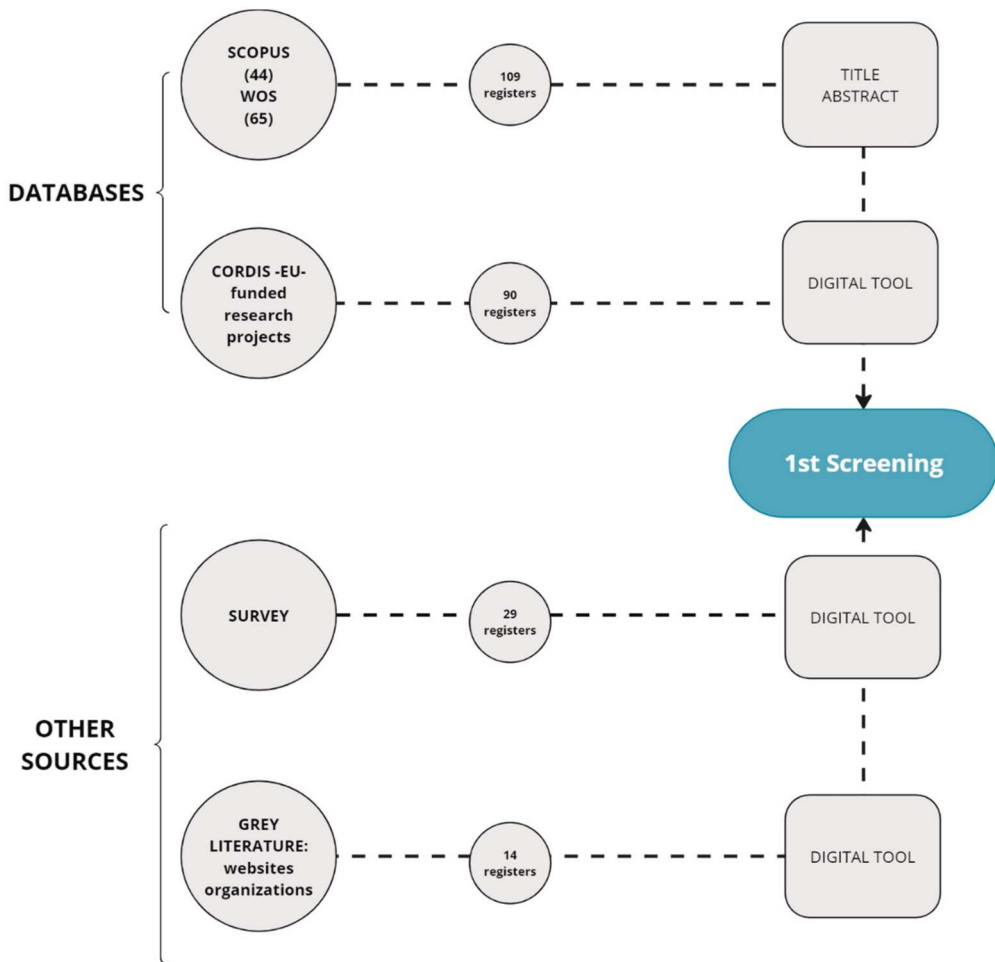


Figure 1. Synthesizes the relationships in acquiring records from databases and other sources.

3.2. Exclusion criteria

This section describes the exclusion criteria adopted to guarantee that the study has been conducted according to the key principles of a high-quality systematic review conducted using PRISMA. Given the various record types, the exclusion criteria had to be tailored to each database's output. This involved recognizing some criteria that apply universally and others that needed to be customized based on the specific characteristics of the analysed record.

The first common criteria is a **scope-related**, which follows the pertinence of the digital tool associated with the interpretation and understanding of a diversity of land-use-related challenges, including climate change, renewable energy and biodiversity. From this lens, several records associated with digital tools developed to support decisions in domains indirectly related to land use have been excluded throughout the screening.

The second exclusion condition relates to **technological criteria**: the digital tool must be accessible for analysis and testing; otherwise, it cannot be considered within the review. Such criteria is specific to the nature of digital tools as they are commonly online platforms, desktop applications, software, mobile apps, and cloud services that could be outdated, inactive or inaccessible, guaranteeing the consistency and reliability of the final outputs for analysis.

The third criteria is **geographical**, excluding digital tools not developed for the European context. Although it may appear restrictive, the range of digital tools from Europe improves the analysis of local data, regulatory needs, privacy and security standards, effectively addressing the unique challenges and priorities of the European socio-economic, environmental, political, and technological landscape.

For WOS and Scopus records, which are associated with journal articles, a second screening stage has been implemented, following two specific exclusion criteria, namely:

- **Manuscript Not Found** – when a manuscript cannot be located even after extensive searching and attempts to contact the authors through email;
- **Manuscript Not in English or Written in Non-Latin Scripts** – when a manuscript is not written in English, especially in languages using non-Latin scripts such as Cyrillic, Arabic, Chinese, or Japanese. The barriers to these manuscripts lie in their translation and interpretation of the contents.

By applying these exclusion criteria, the present systematic review process ensures that only accessible and relevant manuscripts are included, maintaining scientific rigour and quality. Manuscripts that cannot be located despite efforts to contact the authors or those in languages with non-Latin scripts have been excluded to prevent gaps in the review and ensure consistency and comprehensibility.

3.3. Screening

The present section focuses on the screening process once the exclusion criteria have been described and justified. This process is designed to systematically select the records to identify studies that are relevant, accessible, and meet the criteria for inclusion in the final digital portfolio.

Within the PRISMA method, screening is typically a multi-stage process in which potentially eligible studies are first identified from screening titles and abstracts, then assessed through a full-text review (Page et al. 2021). In this context, it is worth noting that the current review has concentrated on the CORDIS database and the findings of an internal survey regarding research projects, in addition to the traditional databases of Scopus and WOS (journal articles).

From a scientific perspective, this aspect is relevant as it opens one of the main challenges of this review: addressing a different screening process between research projects and scientific literature. As García-Holgado, Marcos-Pablos, and García-Peñalvo (2020) mention, no established methodology allows for systematically analysing the studies and progress made through research projects in a specific area or topic. In this sense, the proposed screening process is novel and could be considered a contribution to the systematic review literature related to applying the PRISMA method. According to this method, the screening has been divided into two stages.

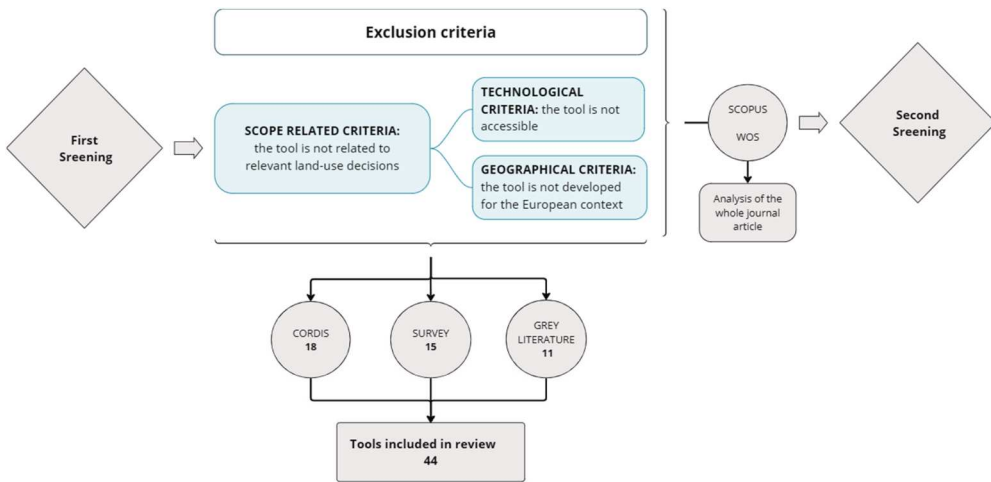


Figure 2. First Screening stage.

The first screening adopted the three common exclusion criteria for all the source information (). This approach has led to harmonising the records with the data extraction, which excludes some digital tools collected from CORDIS, the internal survey and grey literature. In particular, some of the digital tools suggested in the internal survey overlap with the other two databases, requiring a screening process to eliminate duplicate records. Then, applying the scope-related, technological and geographical criteria led to selecting 18 digital tools from CORDIS, 15 from the survey and 11 from the grey literature [Figure 2](#).

In this review process, a second screening stage has been necessary due to the nature of the records in Scopus and WOS databases (). This has involved applying specific criteria to identify manuscripts currently unavailable online, not in English, or written in non-Latin scripts, particularly with journal articles [Figure 3](#).

Screening of records from Scopus and WOS has been more complex due to the inaccuracy of the records when facing the search string and the fact that several journal articles have been excluded because they do not refer to or present any digital tools.

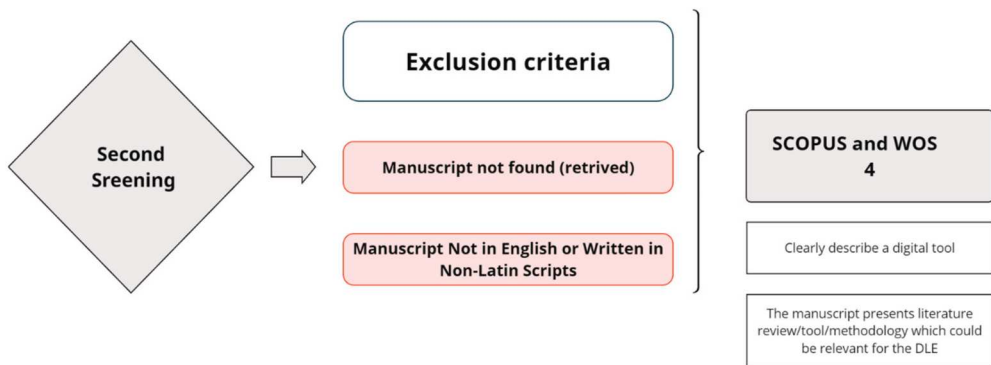


Figure 3. Second screening stage.

This was demonstrated by the final selection of only four journal articles that described and referenced accessible digital tools.

From the two screening stages, 48 digital tools related to land use decisions have been selected. These tools are fully operational and open access and will be described and analysed in the next section of the results.

The interview guide has been regraded to gather information about key motivations and barriers for the uptake in line with the following two open questions:

1. Could you describe the key motivations and barriers for the uptake of your digital tool?
2. How could be increased the uptake of (existing) tools and co-develop recommendations, also with the end-user?

4. Results

The systematic review has identified previous research projects and studies associated with digital land-use decision support tools (Table 2). The results of the systematic review of digital land-use decision support tools were also compiled into a list that includes 48 digital tools (see Appendix A) developed for improved information organization.

Most digital tools are developed by universities or research institutes (Figure 4), driving innovation on this topic. The timeline reveals a concentration of tools launched after 2013, with a peak of eight tools launched in 2018. The oldest tool recorded is from 2003 (ZONATION – <https://zonationteam.github.io/Zonation5/>), and the most recent is from 2025 (<https://swiss-solarwind-explorer-v1.ethz.ch/>) (Figure 5).

Regarding country of origin, EU consortia have developed a significant stake, and eleven single countries have produced digital tools (Figure 6). The results also include three tools developed by entities located outside Europe but with applications in Europe: UNBiodiversity Lab (<https://unbiodiversitylab.org/en/>), InVEST® (<https://naturalcapitalproject.stanford.edu/software/invest/>), and the Global Forest Watch (<https://www.globalforestwatch.org/>).

Table 2. List of 48 digital tools, classified by each source.

Source / Data Base	Number	[ID number] tool Name
CORDIS	18	[1] CO-IMPACT [2] ECOPotential view [3] ERA-PLANET [4] GROW [5] GROW GREEN [6] iSQAPER [7] LANDSENSE [8] MySustainableForest [9] NAIAD [10] NATURVATION [11] NBS Simulation Visualisation Tool [12] OPERANDUM [13] RECARE [14] RUBIZMO [15] SCENT [16] SIM4NEXUS [17] SmartCulTour [18] URBAN GreenUP
MOSAIC Internal Survey	15	[19] CRAFTY [20] Dynamic Energy Atlas [21] Swiss SolarWind Explorer [22] EPIC WebGIS [23] IMPACT tool of the Flemish Climate portal [24] INCA tool [25] InVEST® [26] Land-use Planner [27] Nature value explorer [28] NEXUS Learn [29] PANDORA 3.0 plugin [30] Reinvent your street [31] RuimteModel Vlaanderen / Geodynamix [32] UNBiodiversity Lab [33] Watch-it-Grow
WOS and SCOPUS Grey literature	4	[34] LandsFACTS [35] MPMAS [36] P@stor-all [37] ZONATION
	11	[38] AKIS PORTUGAL [39] C.A.F.E (Carbon, Aqua, Fire & Eco-resilience) [40] ClimateMatch [41] CropSAT [42] E-Planner [43] Global Forest Watch [44] Land App [45] LANDSUPPORT [46] Land-use Finance Tool [47] MicroLEIS DSS [48] Myforest

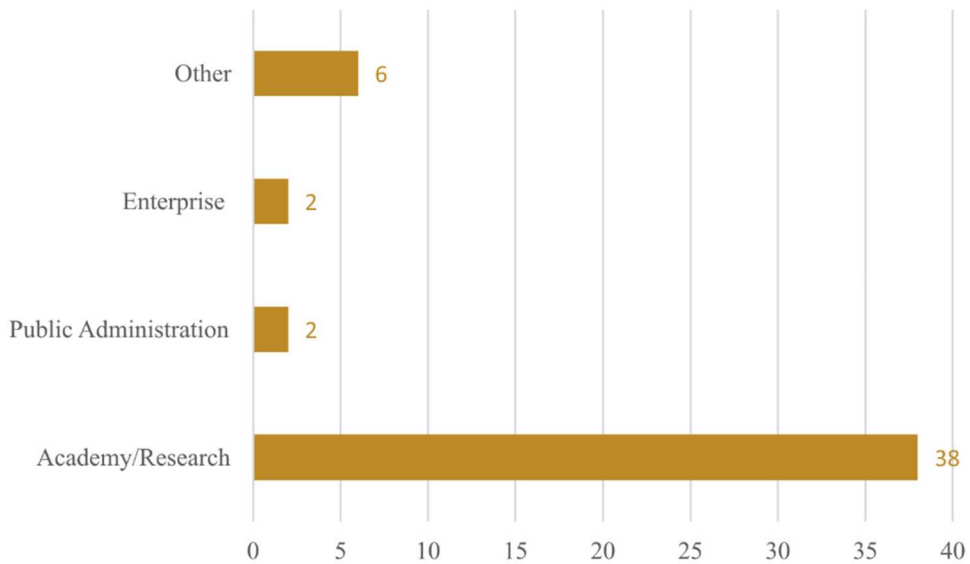


Figure 4. Type of developer of the collected tools.

The main domain of the analysed digital tools is mixed land uses, following agricultural/forestry decision support systems and those related to ecology, biodiversity and conservation () (Figure 7).

The most common types of tools (Figure 8) identified are ‘interaction and visualisation’, followed by those with multiple functions. Interaction and visualization tools are designed to make complex information more accessible and engaging for users by providing visual components, primarily maps, charts, and interactive elements (e.g. EPIC-WebGIS, SIM4NEXUS, and RUBIZMO).

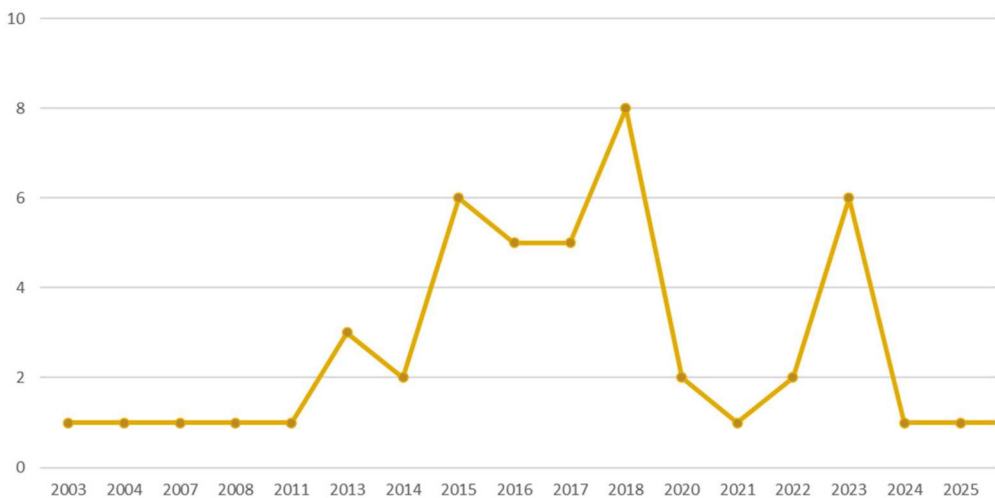


Figure 5. Launching year of the operational tools.

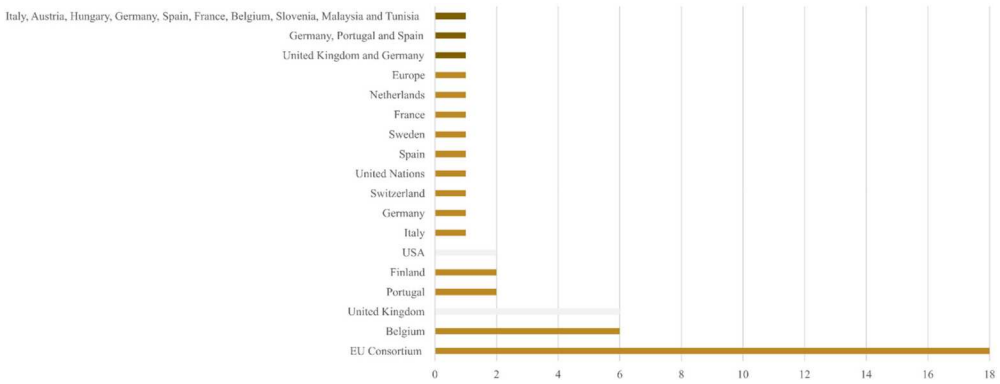


Figure 6. Country(ies) that developed the tool.

The tools with multiple functions reflect a versatile nature, simultaneously combining different capabilities, for example, ‘simulation, land use modelling, scenario modelling’ (CRAFTY), or ‘analysis, interaction, visualisation, and assessment’ (Nature Value Explorer). Tools specifically crafted for performance analysis are tailored to a particular focus, such as addressing environmental risks (OPERANDUM) or financial flows related to land use (Land-Use Finance Tools). The less representative tools concentrate on stakeholder engagement (e.g. NAIAD, SmartCulTour, and NEXUS Learn), simulations (e.g. NBS Simulation Visualisation Tool, MPMAS), scenario modelling (IMPACT Tool), and land-use modelling (ZONATION and MySustainableForest). An interesting result is that 80% of the tools focus on spatially explicit outputs, highlighting the specific function of digital tools in managing complex information and making it accessible to the public audience.

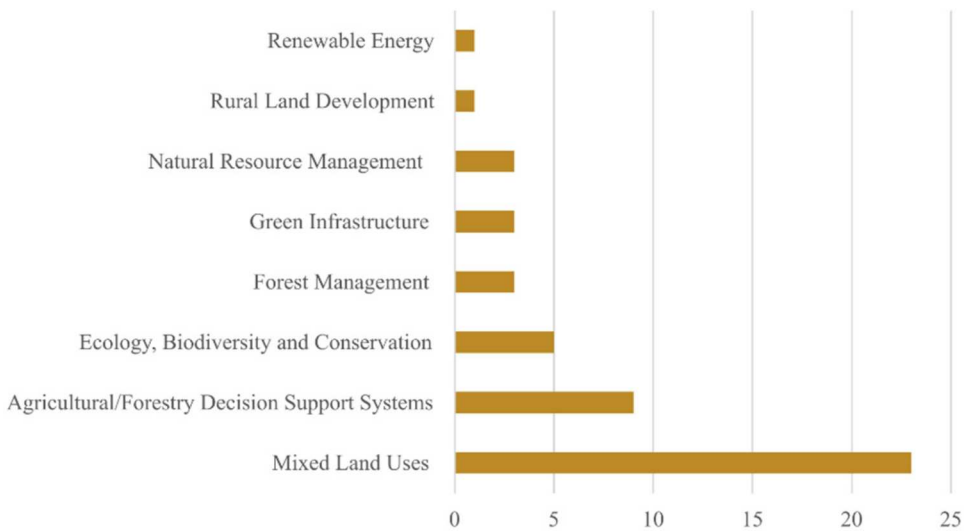


Figure 7. Main land use domain.

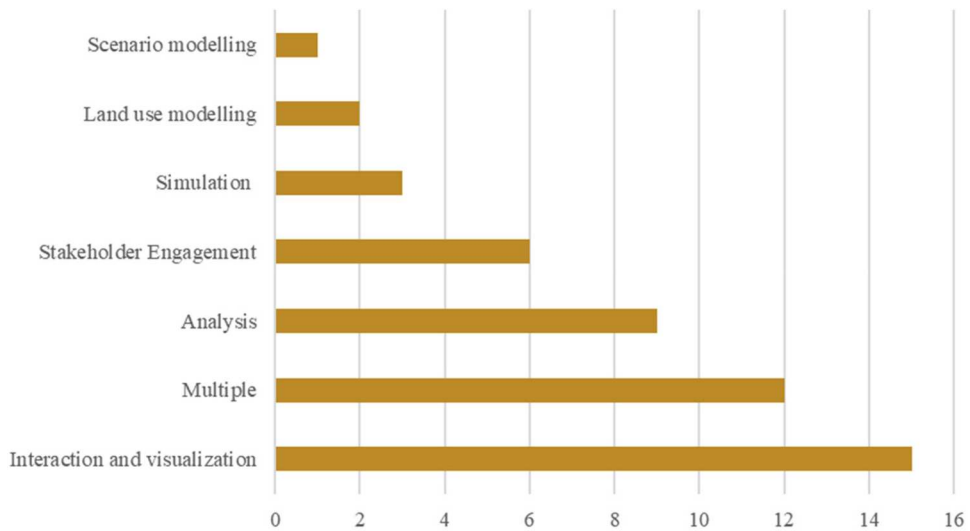


Figure 8. Types of digital tools.

Regarding the policy application (Figure 9), most tools encompass multiple sectors, demonstrating flexibility in addressing different challenges. Among single-focus tools, the agricultural sector is the most prominent, followed by spatial planning and forestry.

Almost 50% of the tools are multiscale, combining European, national, regional or local scales (Figure 10), while the other half relate to local scale.

Regarding tool data, most tools use qualitative and quantitative input data (Figure 11). Still, 22% only use quantitative information, and 25% exclusively work with qualitative data. The input data type (Figure 12) is spatial for almost 40% of the tools, followed by multiple types (ranging from statistics to spatial) and those using expert knowledge. Despite 80% of the tools being spatial explicit, the output is aggregated data (Figure 13), meaning it is not exclusively a cartographical output. Regarding the time frame of the

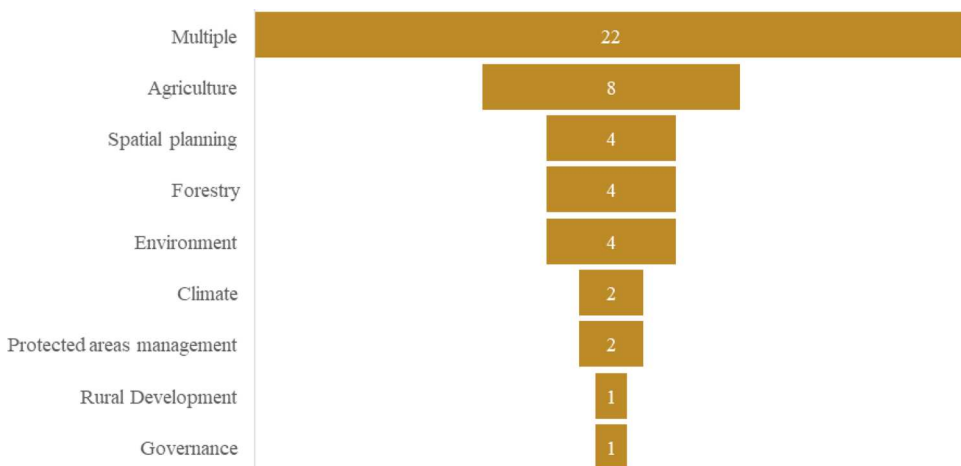


Figure 9. Policy sector related to the tool.

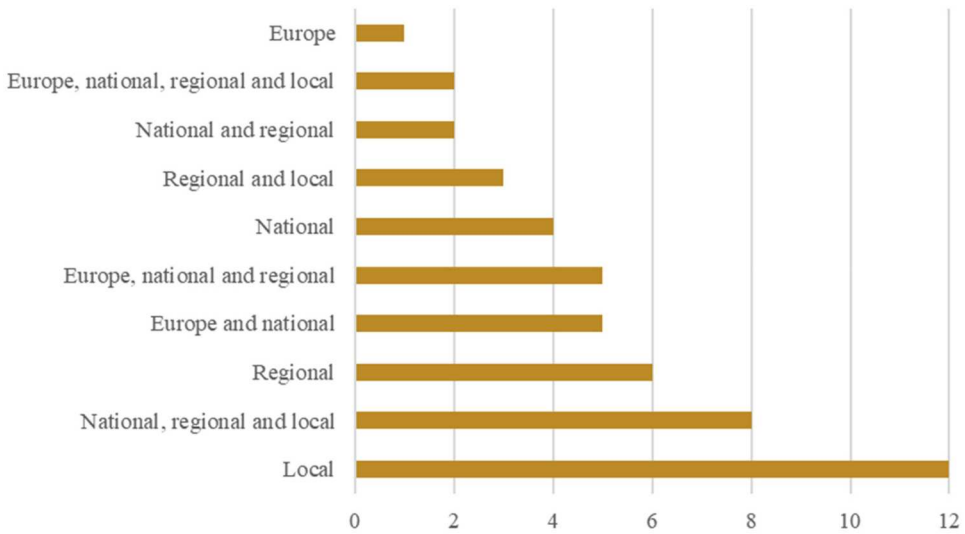


Figure 10. Scale of the tools.

output provided by the analysed tools (Figure 14), about 70% deal with the current time frame, 11% short-medium term, and only 7% provide long-term results (e.g. CRAFTY, Swiss SolarWind Explorer, CO-IMPACT tool). Six tools cover current to long-term results: Dynamic Energy Atlas, Nature Value Explorer, Land-use planner, InVEST, NEXUS Learn.

The information about tool users is scarce, especially concerning the number of users. When analysing the type of end users and considering four categories (Citizens, Academy, Policymakers, and Land Managers), 25 tools address the full range of end users; only one is aimed solely at citizens, and 10 are directed to land managers

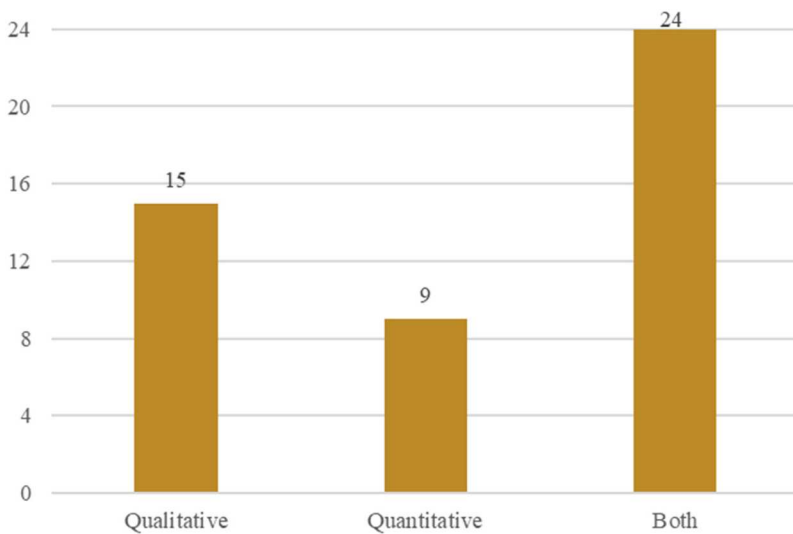


Figure 11. General input data type.

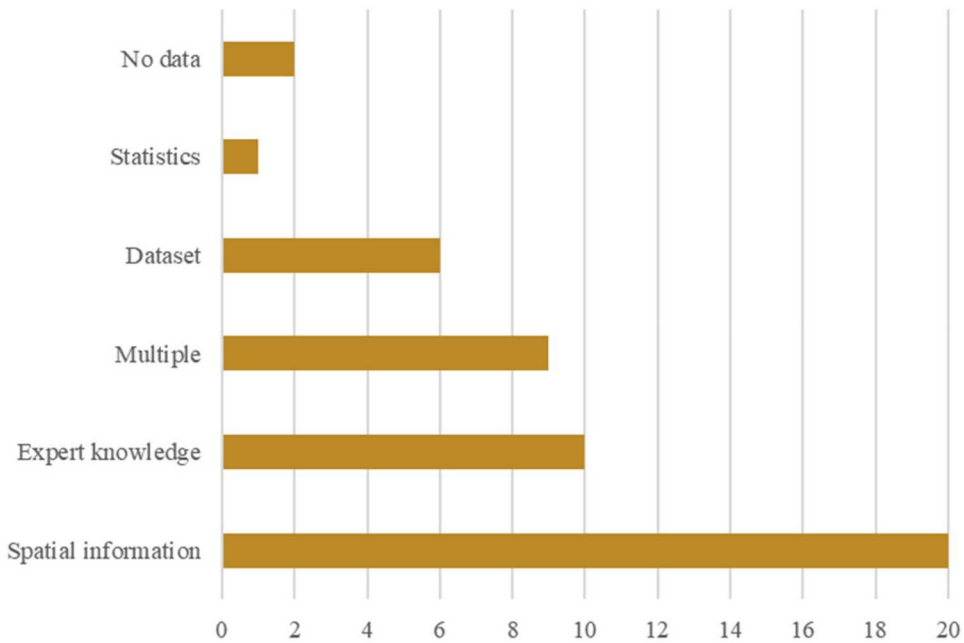


Figure 12. Detailed input data type used in the tool.

(Figure 15). Moreover, only 9% of the tools are considered to have a high time investment requirement, while the rest have low to medium time investment requirements for use or learning to use.

4.1. Co-development recommendations for increasing uptake

In recent years, digital tools have emerged as powerful assets in decision-making, especially in fields requiring integrating scientific knowledge with local contexts, such

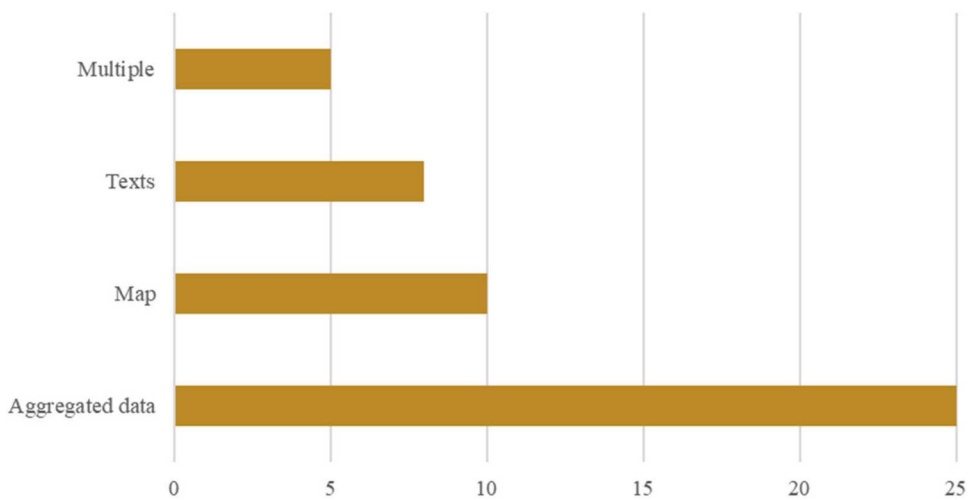


Figure 13. Detailed output data type.

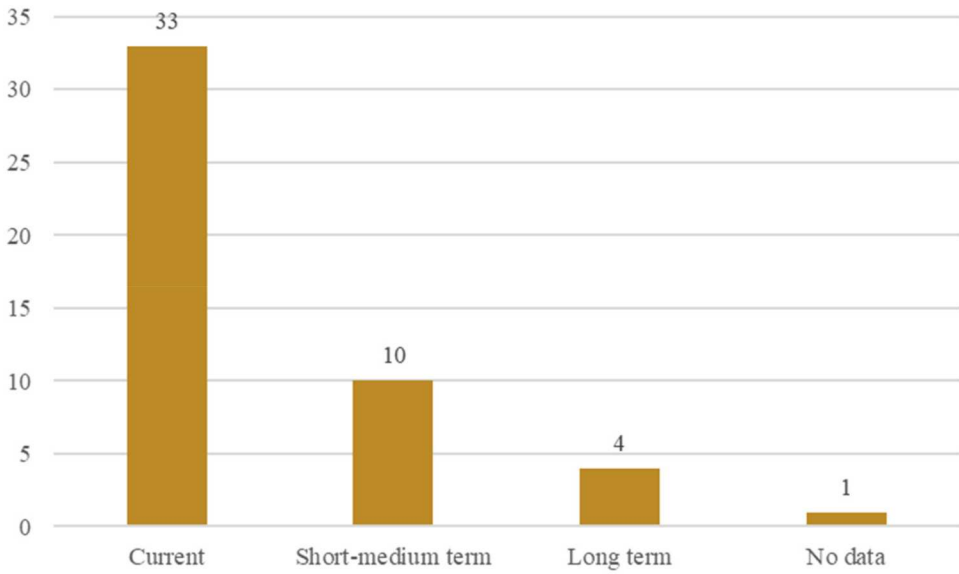


Figure 14. Output timeframe.

as sustainable land-use decisions. In this context, digital land-use decision support tools offer innovative ways to visualize changes, helping stakeholders understand the impact of their choices on land use. This capability fosters better understanding and facilitates informed actions aligned with policy targets, development goals, and stakeholders involved in decision-making.

Focussing on the need and opportunity to increase the uptake of digital tools, this section provides co-development recommendations based on the interpretations of the systematic review results, including specific insights from five developers’ interviews.

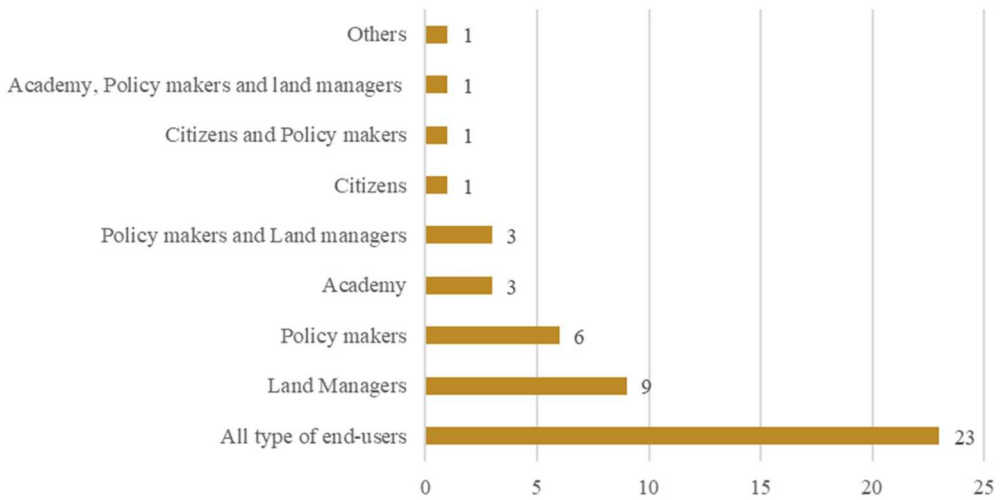


Figure 15. Type of end-user.

One of the other most significant advantages of digital land-use decision support tools is their efficiency, as they can optimize otherwise complex spatial scales and time-consuming processes like data analysis, visualization, and monitoring. This efficiency is vital for time-sensitive projects aimed at climate change adaptation or mitigation and reducing biodiversity loss, where accelerating decision-making is essential.

Digital tools also enhance communication across different sectors, making conveying complex changes to various stakeholders easier and engaging them in different stages of the policy cycle or project phases. This aspect, often challenging to execute with traditional methods, helps deepen understanding of how new policies or projects will impact land use and communities, ultimately promoting more significant involvement in the planning process.

Digital tools also enable access to broader networks and higher levels of decision-making and increase cross-sectoral collaboration, particularly in governance and sustainable development areas. In this context, digital tools are evolving to devise innovative solutions to complex challenges related to land use decisions that could address climate change, biodiversity loss, and renewable energy, thereby helping society take quicker steps toward the urgent ecological transition and sustainable development.

However, despite these advantages, the uptake of these tools is not without challenges and requires careful consideration of the potentials and limitations.

Accessibility remains a significant barrier, and the tools are costly, complex, or simply unknown to potential users. This lack of awareness limits the potential reach of digital land-use decision support tools, and even when people are aware, they may not trust or fully accept the technology, questioning its reliability or applicability. Furthermore, adaptability is an issue. While these tools may excel in specific scenarios, they often struggle to address unique local needs without extensive customization, which can be complex and expensive.

From a technical perspective, there are additional barriers. Many digital tools require advanced modelling skills and are not intuitive, which hinders accessibility for non-experts. In cases where the tools are complex, interpretability becomes a challenge, with users finding it difficult to extract meaningful insights without specialized training. Likewise, data barriers persist, as high-quality, up-to-date information is often needed to leverage digital tools fully. Data development costs, particularly for field observation data, can be prohibitively high, and available data may not always represent the current situation, reducing the accuracy of models and projections.

Insights from the developers' interviews confirm that this framework opens a specific range of recommendations for increasing the uptake of existing tools (Figure 16). One of the most challenging trends for tool developers is overcoming barriers associated with skills to use the tools and the lack of user-friendly manuals.

The main recommendation to uptake referred to by the developers revolves around '**user training and support**', meaning an effort to provide comprehensive learning tutorials/workshops and manuals to empower users, leading to effective adoption of the tool and reducing barriers related to technical skills.

'**Engaging stakeholders**' is the second main recommendation identified by the developers for the successful uptake of digital tools, mainly when dealing with complex, cross-sectoral decision-making processes. Deep engagement fosters trust, adaptability, and a shared understanding of how digital tools can drive meaningful, sustainable change.

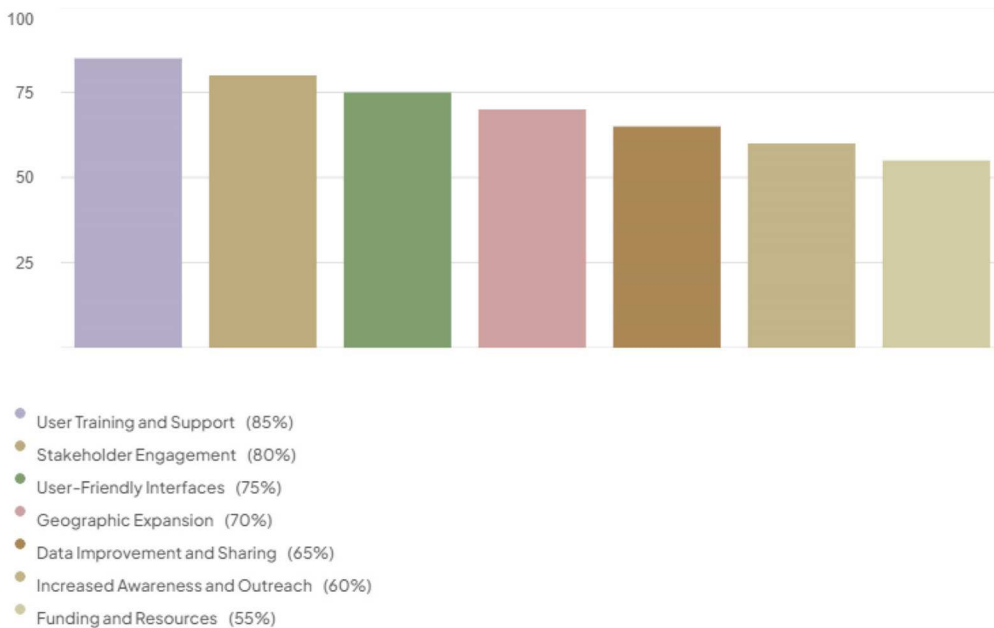


Figure 16. Recommendations for increasing the uptake of existing tools (Relative frequency of total responses).

Developing ‘**user-friendly interfaces**’ and ‘**geographical expansion**’ is another core recommendation that can increase accessibility and encourage adoption by a broader range of users and contexts. The latter aspect led to ‘**Data considerations,**’ which are also critical for ensuring the relevance and applicability of digital tools in decision-making. Addressing data accuracy, availability, and integration can build trust in the tool’s outputs and increase user value.

Finally, ‘**funding and resources**’ form the backbone of uptaking digital tools due to the costs associated with developing, maintaining and divulging digital tools, which vary widely depending on their complexity, functionality, target audience, and geographical scope. By fostering public-private partnerships, adopting transparent reporting practices, and tapping into in-kind resources, organizations can build digital tools that are accessible, impactful, and sustainable over the long term.

Regarding the challenges faced, some of the most relevant quotes from the developers’ interviews indicate that:

‘Two of the biggest constraints linked to the development of the digital tool are related to data and financial costs’;

‘The diversity of data that made the model parameterisation and processing capacity difficult, due to the existence of many processes’;

‘Finding people with the right skills to work with modelling was a challenge to support the development of the tool’;

‘Based on user feedback, a significant obstacle to adopting this digital tool is the challenge of theoretically quantifying data within specific geographic contexts’;

‘One of the main constraints of the digital tool is that it is not possible to quantify everything on a regional scale, and sometimes it becomes difficult to use the digital tool to support implementation’;

‘One of the main barriers to adherence is related to the impossibility of uploading data (from users) to the platform’.

5. Discussion

By systematically analysing 48 digital land-use decision support tools, the study highlights their diverse functionalities—from interaction and visualization to scenario modelling—and the importance of spatially explicit outputs for local and regional planning. In a broader sense, digital tools have the potential to integrate scientific knowledge and advanced technologies with local contexts and knowledge, supporting decision-making processes.

However, digital tools also have some limitations associated with their use, such as accessibility (awareness of the tool’s existence, cost and availability or complexity to learn), lack of trust/acceptance of the technology, and adaptability of the tool to solve a need (Bestelmeyer et al. 2024). In specific contexts, for example, in digital agriculture, more barriers to uptake can be found (Dibbern, Romani, and Massruhá 2024), such as the farmer’s economic and financial condition, the availability of technological infrastructure, the farmer’s educational background, and age. According to Bestelmeyer et al. (2024), integrating digital tools with social networks enhances their relevance and effectiveness. These authors suggest incorporating these tools into community-based collaborative adaptive management, emphasizing feedback among monitoring, learning, and management with multiple stakeholders. Dibbern, Romani, and Massruhá (2024) also highlight the importance of sharing knowledge and resources in a cooperative network to mitigate the digital tool barrier.

Digital tools hold transformative potential, especially in fields as complex as land-use decision-making and its relationships with climate change and environmental crises. In this sense, such potential can be interpreted through the lens of a group of four key motivations in tool development, systematised in the following [Figure 17](#):

While motivations inspire the development of digital tools, barriers often temper expectations. These challenges are not merely technical but reflect deeper systemic issues in data access, policy alignment, and communication. The main barriers in tool development are systematised according to the following four groups ([Figure 18](#)).

These groups help to identify different types of barriers, highlighting the areas that need attention, whether in terms of technical development, data quality and accessibility, governance or communication. While technical barriers pose significant challenges, data barriers are more common among tools, as high-quality, up-to-date information is often needed to leverage their functions. This aspect deals with data development costs, particularly for field observation data, which can be prohibitively high, and available data may not always represent the current situation, reducing the accuracy of models and projections.

The development and application of digital tools for land-use decision-making are often subject to several policy and governance barriers that impact their effectiveness and usage. The challenges mentioned here, ranging from changing demand for the

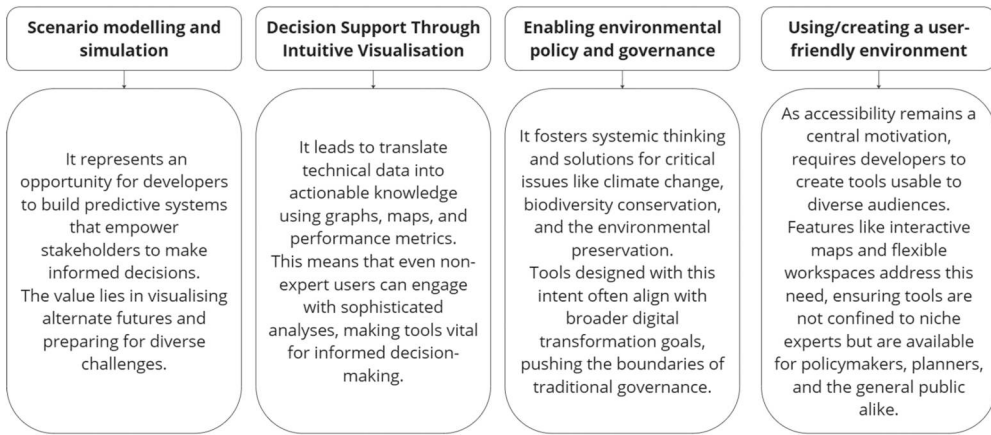


Figure 17. Key motivations in tool development.

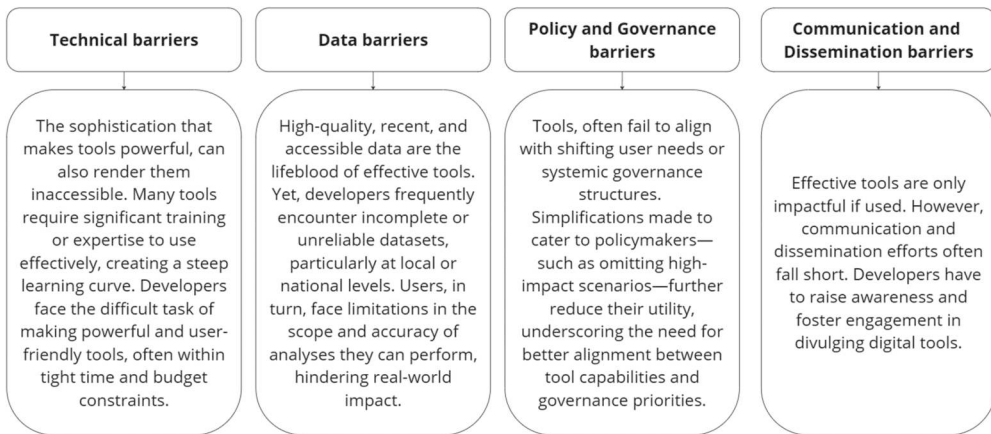


Figure 18. Main barriers to tool development.

tool to difficulties in addressing climate change and societal attitudes towards problem-solving, highlight key areas that need attention in both the design of such tools and the broader policy context in which they are implemented, mainly focusing on policy target seeking.

Finally, communication and dissemination remain significant barriers, which this study also highlights as a limitation in the review process. The lack of access and awareness limits the potential reach of digital land use decision support tools.

6. Conclusion

Decision-making for sustainable land use transformations represents one of the most crucial drivers of society’s future development, especially considering the impacts of climate change and biodiversity loss. Within this discourse, digital tools emerge as promising technologies to support decision-making. Nevertheless, the current literature

analysis reveals a gap in studies that systematically explore existing digital tools, their functionalities, potential, and barriers in the broader context of land use decision support. In order to address this gap, the present study conducts a systematic review of digital tools that have been published in peer-reviewed literature as well as in selected databases. More specifically, it responds to RQ1 (What are the common types of digital land-use decision support tools available in Europe?), identifying 48 tools categorized into interaction and visualization tools, analytical performance tools, stakeholder engagement tools, scenario modelling tools, and land-use modelling systems. These tools are developed by universities, research institutes, and EU-funded projects, with a significant portion being freely accessible and actively maintained.

Regarding RQ2 (What key features and functionalities are typically found in them?), the analysis shows that most tools offer spatially explicit outputs, integrate multiple data sources (both qualitative and quantitative), and are designed for broad stakeholder engagement, including policymakers, land managers, academics, and citizens. However, while some tools provide real-time or long-term projections, most focus on supporting decisions within the current timeframe.

Finally, addressing RQ3 (What are the main barriers and recommendations for their uptake?), the study identifies key challenges in accessibility, trust in tool outputs, and adaptability to different decision-making contexts. Many tools require advanced technical skills, and a lack of digital literacy among potential users hinders their adoption.

To improve uptake, this study recommends fostering user training and support, enhancing stakeholder engagement, developing user-friendly interfaces, ensuring data accuracy and availability, and securing long-term funding to sustain tool development and maintenance.

Overall, this study highlights the transformative potential of digital tools in land-use decision-making while emphasizing the need for improved usability, transparency, and accessibility. By addressing the identified barriers and fostering digital literacy, digital tools can provide valuable contributions in supporting sustainable land use decisions, bridging the gap between data-driven insights and real-world complexity.

7. Limitations and future research

There are limitations to this study that can guide future research directions. Conducted within the geographical focus of Europe, the study highlights the relevance and effectiveness of digital tools in this specific context. While this focus may inspire the adaptation or replication of the identified tools in other regions, some European-restricted aspects, such as policies or data, could limit the soundness and interest in the topic. Such considerations align with future research, which could address a systematic review of digital tools across other continents, facing different land use and decision-making challenges.

Limitations of employing PRISMA are also important to mention, as using this method might have missed some relevant digital tools. A central aspect to consider in this discourse is that the application of PRISMA may not yield significant information regarding digital tools that have not been developed within an EU project listed in CORDIS, or that have not been published in indexed journals in the WOS and SCOPUS databases. The dissemination of some digital tools through grey literature (via institutional websites or other communication channels with a broader audience)

may not be exploited effectively, highlighting one of the significant barriers to uptake identified by the study: their existence is simply unknown to potential users.

Looking forward, digital tools must evolve from static support of land-use decision-making to dynamic catalysts for innovation and collaboration. They should become more inclusive by integrating co-development processes with diverse stakeholders, prioritizing transparency to ensure users understand how outputs are generated and their real-world implications, and transforming them into platforms that inspire and enable society to address the complexities of sustainable land-use management.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by the European Union's Horizon Europe research and innovation programme under grant agreement N° 101081238, project MOSAIC – Joined-up land use strategies tackling climate change and biodiversity loss.

ORCID

Francesca Poggi  <http://orcid.org/0000-0002-3087-7810>

Selma Pena  <http://orcid.org/0000-0001-9141-6076>

Natália Cunha  <http://orcid.org/0000-0002-7541-2232>

Ana Müller  <http://orcid.org/0000-0002-8728-9788>

Beatriz Romãoa  <http://orcid.org/0009-0008-2324-4469>

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