European Journal of Remote Sensing

ISSN: 2279-7254 (Online) Journal homepage: www.tandfonline.com/journals/tejr20

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To cite this article: Katja Berger, Daniela Requena Suarez, Zoltan Szantoi, Nuno César de Sá, Steffen Fritz, Milutin Milenkovic, Joan Maso, Viola Heinrich & Martin Herold (2026) Towards a FAIRer future: insights from Europe's geospatial community, European Journal of Remote Sensing, 59:1, 2676254, DOI: 10.1080/22797254.2026.2676254

To link to this article: https://doi.org/10.1080/22797254.2026.2676254

Published online: 20 May 2026.

EUROPEAN JOURNAL OF REMOTE SENSING
2026, VOL. 59, NO. 1, 2676254
https://doi.org/10.1080/22797254.2026.2676254

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RESEARCH ARTICLE

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Towards a FAIRer future: insights from Europe's geospatial community

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ABSTRACT

Geospatial environmental and Earth observation (EO) data have recently become an indispensable source for a wide range of land management applications, from research to monitoring for land-related policies of the European Union (EU) under the umbrella of the Green Deal. To maximize the potential of these valuable datasets, the four foundational FAIR principles - Findable, Accessible, Interoperable, and Reusable - offer a critical framework for geospatial data management and sharing. Here, we offer our perspective on the current adoption and implementation of the FAIR principles within the European geospatial and EO community, critically reflecting on FAIR geospatial data usage. Despite the push for FAIR principles, European practitioners still face major adoption barriers. Survey results reveal critical gaps between the perceived importance of FAIR principles by data producers and users and their actual implementation. We argue that a lack of incentives for producers and limited user knowledge about the benefits of FAIR data hinder its effective utilization. Addressing these challenges through targeted interventions is crucial for ensuring that all stakeholders can effectively use EO and geospatial data to support informed and timely land-related applications within the EU.

ARTICLE HISTORY
Received 23 January 2026
Revised 25 February 2026
Accepted 11 May 2026

KEYWORDS
Earth observation; user involvement; OEMC project; policy; data sustainability

Introduction

Satellite and Earth observation (EO) data now enable efficient, global land cover monitoring (Herold et al., 2016; Ustin & Middleton, 2021; Xu et al., 2020). These geospatial data streams underpin policy frameworks, notably the European Union (EU) Green Deal and the current Strategic Agenda (Union, 2025), by supporting transparent tracking and compliance. Yet, despite growing data availability, reproducible reuse is limited by inconsistent data practices and documentation (Heinrich et al., 2023; Herold et al., 2019). To address the growing need for improved data reuse, from scholarly research to land management applications and policy-making, a consortium of stakeholders developed the FAIR principles: Findable, Accessible, Interoperable, and Reusable (Wilkinson et al., 2016) (see Figure 1). The original FAIR framework emphasised machine-understandability, making interoperability and automated data discovery central to its design. However, these principles apply not only to data, but also to the algorithms, tools, and workflows used to generate it (Minghini, 2025).

Overall, the FAIR principles provide a robust framework for enhancing the accessibility and usability of research data for the geospatial community, as demonstrated in recent studies (Jakimow et al., 2023; Rautiainen et al., 2024; You & Sun, 2022). For instance, Kutha Krisnawijaya et al. (2025) demonstrated the application of a systematic FAIR implementation methodology within Indonesia's Smart Agriculture project, specifically in dairy and fish farming. The multi-case study illustrates the complexity of achieving interoperability and reusability in multidisciplinary agricultural contexts and underscores the crucial role of standardised metadata, secure access, and semantic protocols. These findings strengthen the argument

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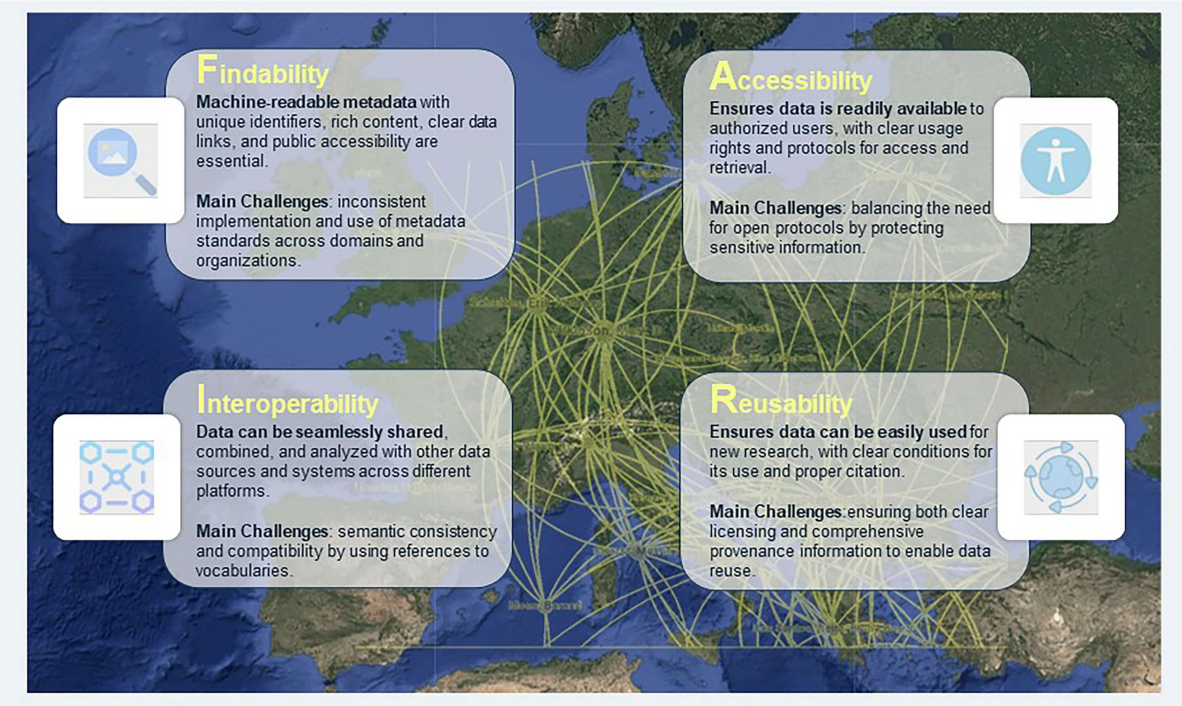

Figure 1. Overview of the four foundational FAIR principles, with main challenges. The background is Europe, shown in RGB (Google Earth Engine base maps), and the illustrative network graph is included for visual effect; connections shown are not intended to represent actual relationships. Source: Wilkinson et al. (2016).

that tailored FAIR implementation strategies are vital for effective data management and sharing in diverse sectors, aligning with broader trends observed across geospatial and EO domains. In the context of EU policies, specifically the Common Agricultural Policy (CAP), shortcomings have been identified by a review (Leonhardt et al., 2024) assessing how publications using Integrated Administration and Control System (IACS) land use data addressed the FAIR data principles. The review revealed significant deficiencies in adhering to FAIR data principles and methodological reporting, hindering reproducibility. Hence, while various standards exist for defining and sharing geospatial data, many still fail to guarantee FAIR-compliant resource distribution (Ivánová et al., 2019).

Despite these challenges, adopting FAIR principles in data publishing significantly boosts the value and reuse potential of digital resources (Commission, 2018). Growing awareness of the importance of open science has led to increased interest in applying the FAIR principles not only to research data, but also to research software (Jensen & Katz 2025).

Building on these challenges, this study has three specific objectives: (1) map the data requirements and operational scales of European geospatial data stakeholders; (2) quantify FAIR data awareness among data producers and users; and (3) identify concrete barriers to FAIR adoption and propose actionable solutions for efficient data sharing between technical remote sensing and policy communities. By integrating stakeholder perspectives with data practice insights, we aim to provide practical guidance for accelerating FAIR implementation in the European geospatial and land sector.

Mapping the community: survey design

A survey was carried out between October 2022 and October 2024 by means of the EU Survey tool to evaluate the experiences of geospatial and EO data users and producers concerning data utilisation, accessibility, and utility, particularly focusing on FAIR data principles. All participants, contacted via email, social media and personal networks, were provided with detailed information about the purpose of the study, the procedures involved, their rights as participants, and options for data sharing. Informed

consent was obtained from each participant prior to data collection (online). This survey was approved by the Ethics Committee of the GFZ Helmholtz Centre for Geosciences (on October, 23, 2025), affirming that the study meets all institutional and relevant national ethical requirements for research involving environmental geospatial data users and producers, and all procedures complied with relevant national and institutional guidelines.

The survey employed a non-probability, self-selected sampling approach among individuals and organisations involved in producing and/or using geospatial and EO data in Europe. As recruitment occurred via professional mailing lists, social media, project and institutional newsletters, conferences, and personal networks, no overall sampling frame or response rate could be established, and the sample is not statistically representative of all geospatial and EO stakeholders in Europe. Nevertheless, the diversity in country coverage, organisational affiliation, and application areas suggests that the responses capture a broad range of perspectives on data utilisation, accessibility, and FAIR data principles. Potential response biases include self-selection bias (e.g. stronger participation by individuals particularly interested in data sharing), as well as possible over- or under-representation of specific sectors, countries and professional networks.

The survey consisted of three blocks. The first collected participant background for stakeholder categorisation. The second explored data preferences, indirectly assessing FAIR understanding by querying users on data types, characteristics, and challenges, and producers on offered data and issues. The third examined both groups' familiarity with and implementation of FAIR principles, including user obstacles to FAIR data use and producer barriers to FAIR-compliant output. Full questions are in the associated repository (see data availability statement).

A total of 170 participants from 30 countries responded, with 80% representing European nations. The largest group of respondents was affiliated with academia (62%), followed by governmental/public sectors (15%) and private companies (15%). The most common application areas selected were agriculture/land degradation (21%) and nature conservation/biodiversity (18%). The majority of respondents identified as data users (74%, $N = 125$), while 26% ($N = 45$) were data producers/providers.

Geospatial data in practice: priorities and usage trends

Among various geospatial products, open satellite-based remote sensing data and their derivatives were the most sought-after by nearly 90% of users and also the most frequently provided by producers (66%). In contrast, a significant supply-demand gap was revealed for in-situ data: while half of the users require such data, only 25% of producers provide it. This shortage highlights the challenges users face in accessing suitable ground reference data and raises questions about whether producers fully understand the specific need for in-situ data used in mapping, specifically for model building and validation purposes. Further, a discrepancy in observational scales could be observed: producers focus rather on larger scales, with 59% supplying global data, although only 34% of users required it. A similar mismatch appeared at the continental level. In contrast, users showed greater demand for smaller scales, with national (50%) and regional (42%) data sought more frequently than producers provided (36% and 23%, respectively).

Shifting focus from data supply patterns to the qualities both users and producers perceive as valuable for end-users in geospatial data, the survey explored the relative importance of key attributes such as findability, openness, and accessibility (see Figure 2). Both users and producers highly prioritised online findability and openness of geospatial data. Interestingly, easy integration into existing workflows seemed a higher priority for producers, while transparency of data sources was indeed more relevant for users. Clear licensing, metadata, and documentation were considered similarly important by both groups. Interoperability achieved a higher importance for users (for 'extremely important'). A notable finding was the lowest priority assigned to data reproducibility, a core FAIR principle, possibly due to respondents confusing it with fully independent replication (requiring the original research context) rather than straightforward re-analysis using shared data and code. For users, data reproducibility ranked higher for the 'extremely important' option than data retrieval via domain-relevant community standards.

Overall, these perceptions of users and producers regarding geospatial data features and associated challenges reveal a preference for practices aligned with FAIR principles, even without explicit questioning about the framework itself.

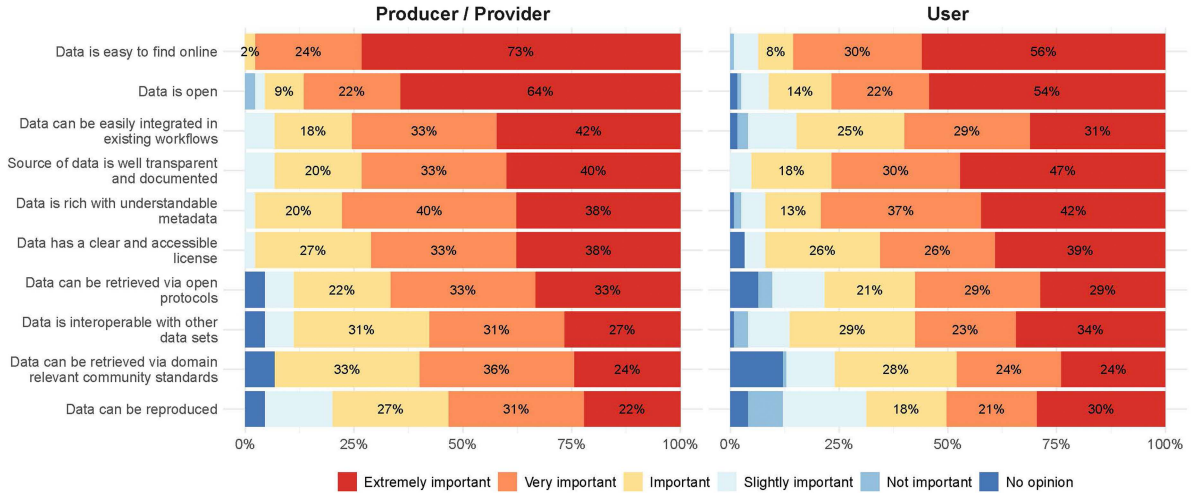

Figure 2. Survey results about the question for users: "How important are the following features of geospatial data to you?" and producers: "From your point of view, what are important features of geospatial data for the users?". (*N* users = 125, *N* producers = 45).

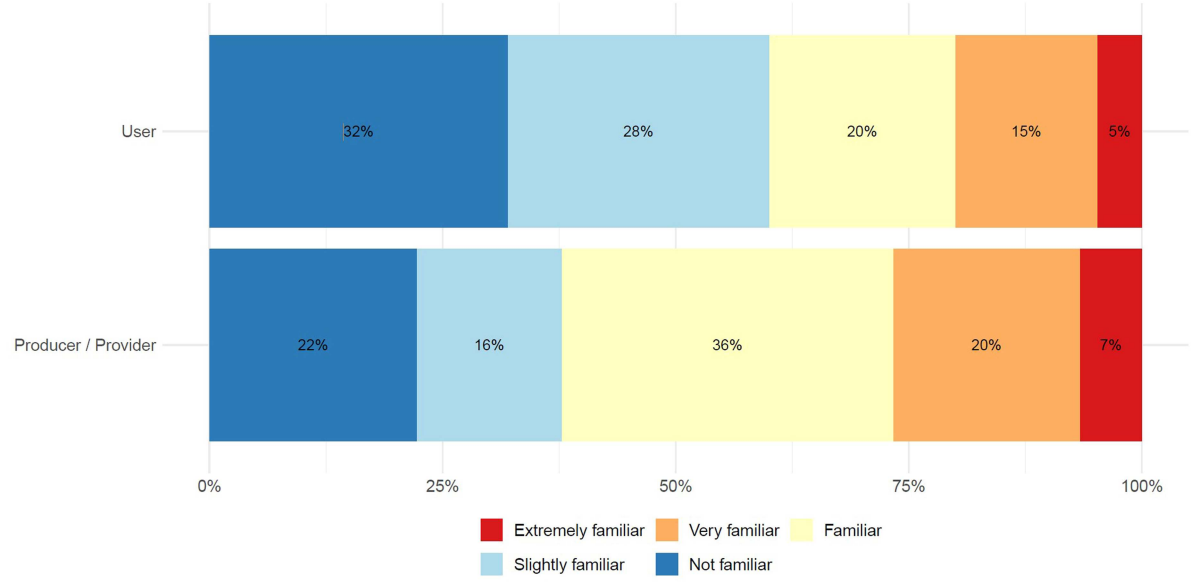

Figure 3. Survey results about the question asked to both groups, users and producers: "How familiar are you with the FAIR data principles?" (*N* users = 125, *N* producers = 45).

Perspectives on FAIR principles implementation and barriers

The implementation of FAIR data principles remains uneven across the geospatial EO community, highlighting persistent gaps in awareness and practice between data users and producers. Remarkably, 32% of users and 22% of producers reported being unfamiliar with the FAIR principles (see Figure 3), despite their widespread promotion within research communities. Overall, 60% of users showed lower awareness of FAIR compared to 38% of producers.

Consistent with this disparity, a substantial share (42%) of data producers and providers indicated that they follow the FAIR principles by responding to the question "Are you providing FAIR data?" with "yes". However, this reflects self-reported compliance, i.e. their perception of implementing FAIR principles in

their workflows. The subjective measure captures FAIR awareness and intentions among stakeholders but does not constitute objective technical validation of FAIR compliance.

In contrast, user engagement with FAIR data was limited, with only 21% confirming its use and 28% being unaware of it (not shown). Notably, 51% of users expressed uncertainty about the FAIR status of their data. These results differ from the findings of Jensen & Katz (2025), where funders (governmental and non-governmental organizations, $N = 71$) demonstrated very high familiarity with FAIR data, underscoring strong role- and domain-specific disparities in FAIR knowledge.

Moreover, both users and producers prioritised accessibility and findability as the most crucial FAIR principles (Figure 4). These findings align with previous results (Figure 2), where data accessibility and openness were seen as highly relevant. Although still important, reproducibility and interoperability were perceived as less important from both groups. There is a tendency among producers to give the FAIR principles more relevance, which is certainly intrinsically related to the overall higher awareness and use of FAIR practices among producers than by users.

Survey respondents identified several key barriers to FAIR data implementation. Producers highlighted resource constraints (26%) and a lack of incentives (21%) as the primary barriers to producing FAIR data. Other challenges included potential misuse, inadequate guidelines, restrictive regulations, and competitive disadvantages. Notably, technical limitations were perceived as less significant obstacles, suggesting a general readiness to adopt FAIR principles if suitable incentives are in place. This finding underscores a clear policy gap: the absence of institutional mechanisms (e.g. funding schemes, reporting requirements, or reward systems) that could foster FAIR-aligned data sharing. We therefore argue that better policy alignment with FAIR data principles is essential to enhance the usability of research outputs in public decision-making.

In contrast, users reported a lack of awareness about FAIR data (24%) and limited understanding of its benefits (20%) as the most substantial barriers to its utilisation. Hence, policymakers could be urged to support targeted capacity-building actions, such as training programmes, FAIR data literacy modules in funding calls, or mandatory FAIR compliance support, especially within public institutions and environmental agencies that rely on open data for their assessments.

From a user perspective, FAIR data principles ideally eliminate utilisation barriers, but challenges remain, including assessing dataset "FAIRness" without clear guidance or tools. Producers face insufficient

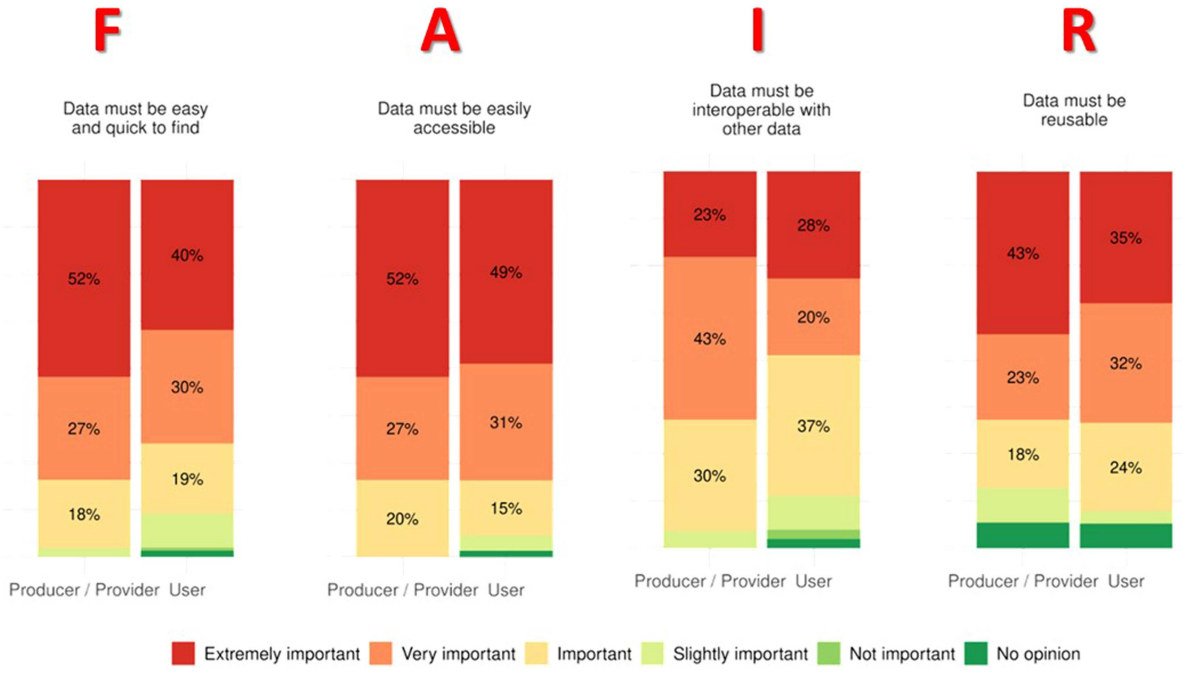

Figure 4. Survey results about the question: "How important are the following FAIR principles to you"?

personnel, time, and funding, exacerbated by time-intensive tasks like detailed READMEs, ontology annotations (e.g. AGROVOC), schema.org metadata, and deposition in curated repositories (e.g. Zenodo, Dryad). The lack of actionable guidelines and incentives further hinders adoption, underscoring the need for awareness, education, and incentives among both groups.

Discussion

FAIR principles promote data sharing in science and require implementation measures for full benefits. While FAIR data principles have become central to the open science discourse, their effective implementation remains uneven across geospatial communities. Our survey insights reveal that technical barriers are no longer the main constraint, but institutional factors, such as staffing shortages, time limitations, and restricted funding, now play a more decisive role. This finding calls for renewed engagement from policymakers to embed FAIR data principles into funding instruments, evaluation frameworks, and reporting mechanisms, thereby ensuring that open and interoperable data truly serve evidence-based policy and societal needs. A study demonstrated that not following the FAIR principles in research data costs the European economy at least €10.2 billion each year (Commission, 2018). This provides clear reasons for the EU and research institutions to invest in FAIR data practices, since poor data sharing practices affect not only individual scientists but also the quality of research, and hence the pace of innovation. Platforms like the Copernicus Data Space Ecosystem (CDSE) already demonstrate scalable solutions: by leveraging openEO APIs, users can process and analyse EO data to automatically generate FAIR-compliant outputs, such as SpatioTemporal Asset Catalogue (STAC) metadata with provenance tracking, eliminating manual metadata burdens and accelerating policy-relevant applications (CDSE, 2026).

The observed discrepancy in spatial scales, where 59% of producers supply global data despite only 34% of users requiring it, highlights a gap between data provision and user needs. This suggests that data providers could benefit from more systematically assessing user requirements and tailoring their data products accordingly. Strengthening capacities to effectively use large-scale datasets for local applications could also enhance data reusability and uptake.

Both users (on their own needs) and producers (on user needs) prioritise findability and openness, confirming that accessibility remains a primary driver of EO data uptake across the data pipeline. Producers attribute higher importance to workflow integration, reflecting ongoing challenges in data preparation, pre-processing, and automation within production environments. In contrast, users place greater emphasis on source transparency, which underpins traceability and is essential for confidence in policy and reporting contexts. The relatively low ranking of reproducibility among both groups contrasts with the FAIR data principles but appears consistent with current operational EO priorities, where timeliness, efficiency, and interoperability often outweigh the ability to exactly replicate analytical outcomes, e.g. Camia (2023). This pattern suggests a pragmatic balance between FAIR ideals and the constraints of real-world applications, particularly in policy-driven or service-oriented settings where the value of EO data is realised through integration and decision relevance rather than methodological purity, e.g. Berger et al. (2026); (Schiavon et al., 2023). Awareness and adoption of FAIR data practices, such as depositing data in standardised repositories (Wilkinson et al., 2016) can be strengthened through targeted initiatives like the FAIR-IMPACT project's domain-specific workshops at international conferences (EOSC, 2025), with the integration of FAIR training into national PhD programmes via the Data Archiving and Networked Services (DANS). These efforts include hands-on workshops, online self-assessment tools (e.g. FAIR-Aware: https://fairaware.dans.knaw.nl/), and repository certification drives, resulting in increased Persistent Identifier (PID) usage and standardised metadata deposition.

Scientific journals further incentivize compliance by mandating FAIR-aligned metadata and data availability statements. Engaging scientists, industry professionals, and policymakers through these channels accelerates adoption. Leading projects include the EU-funded Open-Earth-Monitor Cyberinfrastructure (OEMC, https://earthmonitor.org/), which assesses stakeholder needs to maximise FAIR environmental data uptake, and the CDSE, which embeds FAIR principles using openEO to enable compliant open science solutions.

Furthermore, the European Space Agency (ESA) demonstrates a strong commitment to the growing recognition of FAIR data principles, mandating adherence to these guidelines in several of its projects, particularly those focused on Earth System Science and Applications. For instance, within the EO Science

for Society block (EO4Society), the goal is to combine Europe's excellence in EO systems, applications and science with other scientific disciplines and emerging big data technologies to maximise impact and benefits for society. The adherence to FAIR is one of the main characteristics of the EO4Society solutions to enhance knowledge sharing within the target user community. In this context, processing workflows should be deployed on cloud and high-performance computing platforms, which ensures efficient, location-independent processing while adhering to FAIR data principles. These solutions are specifically designed to support the implementation of global sustainable development and EU agricultural and environmental policies.

Regulation (EU) 2023/2854 (Data Act) (EU, 2023) mandates that participants in data spaces provide machine-readable dataset descriptions, covering content, conditions of use, licences, collection methods, quality and uncertainty, to ensure findability, accessibility and reuse. It further requires publicly available, standardised documentation of vocabularies, taxonomies and code lists used in the data and associated services. Hence, for EU Green Deal policies like the CAP 2023-2027, the EU deforestation regulation (EU 2023/1115), and the land use, land-use change and forestry (LULUCF, EU 2023/839), research outputs, such as algorithms and products for forest cover, crops, and commodities, should adhere to FAIR principles whenever feasible (Leonhardt et al., 2024). This enhances data accessibility, interoperability, cross-sectoral use, transparency, and traceability (Berger et al., 2025). FAIR compliance streamlines data collection and reporting, reducing administrative burdens on operators, national authorities, and CAP paying agencies. It also fosters efficient stakeholder collaboration to address deforestation, forest degradation, and food system monitoring. Since national data producers are unlikely to fully adopt FAIR without leadership from the research community, researchers should pave the way for broader governmental uptake by demonstrating its practical value in data sharing, interoperability, and reuse.

FAIR aims to maximise findability, accessibility, interoperability and reusability of data, which often implies more storage, richer metadata and long-term preservation. These practices can increase energy use and hardware requirements in repositories and data centres, making the environmental footprint of data life-cycles (production, storage, transfer, archiving) a relevant constraint (Paris-Saclay, 2024). We therefore suggest complementing FAIR with an explicit sustainability dimension ('Green FAIR'), defined as the alignment of FAIR-oriented data sharing with environmentally sustainable data life-cycles. Potential indicators for Green FAIR could include energy or emissions per TB-year stored, per data access, and storage utilisation ratios (Bachras & Jacobsen, 2026; Carrier, 2023). Integrating such indicators with FAIR assessments could help data providers and funders to support open and interoperable data while limiting unnecessary resource use. Furthermore, initiatives such as the Green Deal Data Space (Schleidt et al., 2025) illustrate how FAIR principles are being implemented to support the EU Green Deal by integrating environmental data in interoperable infrastructures. Our notion of 'Green FAIR' extends this by explicitly incorporating the environmental footprint of data collection, storage and access as an additional criterion alongside FAIR. The European Strategy for Data (2020, updated 2025) provides the policy foundation for this evolution, promoting sector-specific data spaces (including geospatial high-value datasets) that enable FAIR data flows across EU borders while ensuring trust, interoperability, and economic value. Finally, the EU's GreenData4All initiative exemplifies this policy momentum by modernising INSPIRE rules to enhance FAIR-compliant sharing of environmental geospatial data, supporting Green Deal priorities while addressing user needs for accessible, interoperable data ecosystems.

Conclusion

Maximising the value of geospatial and EO data depends on robust, FAIR-aligned data sharing practices that bridge the gap between scientific research and real-world applications. Our survey addressed its objectives by: (1) revealing distinct data requirements, with producers operating globally while users focus nationally/locally, among others; (2) quantifying FAIR awareness gaps with 60% of users showing lower awareness of FAIR compared to 38% of producers, and only 42% of producers self-report full compliance; and (3) identifying key barriers for FAIR-aligned data sharing, like lack of incentives, resource constraints and inadequate guidelines.

Key recommendations to drive FAIR adoption:

- **Awareness campaigns for data users** (from scientists to EU and national/regional policymakers in environment and agriculture ministries) via targeted EU workshops and EO portals like Copernicus

Land Monitoring Service. For instance, expand the existing Copernicus Land Monitoring Service webinar series, or training sessions, including dedicated 1-hour modules on "Accessing FAIR Geospatial Data".

- **Incentives and tools for producers to simplify metadata/vocabulary**: funding bonuses (+5-10% project budgets in Horizon Europe or national programmes) for FAIR-compliant datasets and automated tools like VocBench (for collaborative vocabulary management: https://vocbench.op.europa.eu/).
- **Clear guidelines for FAIR implementation**: producers should use DOI assignment (DataCite) and standardised vocabularies (e.g. Infrastructure for Spatial Information in Europe (INSPIRE), or see (Cox et al., 2021)); and additionally, explore CDSE openEO platforms to produce FAIR outputs automatically. Users should explore National open data portals because they provide centralised, standardised access to FAIR-compliant geospatial datasets across local, national, and EU levels.

Looking ahead, we propose 'Green FAIR' practices to address the environmental footprint of data infrastructures, extending initiatives like the Green Deal Data Space. These strategies will strengthen the FAIR ecosystem for researchers and policymakers implementing EU land policies (e.g. LULUCF, CAP), ensuring accurate, accessible geospatial and EO data supporting informed decision-making, monitoring, reporting, and enforcement.

Author contributions

Katja Berger: Conceptualisation, Writing - original draft, Methodology, Investigation, Formal analysis, Visualisation. Daniela Requena Suarez: Visualisation, Formal analysis, Writing—review and editing. Zoltan Szantoi: Supervision, Writing - original draft. Nuno César de Sá: Visualisation, Methodology, Writing - original draft. Steffen Fritz: Writing - review and editing. Milutin Milenkovic: Writing - review and editing. Joan Maso: Writing - review and editing. Viola Heinrich: Writing - review and editing. Martin Herold: Supervision, Writing—original draft, Project administration, Funding acquisition.

Disclosure statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding

KB thanks the funding by the European Union to the Open-EarthMonitor Cyberinfrastructure (Grant No. GA101059548) and JM for the All Data for The Green Deal (AD4GD) (Grant No.: 101061001). KB further thanks ESA World AgroCommodities under ESA contract N° 4000145440/24/I-EF. KB also thanks for the funding of the Open Geospatial Carbon Registry (OGCR) project of the European Union's Horizon Europe programme under grant agreement 101218854.

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Data availability statement

The repository of underlying data, including the questions of the survey and the responses, as well as the R code (R Core Team, 2023) for generating Figures 2-4, can be found here: https://zenodo.org/records/14865261.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used Perplexity in order to improve the readability and language of the manuscript. After using this service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

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