National Digital Infrastructure: clustering global open-source solutions for sovereign monitoring of the environment

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Abstract: The UN General Assembly (2015) emphasized the need for sustainable pathways to enhance resilience for people and nature, with future development driven by data and evidence. Sustainable development frameworks like the UN 2030 Agenda and the Paris Climate Agreement highlight the importance of data in decision-making, while respecting national policies and priorities. As Earth observation data and digital solutions advance, they offer more efficient, timely, and detailed statistics, with reduced costs. However, concerns about data and technological sovereignty have emerged. This paper introduces a flexible, sovereign national digital infrastructure framework for environmental monitoring, land management, and fulfilling reporting obligations. It combines customizable open-source solutions like the Open Data Cube and Living Earth to ensure data sovereignty. The paper demonstrates the framework's capability in Wales, where it has been successfully operationalized. We show that the NDI's structure, flexibility, and interoperability support holistic environmental monitoring and national reporting obligations. By enabling data sharing across organizations, it helps minimize inconsistencies and duplication, while improving transparency, traceability, and reproducibility. The NDI also has potential to foster collaboration between government agencies, environmental organizations, local communities, and stakeholders, supporting sustainable outcomes and promoting inclusivity in environmental and agricultural policy decision-making.

Keywords: Digital Infrastructure, Earth Observations, Open Data Cube, Living Earth, sovereignty, monitoring, reporting, open-source, transparency

1. Introduction

As emphasized by the United Nations (UN) General Assembly (2015), the World needs to shift to pathways that are more sustainable and ensure resilience of people and nature to adverse change. In support, future development strategies and decision-making need to be driven by data and backed up by evidence. Both collectively a) allow better identification of issues and obstacles to achievement, b) inform decision-making and support formulation of solutions, including through changes in policy and land management, c) ensure greater transparency and accountability of actions and responsibilities, and d) facilitate monitoring of progress towards goals and ambitions and effectiveness of proposed solutions and actions (UN General Assembly, 2015).

A number of sustainable development and global priority agendas have emphasized the importance of data to support evidence-needs. These include the UN 2030 Agenda for Sustainable Development (Anderson et al., 2017; Avtar et al., 2019; O'Connor et al., 2020), the Sendai Framework for Disaster Risk Reduction (Borges et al., 2022), the UN System of Environmental Economic Accounting (Vallecillo et al., 2019; La Notte et al., 2021) and the Paris Climate Agreement (ESA, 2022; Hegglin et al., 2022). Nevertheless, whilst these provide direction, consideration of the different national realities and respecting national policies and priorities is paramount and was highlighted by the UN General Assembly (2015) in the 2030 Agenda for Sustainable Development. In this regard, data-driven strategies can indeed provide a tool for bolstering national efforts at managing the environment (land, water and atmosphere) and economic development initiatives as well as fulfilling reporting obligations. Many countries have already established national strategies that foster data-driven developments and policies, with examples being the Data and Digital Government Strategy (Australian Government, 2023) and the Digital Switzerland Strategy (Swiss Confederation, 2023).

Geospatial information obtained from Earth Observations (EO) have played a fundamental role in data-driven governance. Satellite sensors in particular capture data that can be used, historically and/or in near real time, to measure and monitor Earth system states and dynamics. Since the launch of the Landsat-1 Multispectral Scanner System (MSS) in 1972, the spatial, spectral, and temporal resolutions of EO sensors, as well as their diversity (e.g., optical, thermal, RADAR and LIDAR) have continually improved. In addition to sensor refinement and enrichment, efforts over the past two decades to increase the openness and ensure continuity of data streams have led to a significant uptake in the use of EO data. Satellite data and derived products are also increasingly providing more timely inputs to national statistical and accounting systems (Paganini et al., 2018; Richards et al., 2021; Australian Bureau of Statistics, 2024). This new era was highlighted by the Task Team on Satellite Imagery and Geospatial Data of UN Global Working Group (GWG) on Big Data, who stated that "*EO data have significant potential to provide more timely statistical outputs, to reduce the frequency of surveys, to reduce respondent burden and other costs, to provide data at a more disaggregated level for informed decision making and to provide new statistics and statistical insights"* (UN Task Team on Satellite Imagery and Geospatial Data, 2017).

Despite the benefits of EO, the growing complexity and diversity of satellite sensors and measurements, the long-term continuation of both existing and new missions, and the expanded access to observations and derived products—collectively referred to as the Volume, Velocity, and Variety of EO data (Laney, 2001)— have led to an exponential increase in what is known as 'Big Earth Data' (Overpeck et al., 2011; Lewis et al., 2017; Guo, 2020; Guo et al., 2020). Big data (which includes that obtained through EO) are defined as "*sets of information that are too large or too complex to handle, analyse or use with standard methods*" (Oxford Advanced Learner's Dictionary, 2023) and searching, accessing, processing, and/or analyzing these poses an enormous technological challenge. Consequently, this has limited the routine uptake of EO satellite data by many end-users across multiple sectors and regions and their wide use in decision-making processes related to policy and environmental management (e.g., land management) (Mugo, 2023).

As the need for novel technologies and approaches to deal with Big Earth Data management and analysis has been recognized, several solutions and platforms have been proposed and developed based on the 'moving code' paradigm (Gomes et al., 2020). This approach relies on moving the algorithms from the client side to a specific service instance, where data are stored and which runs the code and provides its execution outputs through a Web Service interface, with this replacing the more traditional and often cumbersome direct download and processing through individual computers/servers (Müller et al., 2010). Organizations providing these solutions have developed cloud-computing platforms such as the Amazon Web Services (AWS, 2016), the European Commission-funded Data and Information Access Services (DIAS; Copernicus, 2018), Google Earth Engine (Moore & Hansen, 2011; Gorelick et al., 2017), the System for Earth Observation Data Access Processing and Analysis for Land Monitoring (SEPAL) (Tondapu et al., 2018) and Microsoft's Planetary Computer (Augspurger, 2021; Di Leo et al., 2023). These platforms continue to gather interest as they allow simple access to Big Earth Observation Data and concurrently provide high-performance computing resources and tools to process these via the Internet (Gomes et al., 2020; Wagemann et al., 2021). However, prior to selecting a solution, end-users need to thoroughly assess their specific local requirements, giving consideration (where appropriate) to governance prerequisites, institutional capabilities, geospatial analytics proficiency, associated expenses, and the long-term viability of the respective tool(s) or EO analysis platforms (Dhu et al., 2019). As pointed out by Sudmanns et al. (2022), it is crucial to acknowledge that these solutions have significant drawbacks and may not meet the requirements of individual or all users.

In an overview and comparison of platforms for Big Earth Observation Data management and analysis, Gomes et al. (2020) highlighted that most currently operating cloud-computing platforms rely on proprietary closed source software. This limits capacity to add new software tools that utilize the storage and processing modules available internally within the platform. Furthermore, they do not allow collaborative development or participation in governance by members external to the responsible teams. The UN General Assembly (2015), in its 2030 Agenda for Sustainable Development, recognized that "*there are different approaches, visions, models and tools available to each country, in accordance with its national circumstances and priorities, to achieve sustainable development*". Therefore, being able to integrate additional national datasets, tools and/or models (public or otherwise) is crucial. It is also important to consider potential challenges such as interoperability limitations, difficulties in sharing workflows, issues with infrastructure replicability, as well as hidden costs, limited access to well-documented datasets, unclear decision-making processes, and varying or opaque business models (Gomes et al., 2020; Schramm et al., 2021; Sudmanns et al., 2022). These elements are especially decisive when data and platforms are used by governments and other agencies when developing local to national policies (including visions) and making decisions. In the context of constantly evolving international geo-economic and techno-scientific environment and growing geopolitical uncertainties, the concept of and concerns regarding data and technology sovereignty have gained prominence in recent national and international debates (Edler et al., 2020).

Data/technological sovereignty is crucial for national governments and their agencies as it emphasizes the right of a country to control the access (including confidentiality), storage, and processing of data within its jurisdiction (Hummel et al., 2021). This is key in preserving the ability to govern national internal affairs without external interference (Hinsley, 1986; James, 1986) nor one-sided structural dependency (Edler et al., 2023). Consequently, relying on a global platform, including those mentioned above, could lead to a loss of control and, to some extent, jeopardize national and international reporting obligations, as well as the national strategies, autonomy and security. Besides, as mentioned by Sudmanns et al. (2022), most end-users are mainly interested in repeated analyses within the same limited area (e.g., country or region), and do not require the high-performance computing resources provided by these platforms for processing over large areas including globally. Hence, whilst providing high capability in big data processing, these cloud-computing platforms may not be well-suited for national governance, including at sub-national levels such as regional or local.

In this context, this paper presents a newly developed and implemented framework that clusters globally available open-source solutions to provide a flexible and sovereign national digital infrastructure for monitoring of the environment, managing land, and fulfilling reporting obligations. This work builds on lessons learned from the various national digital infrastructures and aims to facilitate the traceability, sharing, and interoperability of approaches adopted by a range of organizations operating nationally or sub-nationally. Indeed, while presenting a flexible and internally controlled infrastructure for local to national decision-making making and digital/data sovereignty, this paper also provides a framework for developing an open standard system that might facilitate the interoperability, transparency, reproducibility of data and reported information. In this paper, the generic capability and structure of the developed framework is demonstrated for Wales, a devolved country of the United Kingdom (UK), where it has successfully been operationalized by the Welsh Government.

2. National Digital Infrastructure: a flexible and open framework

2.1. Core technology: Open Data Cube

The Open Data Cube (ODC) is a free open-source management and analysis architecture solution for handling big geospatial data, including Big Earth Observation Data (Open Data Cube, 2023). The ODC utilizes a PostgreSQL database and a range of tools and functionalities that allows for efficient spatio-temporal querying, visualization, and analysis of indexed (i.e., catalogued) data and can be easily deployed and run on either a local machine or server via a Docker container (https://github.com/opendatacube/datacube-core). The scalable architecture of the ODC supports parallel processing and distributed computing, making it ideal for handling complex geospatial analyses. Its modular design allows for customization and integration with other tools and libraries, enabling users to build tailored solutions for their specific requirements.

The ODC was developed by Geoscience Australia in collaboration with several partners, including the Committee on Earth Observation Satellites (CEOS). The ODC builds on the Australian Geoscience Data Cube (AGDC), now called Digital Earth Australia (DEA), which also involves the National Computational Infrastructure (NCI) and the Australian Commonwealth Scientific Industrial Research Organisation (CSIRO) (Lewis et al., 2017; Killough, 2018; Gavin et al., 2018). The project provides publicly accessible documents that outline the platform's governance process (https://github.com/opendatacube/governance) and offers guidance on creating or integrating new features into the platform (Gomes et al., 2020). The free and open-source nature of the ODC, its interoperability and flexibility enable this tool to meet the data/technological sovereignty required by national governments and hence was chosen as the core technology for the National Digital Infrastructure (NDI) framework (Figure 1). Several countries (e.g., Australia, Mexico, Switzerland, Colombia, Tanzania, Armenia) have already adopted this technology to manage national data (Giuliani et al., 2017a; Gavin et al., 2018; Ornelas De Anda et al., 2019; Asmaryan et al., 2019; Ferreira et al., 2020; Chatenoux et al., 2021; Yuan et al., 2021, Killough et al., 2022), thus facilitating the data sharing and interoperability of this system with those existing.

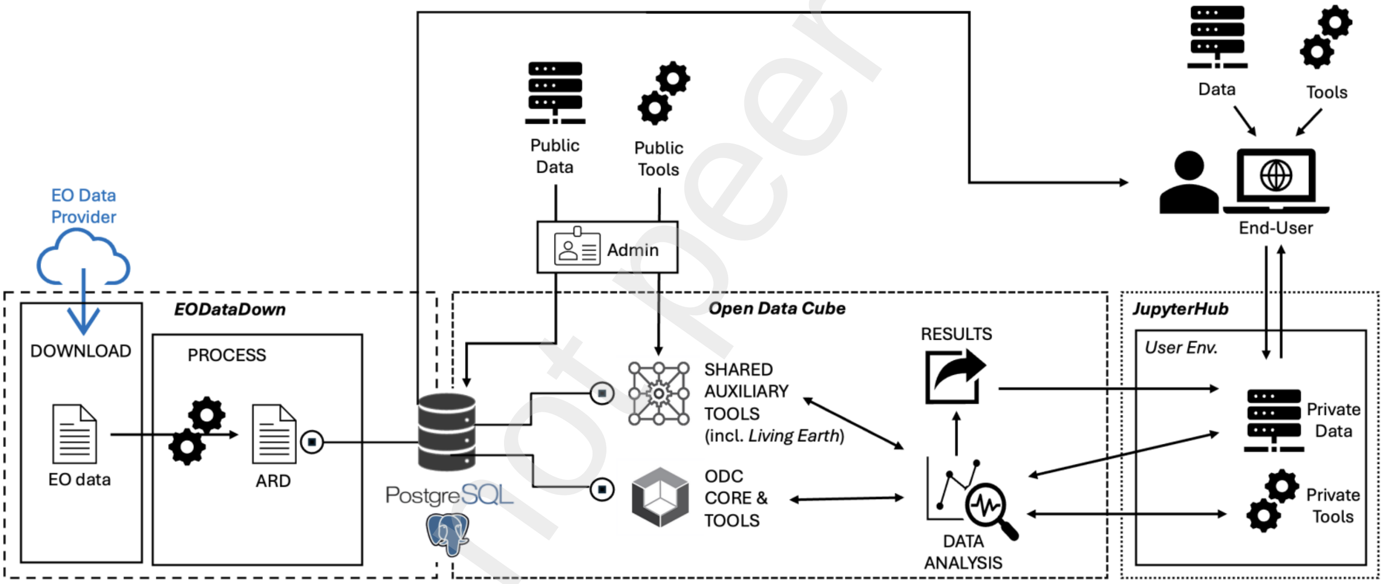

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Figure 1. Flexible and Open framework for the National Digital Infrastructure.

2.2. Automatic Analysis Ready Data: EODataDown

At the core of any EO data cube deployment is the underpinning concept of Analysis Ready Data (ARD) (Dhu et al., 2017; Strobl et al., 2017; Killough, 2019; Killough et al., 2020; Killough et al., 2021). The ODC allows geospatial (including EO) data to be analyzed efficiently and effectively. However, to allow EO from various sources (i.e., different sensors) to be used and analyzed, pre-processing (i.e., processing chains and/or algorithms) need to be standardized using appropriate and recognized methods. Most end-users of EO data lack the expertise, infrastructure, bandwidth or even just time to perform such task (Lewis et al., 2018). Consequently, countries and international organizations have expressed the need to access EO data that have been processed to a level that allows immediate analysis with minimum additional effort and that are interoperable through time and with other datasets. Thus, CEOS has developed the concept of 'Analysis Ready Data' (ARD) and 'CEOS ARD for Land' (CARD4L) products, which are data that are compliant with Product Family Specifications (PFS) defined by the CEOS Land Surface Imaging Virtual Constellation (LSI-VC) team (Killough et al., 2020). Nowadays, ARD product specifications exist for land surface and aquatic reflectance, surface temperature, nighttime lights surface radiance and Synthetic Aperture Radar (SAR). Additional PFS are being developed (e.g., LiDAR Terrain and Canopy Top Height) (CEOS, 2024). More and more satellite EO datasets are being produced with the view of receiving the CEOS Analysis Ready Data (CEOS-ARD) certification, with 14 datasets already credited, 1 under pre-review and 23 under development or assessment.

CEOS-ARD datasets are not necessarily free, open, up-to-date and/or globally available to use for routinely monitoring land and water surfaces. For example, the Advanced Land Observing Satellite-2 (ALOS-2) Phased Array L-band Synthetic Aperture Radar (PALSAR-2) 'Global Mosaics' CEOS-ARD product has these attributes but is only available as an annual composite. The 'Sentinel-1 RTC' CEOS-ARD allow routine monitoring of land but are only freely available for Africa through Digital Earth Africa (Yuan et al., 2022). Indeed, Sinergise, who is the company responsible for processing Sentinel-1 CEOS-ARD for the Digital Earth Africa project, also created a tool that allows generation of Sentinel-1 CARD4L compliant data (https://apps.sentinel-hub.com/s1-card4l/) for any location through the SentinelHub. However, the tool uses AWS S3 buckets to store the requested data, and users need to pay for the transfer of these (Sinergise, 2021). Relying on AWS further limits the opportunity to create the open, interoperable and internally controlled infrastructure (i.e., true digital sovereignty) required by national governments (Kushwaha et al., 2020). Finally, the CEOS-ARD certification ensures that datasets are provided with minimum pre-processing steps, but users may need to undertake additional steps depending on their data usage. In this context, most countries that have adopted the EO data cube technology to inform their policies and support decision-making are also pre-processing EO data into a form that allows them to meet national requirements and be interoperable with other national datasets. For example, Switzerland used the LiMES framework to automatically process Landsat, Sentinel-2, and Sentinel-1 data to an ARD format (Giuliani et al., 2017b; Giuliani et al., 2017a; Giuliani et al., 2018; Chatenoux et al., 2021), whereas Australia has adopted DEA ARD standards for Landsat and Sentinel-2 data that include implementation of nadir Bidirectional Reflectance Distribution Function (BRDF) and terrain illumination correction (Lewis et al., 2017; Dhu et al., 2017). Therefore, it is important that the tools and software integrated in the solution proposed in this paper allow generation of ARD according to the nationally-recognized standards.

In order to comply with the digital sovereignty requirements of the public sector, the proposed solution builds on the Earth Observation Data Downloader (EODataDown) Free/Libre Open Source Software (Bunting, 2020). EODataDown is a Python written software which allows automatic downloading and pre-processing of EO data to an ARD format. By default, it contains a few functionalities for downloading and pre-processing data from a specific list of sensors (i.e., Sentinel-2, Sentinel-1, Landsat 1-8, GEDI, ICESAT-2) and platforms (e.g., Alaska Satellite Facility (ASF), Google Cloud). However, its modular design allows for customization and integration with other tools and sensors, enabling users to build tailored solutions for their specific requirements (John et al., 2021; John, 2023). In EODataDown, the downloaded and processed data are indexed within a PostgreSQL database, similarly to the ODC. This shared technology facilitates the connection of these two open-source solutions into one infrastructure (Figure 1). EODataDown further offers a web interface which allows visualization and direct desk downloading of the ARD indexed in the PostgreSQL database (Rosenqvist et al., 2020).

2.3. User access and interaction: JupyterHub

JupyterHub is a free and open-source solution that allows multiple users to access and interact on a shared environment (Perkel, 2018; Brown, 2018). Integrated in the NDI framework, using Zero to JupyterHub (https://z2jh.jupyter.org/) with Kubernetes, JupyterHub allows users to access ODC through a web browser in an easy way. Each user is provided with their personalized environment through individual Docker containers, ensuring a secured space for them to work in without disrupting others. This setup also grants individuals with specific computational resources for running applications (e.g., CPU, memory, storage). Within their private workspace, users can write and execute code that interacts with the ODC datasets, allowing them to manipulate and analyze the data in a collaborative and interactive environment. Additional data, libraries and tools can also be easily uploaded and downloaded by users to/from their private workspace using the JupyterLab interface (Figure 1). These can be used as standalone, or with any of the tools/data available in the NDI to all users, thereby providing a fully flexible and tailored solution. Several user authentication methods can be used with JupyterHub (JupyterHub, 2024), including local authentication, the Pluggable Authentication Module (PAM) or the lightweight directory access protocol (LDAP). OAuth authentication can also be configured to allow users to sign in using their credentials from other OAuth providers including GitHub (https://github.com).

2.4. Tailored environmental monitoring: Living Earth

The NDI framework has a modular design which allows for customization and integration with other tools and libraries, as well as data. This flexibility allows individual nations and end-users to build tailored solutions that meet their specific requirements. There are two types of tools and data that can be incorporated into the NDI: privately owned and publicly shared. Privately owned data/tools can be added by end-users directly through JupyterHub (see Section 2.3.), while publicly shared ones are integrated by NDI administrators. Indeed, some tools and data are of public interest and/or used by many stakeholders. When there is a consensus on their value, these data can be integrated directly into the PostgreSQL database by an administrator, and the tools can be provided to all users as part of the shared infrastructure.

This paper intends to introduce an open and flexible NDI framework for sovereign monitoring of the environment. In this regard, an open and flexible tool called *Living Earth* has been integrated into the publicly shared toolboxes (Figure 1). *Living Earth* is a free and open-source software package, under Apache 2.0 license (https://bitbucket.org/au-eoed/livingearth_lccs), which allows characterization, mapping and monitoring of land and water (Owers et al., 2021; Planque et al., 2020; Lucas et al., 2019; Lucas et al., 2018). Developed in a collaboration with Australia (Geoscience Australia) and the UK (Aberystwyth University), the system classifies land cover according to the internationally recognized and globally applicable United Nations Food and Agricultural Organization's (FAO) Land Cover Classification System Version 2 (LCCS-2; Di Gregorio, 2005). *Living Earth* has been optimized for EO data (Owers et al., 2021) and can be run as standalone or implemented in various technological facilities, including data cubes (e.g., DEA), High-Performance Computing infrastructures (e.g., Australia's National Computational Infrastructure (NCI), Supercomputing Wales) or cloud services (Owers et al., 2022; Owers et al., 2021). The main advantage of *Living Earth* is its flexibility as the system gives users access to tailored ready-to-use products with which to characterize, map and monitor the environment thereby informing policy review and development, decision making with regard to land management and obligatory reporting of environmental states and conditions at national levels (including SDGs; Owers et al., 2021).

Contrary to most land cover classification systems, *Living Earth* does not provide a static two-dimension map. Instead, the system stacks environmental descriptors (EDs) to physically describe the environment. In this respect, users can add as many EDs as they need to characterize an area, including those not originally included in the FAO LCCS taxonomy (e.g., water temperature, plant species type or biomass). To ensure full flexibility and compliance with national sovereignty requirements, options are available for modifying the original FAO land cover classes (e.g., by including different categorical divisions of continuous variables such as annual water persistence). Finally, the system is independent of time or spatial scale and therefore can be used with any spatial resolutions and temporal frequencies of the observing sensors. All these functionalities ensure that *Living Earth* is fully flexible in mapping and describing land covers and allows generation of ready-to-use products that are in line with local priorities and values, and which align with national sovereignty principles. In Australia, *Living Earth* has been used to map land covers annually since 1988 from the entire archive of 30 m Landsat data and from EDs (i.e., the extent of vegetated, aquatic, cultivated and artificial covers; Owers et al., 2022; Lucas et al., 2019) that provide the broad land covers. Each is then further described using a range of EO-derived categorical and continuous EDs (i.e., lifeform, canopy cover, and water persistence and seasonality). *Living Earth* is being applied in Switzerland using same EDs to those used in Australia but additionally integrates snow persistence, as this ED is of national significance (Poussin et al., 2024). Options are also being developed for extending the classifications to underwater (freshwater, intertidal and subtidal) environments.

3. Study case: Application to Wales

3.1. Study area

Wales' land area occupies 20,782 km^2 of land, with 2,700 km of coastline separating it from the 15,946 km^2 of inshore sea, and is associated with the Atlantic biogeographical region (European Environment Agency, 2017). The climate is characterized by humid and mild weather conditions, with an annual average precipitation (falling as rain or snow) of 1465 mm and annual average temperature of 9.4 ^{o}C for the period 1991-2020 (Met Office, 2020). Despite being part of the same biogeographical region, Wales' diverse topography and geology creates a mosaic of habitats that host a wide variety of species. These include rare and endemic flora and fauna species, including some of national and international importance such as *Cotoneaster cambricus* and Ley's whitebeam (*Sorbus leyana*) and a number of seabirds (Smith et al., 2023). The diversities of topographies across Wales play a crucial role in creating a range of environmental settings that support 55 habitats of principle importance including upland oak woodlands, costal saltmarshes, intertidal mudflats, upland heathlands, blanket bogs, or purple moorgrass and rush pastures (NRW, 2016; Welsh Government, 2016). Despite representing only 8 % of the United Kingdom area, Wales is home to estimated 50,000 species of the 70,000 found in the UK (Noebels et al. 2023; Collins, 2021). However, despite this richness of habitats, Wales's flora and fauna are facing significant challenges. In the last *State of Nature* report, Smith et al. (2023) reported that 18% (one in six) of the Welsh species are at risk of extinction and species' abundance has decreased on average by 20% since 1994. Land management practices and climate change have been identified as the main drivers of biodiversity loss (Smith et al., 2023). In Wales, 90% of the land area is used for agriculture (Welsh Government, 2022a) and only 11% of the land is protected, with just 35% of these protected sites being in favourable condition (Smith et al. 2023). As a result, in June 2021, the Welsh Parliament declared a nature and climate emergency and called on the Welsh Government to *"introduce legally binding requirement to reverse biodiversity loss through statutory targets"* and *"legislate to establish an independent environmental governance body for Wales"* (Welsh Parliament, 2021).

3.2. Key environmental and land management policies

The new legislative framework introduced in Wales in 2015-2016 marked a significant shift towards a more sustainable and forward-thinking approach to policy making. The *Well-Being of Future Generations (Wales) Act 2015* emphasizes the importance of sustainable development and requires public bodies in Wales to consider the long-term impact of their decisions on future generations (National Assembly for Wales, 2015a). The *Planning (Wales) Act 2015* aims to update the planning process, making it easier for communities to have a say in local development projects (National Assembly for Wales, 2015b). The *Environment (Wales) Act 2016* focuses on protecting and enhancing the natural environment, including measures to maintain and enhance biodiversity, promote ecosystem resilience, and improve water and air quality (Welsh Government, 2024a; National Assembly for Wales, 2016). One crucial aspect of the legislative change has been the United Kingdom's departure from the European Union (UK Parliament, 2018). Following this departure, the *Agriculture (Wales) Act 2023* has been implemented to ensure that Welsh agriculture complies with the new legislative framework, and especially with the *Well-Being of Future Generations (Wales) Act 2015* and *Environment (Wales) Act 2016* (Welsh Government, 2023). Together, these acts represent a commitment to building a more resilient and environmentally conscious Wales.

The introduction of these acts has had a significant impact on national environmental policies and reporting obligations in Wales. For example, the *Natural Resources Policy* marks a significant step forward in the enforcement of the *Environment (Wales) Act 2016* (Welsh Government, 2017), which seeks to ensure responsible management and protection of Wales's natural resources for current and future generations. Other strategies have been revised and updated. As examples, the *National Strategy for Flood and Coastal Erosion Risk Management* (Welsh Government, 2020) addresses the increasing threat of extreme weather events, and the *Woodlands for Wales* strategy (Welsh Government, 2018) aims to promote sustainable management of woodlands and forests. In terms of land management, the *Agriculture (Wales) Act 2023* has introduced the *Sustainable Land Management* framework, which focuses on encouraging sustainable land management and protecting biodiversity (Welsh Government, 2024a; Welsh Government, 2023). To assist farmers in adopting this framework, the *Sustainable Farming Scheme* (SFS) is being developed to replace the subsidies previously provided by the European Union through the Common Agricultural Policy (CAP). The SFS is being co-developed with farmers, agricultural experts, environmental organizations and government officials, and intends to adhere fully to the principles of co-design (i.e., transparency, inclusivity, shared power and participation; Lyon et al., 2023). The scheme specifically aims to empower farmers to take ownership of their sustainability practices and drive positive change towards a more environmentally friendly and socially responsible farming sector in Wales.

3.3. National requirements for the NDI

Overall, the new legislative and policy framework in Wales encourages a more holistic, cooperative, and proactive approach and establishes clear environmental goals and targets. These targets are legally binding and require regular reporting and monitoring to ensure progress is being made by all parties involved (i.e., from government to farmers). To completely embrace the revised legislative framework, the Welsh Government must ensure that the decisions made are in line with local priorities and values and, therefore, must have control over its own data and digital infrastructure.

The paper proposes a flexible structure that can adapt to national requirements but is also relevant locally. The generic capability and structure of this framework is customized and demonstrated for Wales according to its specific requirements. Based on consultation with Welsh Government, these included:

- Alignment with national sovereignty principles.
- Open, transparent and interoperable.
- Providing ready-to-use products and functionalities at appropriate spatial scales (nominally 10-20 m) that can support policy-making and reporting obligations.
- Minimizing *in house* maintenance and cost.

3.4. Welsh NDI: implementation

The generic capability and structure of the NDI is presented (c.f., Section 2). In addition to the embedded functionalities provided by the framework, such as ODC tools or capacity to download Sentinel-1 Level-1 data from the ASF platform (using the

EODataDown system), the entire NDI was tailored to meet national requirements (c.f., Section 3.3) whilst also achieving national data/digital sovereignty of the core digital infrastructure, data and applications.

3.4.1. Tailored digital infrastructure

In developing an NDI, an understanding of user needs was critical. In Wales, some users still require and request capacity to download a few scenes on their personal/professional computer. This was achieved by implementing a web interface for EODataDown's that allowed visualization and desk downloading of the indexed data (c.f., Section 2.2 and Figure 2). To improve the user experience, the JupyterHub was configured using GitHub for authentication. This eliminated the need for users to create and remember another set of login credentials and concurrently provided secure authentication mechanisms (including two-factor authentication) and capacity for administrators with specified roles to easily manage user access and permissions.

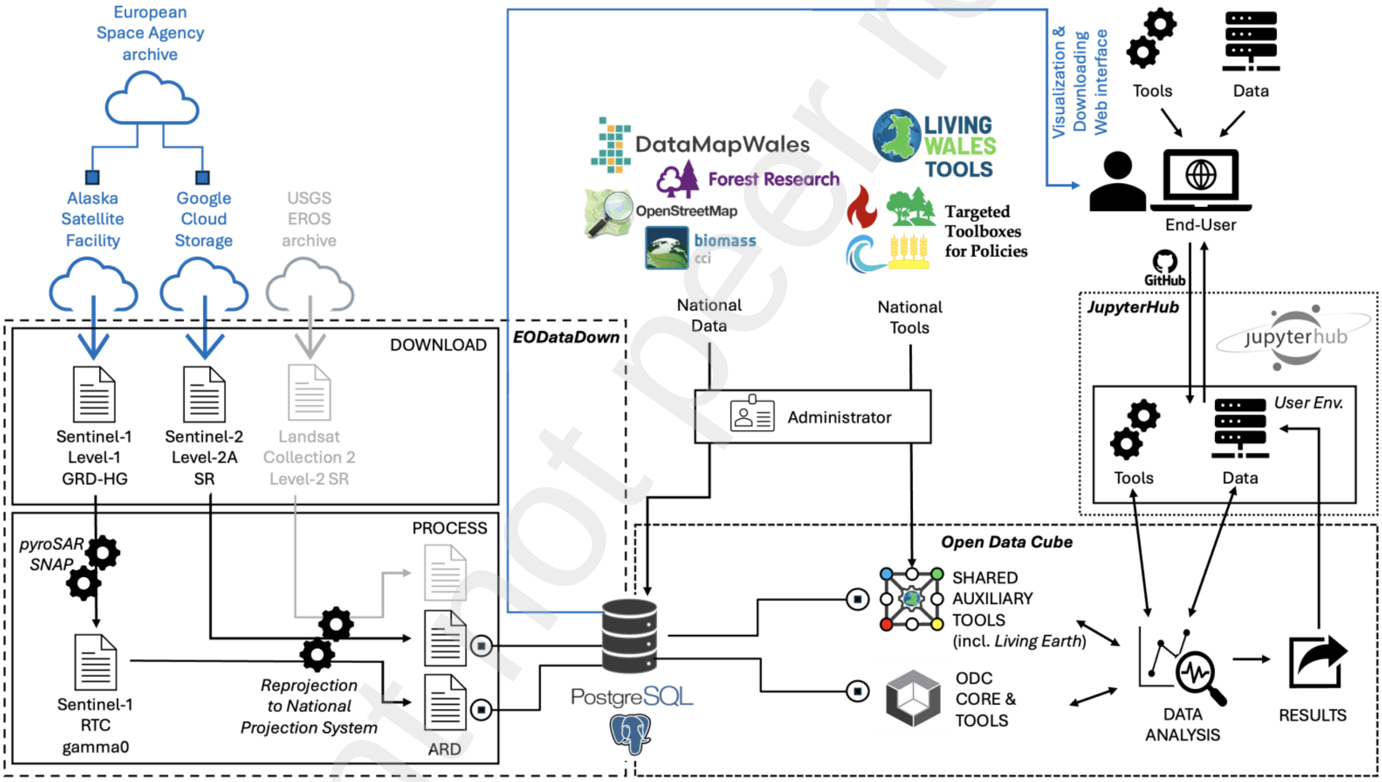

Figure 2. The National Digital Infrastructure for Wales. The downloading and processing of Landsat Collection 2 Level-2 Surface Reflectance (SR) has been developed but not implemented in the operational Welsh NDI.

In the list of requirements set by Welsh Government (see Section 3.3.) was the reliance on open and interoperable solutions within the NDI, with minimum *in house* maintenance and cost. For this reason, EODataDown was modified to allow generation of Analysis Ready Data (ARD) using the free open-source solutions developed, provided and maintained by official Space programs (where existing) including the European Space Agency's (ESA) Sentinel Applications Platform (SNAP) for processing SAR data. SNAP is an open-source and globally recognized architecture for ESA Toolboxes (Weiß and Fincke, 2022). In the Welsh NDI version of EODataDown, SNAP was integrated via the pyroSAR Python library (https://pyrosar.readthedocs.io/en/latest/), which provides a Python wrapper to SNAP (Truckenbrodt et al. 2019) and allows parsing of various options for tailored solutions.

EODataDown has been further customized to directly ingest freely-available CEOS-ARD certified EO data. With this purpose, a pipeline for downloading and reprojecting (to the national projection system) the Sentinel-2 Level-2A surface reflectance product from Google Cloud Storage (gs://gcp-public-data-sentinel-2/L2/) has been developed and implemented (Figure 2). Download from Google Cloud Storage was preferred as ESA only allows a maximum of two concurrent downloads on its platform (Rigoli et al., 2021). However, flexibility for downloading data directly from the official ESA platform exists. Capacity to download 30 m CEOS-ARD Landsat Collection 2 Level-2 data via the USGS/EROS M2M API (https://m2m.cr.usgs.gov/), and reproject to the national projection system (i.e., as for Sentinel-2), was also developed (Figure 2) but not yet implemented in the operational Welsh NDI. This was partly because the use of "*high resolution (10-20 m)*" was one of the requirements set by Welsh Government.

3.4.2. Tailored Earth Observation: downloading and pre-processing

All EO data are automatically downloaded and pre-processed through EODataDown and then indexed into the PostgreSQL server shared with the ODC. In the Welsh NDI, free and open-source Sentinel-2 optical and Sentinel-1 SAR data acquired over Wales are automatically downloaded (Figure 3). Sentinel-2 scenes were downloaded for tiles overlapping with the Welsh land area but also with the watersheds of rivers where the source or outflows are in Wales (including the River Wye and River Severn), with this benefiting, for example, flood applications and avoiding differences in cross-border land classifications. Given the large volume of data associated with Sentinel-1, these were cropped to bounding box extent of Wales (Figure 3) which also included these catchments. All scenes downloaded were then processed to the following standards, twice daily.

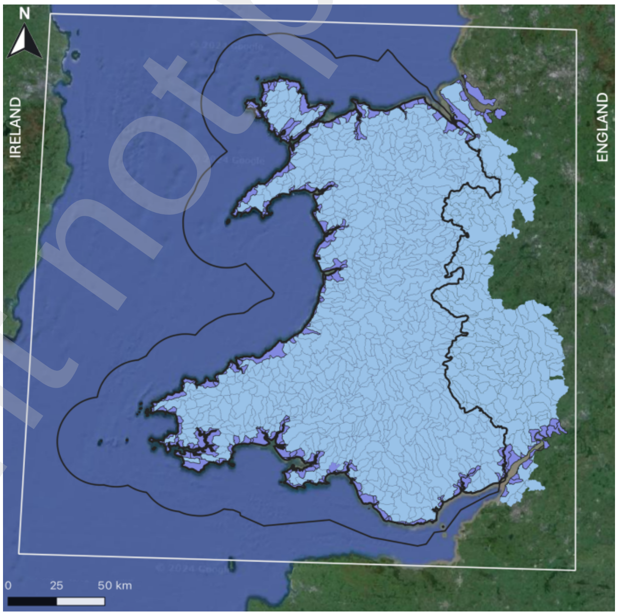

Figure 3. Limits of the area for searching and downloading EO data for the Welsh NDI (in white). The black bold line delineates the land and inshore regions of Wales. The light blue and purple polygons indicate the river waterbody and coastal catchments for the Water Framework Directive in Wales, respectively.

3.4.2.1. Sentinel-2

The ESA-Copernicus Sentinel-2 mission includes two polar-orbiting satellites that each support the optical MultiSpectral Instrument (MSI). These satellites have been placed in the same sun-synchronous orbit and are phased at 180° to each other. Together they provide capacity for the Earth to be observed every 5 days at the Equator. Sentinel-2 multispectral data acquired over Wales have been downloaded as an atmospherically corrected (Level-2A) product (i.e., CEOS-ARD certified) with a spatial resolution of 10 m, 20 m, and 60 m depending on the spectral band (SentinelHub, 2024). All data have been reprojected to the British National Grid (EPSG: 27700) and indexed into the PostgreSQL server (Figure 2). ESA only provides Sentinel-2 Level2-A products from April 2017 and hence, the provision of data for the full 2017 year required processing of the three missing months (i.e., January-March) from Level1-C Copernicus products to Level2-A using the official Copernicus Sen2Cor version 2.5.5 software (https://step.esa.int/main/snap-supported-plugins/sen2cor/) and the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM). A comparative analysis of surface reflectance values obtained through this processing and the official Level 2A products supplied by ESA-Copernicus for May 2017 was conducted, with this indicating minimal differences between the two (not shown here).

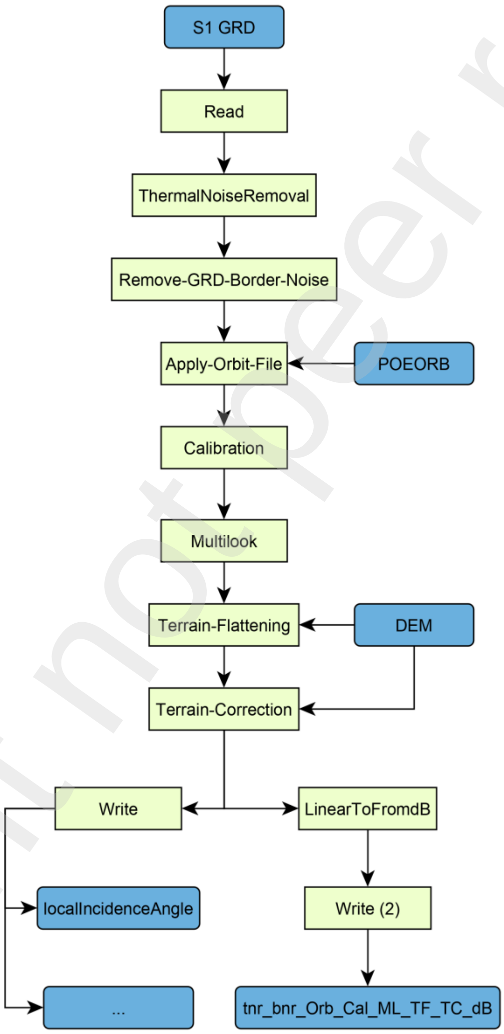

Figure 4. Workflow diagram for processing a Sentinel-1 Ground Range Detected (GRD) scene to ARD radiometrically terrain corrected (RTC) backscatter using the ESA's SNAP software wrapped in pyroSAR (image source: Figure 4, right, in Truckenbrodt et al., 2019).

3.4.2.2. Sentinel-1

The ESA Sentinel-1 mission, when in full operation, is comprised of a constellation of two polar-orbiting satellites supporting a C-band Synthetic Aperture Radar (SAR) that can acquire data both day and night and regardless of most atmospheric conditions. This is particularly relevant to Wales where images are acquired at least every 6 or 12 days (depending on whether one or two satellites are operating) despite the prevalence of cloud cover in most months. For Wales, Sentinel-1 Level-1 Ground Range Detected High-Resolution (GRD-HD) Dual-Polarization data acquired with Interferometric Wide swath (IW) mode are downloaded from the Alaska Satellite Facility (ASF) and processed to an ARD format (i.e., radiometrically terrain-corrected (RTC) SAR gamma nought backscatter), as suggested by Truckenbrodt et al. (2019), before ingestion into the PostgreSQL server (Figure 4). Similarly to Sentinel-2, download from ASF has been preferred over the ESA platform, as the latter limits the number of concurrent downloads (Rigoli et al, 2021). During the Sentinel-1 pre-processing, the 'terrain-flattening' and 'terrain-correction' steps (Figure 2) used the auto-downloaded 'SRTM 1Sec HGT' DEM. The distributed Sentinel-1 data include both VH (Vertically transmitted, Horizontally received) and VV (Vertically transmitted and received) polarizations, in decibel (dB), with 10 m spatial resolution.

3.4.3. Auxiliary data and tools for tailored usage

The modular design of the NDI framework allows for customization and integration with other tools and libraries, as well as datasets. This enables end-users (individuals, groups or organizations operating from local to national levels) to build tailored solutions for their specific requirements. As mentioned in Section 2, a) publicly shared, and b) privately owned tools and data can be added and used in the NDI. Privately own data/applications can be easily added by any user of the NDI through their private workspace using the JupyterLab interface to obtain a solution that perfectly matches one or more specific and/or personal requirements (see Section 2.3.). However, to fulfil Wales' aim of adhering fully with the principles of transparency and accountability and ensuring shared power and participation (c.f., SFS in Section 3.2.), a unified approach to data access and reported information is crucial. Therefore, to facilitate this, the Welsh NDI provides a publicly shared space that gives real-time access to relevant data and a range of monitoring and reporting tools.

3.4.3.1. Public national datasets

DataMapWales is the national Geographic Information Systems developed by the Welsh Government (https://datamap.gov.wales/) that provides access to a wide range of data and maps from the Welsh public sector and aims to make information about Wales easily accessible and usable for a wide range of users, including policymakers, researchers, businesses, and the general public. Data in the catalogue can be downloaded to desktops for further analysis, noting that not all are publicly available.

Open environmental maps distributed by Welsh Government and its environmental executive agency (i.e., Natural Resources Wales) through DataMapWales were identified as important for monitoring and reporting obligations in Wales. These were then integrated into the Welsh NDI to allow direct viewing and integrated analysis within this single unified environment and avoid the need for download before use. These included the Phase 1 Habitat map (JNCC, 2010; Lucas et al., 2011, Punalekar et al., 2024), which was developed alongside the Habitat Survey of Wales and currently remains the national reference provided by Natural Resources Wales (NRW), NRW's Saltmarsh Extent, the recently updated peatlands of Wales (Welsh Government, 2022b), the Mean High Water Spring tides (MHWS), representing the maximum tidal area reached during spring tides; Welsh Government, 2024b), a Wales-wide Digital Terrain Model (DTM; and derived slope) obtained primarily from the Historic LiDAR Archive, and National Forest Inventory (NFI) woodlands provided by Forest Research and containing key information for national reporting obligations. All the datasets, listed in Table 1, have been rasterized or rescaled to 10-m spatial resolution prior to integration within the PostgreSQL database of the ODC by the Welsh NDI administrators and are available to all users as ARD as part of the shared infrastructure (Figure 2).

Table 1. Auxiliary datasets openly available in the shared space of the Welsh National Digital Infrastructure, with their data cube name, description, creation period and source provider. Providers are Natural Resources Wales (NRW), Welsh Government (WG), Open Street Map (OSM) and Forest Research (FR).

Dataset	Data cube name	Description	Period	Source
Phase 1 Habitat	*nrw_phase1_datamap*	Habitat type map	70s-90s	NRW [1]
Saltmarshes	*nrw_saltmarshes_lle*	Extent of saltmarsh in coastal and transitional waters	2017	NRW [2]
Topography	*eoed_topo_eoed*	DTM and slopes derived from the national LiDAR (0.25 -2 m)	2002-2015	NRW [3]
Peatlands	*wg_peatlands_datamap*	Distribution of Welsh peatlands	2022	WG [4]
Mean High Water Spring (MHWS) tides	*wg_mhws_datamap*	Maximum tidal area reached during spring	2023	WG [5]
Linear features	*osm_free_geofabrik*	Roads, railways, buildings, and waterways	2019	OSM [6]
National Forest Inventory (NFI) woodlands	*nfi_woodland_fr*	Woodland type	2017-2021	FR [7]

1 https://datamap.gov.wales/layergroups/geonode:nrw_terrestrial_phase_1_habitat_survey
2 https://datamap.gov.wales/layers/inspire-nrw:NRW_SALTMARSH_EXTENTS
3 https://datamap.gov.wales/layers/inspire-nrw:NRW_LIDAR_ARCHIVE_TILE_CATALOGUE
4 https://datamap.gov.wales/layers/geonode:peatlands_of_wales_scg8
5 https://datamap.gov.wales/layers/geonode:wnmp_areas
6 https://download.geofabrik.de/europe/united-kingdom/wales.html
7 https://data-forestry.opendata.arcgis.com/

3.4.3.2. Publicly shared tools and applications

In Wales, as part of the *Living Wales* project (https://livingearthhub.org/europe/wales/; Planque et al., 2020), algorithms have been developed to retrieve or classify the EDs required by *Living Earth* to construct the land cover maps according to the Food and Agriculture Organisation (FAO) Land Cover Classification System (LCCS) (Section 2.4.). These algorithms, described in Table A1, use the Sentinel-1 and Sentinel-2 ARD (see Section 3.4.2), as well as auxiliary datasets (see Table 1), available in the publicly shared space of the Welsh NDI. In addition to the mandatory overarching EDs (i.e., vegetated, aquatic, cultivated, artificial), algorithms were also developed to retrieve lifeform (i.e., woody, herbaceous), leaf type, phenology and water persistence and seasonality EDs (see Table A1). As mentioned in Section 2.4., to ensure full flexibility and compliance with national sovereignty, options for modifying the original FAO LCCS classes exists in *Living Earth*. To align with Wales' national requirements, the EDs of water persistence and seasonality were merged into an ED termed water/wetness persistence, water/wetness persistence has been allowed in all vegetated areas, and non-perennial class (i.e., < 9 months) have been discretized into one-month range, instead of 3-month range, categories. Knowledge of the persistence of open water alongside soil wetness in vegetated areas is particularly relevant to Wales, as the country is increasingly being subjected to prolonged period of rainfall and intensive rainfall events (Kendon et al. 2021; Jenkins et al., 2008), leading soils to be at or beyond saturation point for extended periods (NFU Cymru, 2024). With climate change, this trend is expected to continue (Thompson et al. 2017) and being able to monitor water/wetness persistence in terrestrial cultivated areas is key for Wales, as this has had a significant impact on cropping systems.

Living Earth and the associated *Living Wales* plugins for ED retrieval and land cover map generation are all available as part of the publicly shared infrastructure (Figure 2). Summaries of EDs (e.g., water/wetness persistence) and land cover maps have been generated annually from 2018, which was the starting year of the *Living Wales* project. National-level accuracy assessment of the most recently provided layers (i.e., 2023) has been undertaken using an area-based random stratified approach (Stehman and Foody, 2019; Olofsson et al., 2014) to establish representative locations for sampling, and Google Earth imagery and 3-m resolution PlanetScope images acquired over that year for visual interpretation. For the *Living Wales* land cover base map (comprised of the mandatory overarching EDs; Lucas et al., 2022), 2700 reference points were identified whilst a further 894, 869 and 884 were associated with the EDs of lifeform, leaf type and leaf phenology. From the resulting confusion matrices, Overall (OA) and both User (UA) and Producer (PA) Accuracies were calculated. Accuracy statistics for water/wetness persistence were unable to be obtained because of the lack of appropriate and timely reference ground data, particularly as the maps are produced from time-series of Sentinel-1 SAR data. However, comparison with water/wetness extents mapped from other national layers, such as the MHWS layer, demonstrated a good correspondence (not shown in this paper).

To ensure that the delivered applications/products are fully compatible with the Welsh national ambitions and can be used for reporting obligations, an application allowing the translation of the *Living Wales* land cover maps to habitat types aligning with the Phase-1 Habitat Taxonomy has been developed and included in the Welsh NDI. The application has been used to generate annual habitat maps (both detailed and broad) for Wales from 2020. Detailed explanations about the translation scheme are provided by Punalekar et al. (2024). All annually derived products (i.e., EDs and land cover and habitat maps) are indexed in the PostgreSQL server and available to all users (Figure 2). Additional EDs (i.e., crop type; Planque et al., 2021) and the European Space Agency's (ESA) Climate Change Initiative (CCI) Woody Above Ground Biomass (Mg.ha^{-1}; Hunka et al., 2023; Santoro et al., 2023), have also been integrated in the Welsh NDI for available years (i.e., 2018, and 2010 and 2015-2021 respectively).

Finally, in addition to the *Living Earth*-related plugins/products, a series of applications allowing the generation of ready-to-use products have been developed and made available in the publicly shared space of the infrastructure, including for Near-Real Time (NRT) monitoring and report writing (see Section 4.1.2.). These have been developed to ensure that the Welsh NDI provides a complete range of ready-to-use products and functionalities with which to perform policy-making and reporting obligations. The applications are relevant to Welsh national policies and regulations and can be grouped into four toolboxes, namely flood, fire, forest and crop monitoring, with all functioning with the EO ARD available in the Welsh NDI.

4. Results and Discussion

4.1. Sovereign system for holistic monitoring of the environment

Data/technological sovereignty asserts a country's right to control the access (including confidentiality), storage, and processing of data within its jurisdiction to govern national affairs (Hummel et al., 2021; Hinsley, 1986; James, 1986). In Wales, the NDI has been tailored and implemented to meet these criteria. First, to ensure that the access and storage are fully controlled by Wales, the NDI was initially deployed on a national server with a dedicated 20 core, 2.5GHz, processor, 256GB RAM, and four 18TB disks for storage. Second, the Welsh NDI was customized to enable choice and control of EO data providers, processing levels, and other tools and data within the infrastructure.

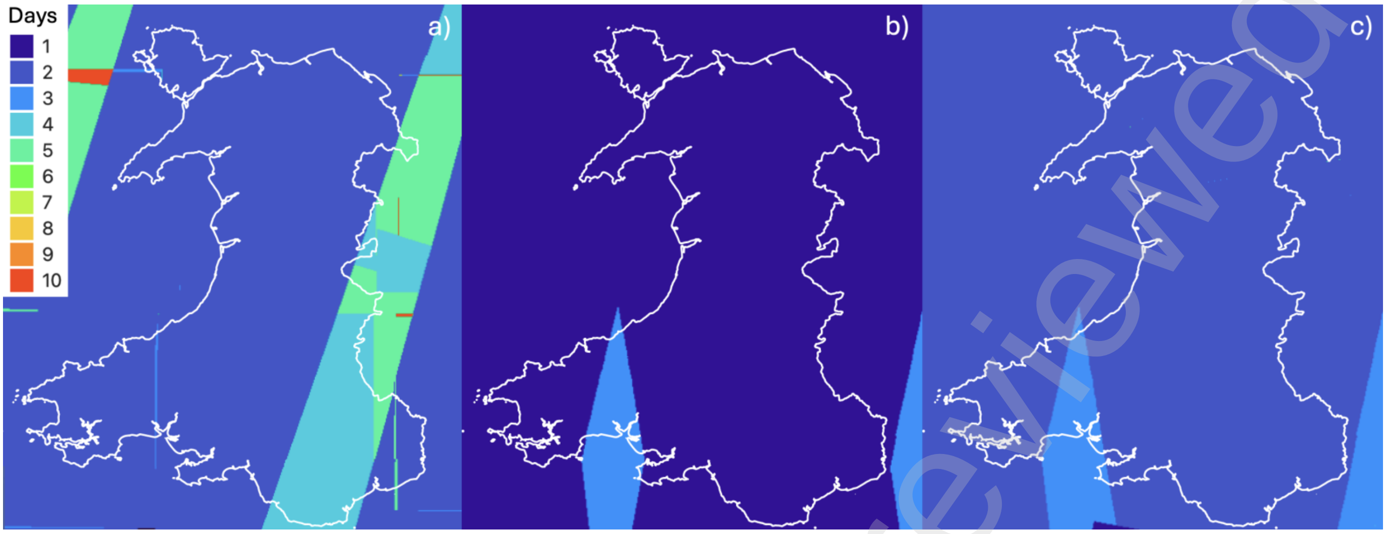

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Figure 5: Frequency of data for Wales with a) both Sentinel-2, b) both Sentinel-1, and c) Sentinel-1A sensors

4.1.1. Earth Observation Analysis Ready Data

In Wales, Sentinel-1 Level-1 GRD-HD Dual-Polarization data acquired with Interferometric Wide swath (IW) from the ASF platform, and Sentinel-2 Level-2A surface reflectance products from Google Cloud Storage, were processed according to national requirements (see Section 3.4.2). The resulting ARD are automatically indexed in a PostgreSQL server and feed the ODC (Figure 2). Using CronJob, the system searches, downloads, pre-processes, stores, and indexes EO data twice daily. A total of 8,176 Sentinel-1 scenes were downloaded and pre-processed for the period 2014-2024 (i.e., 14 Nov 2014 – 31 Dec 2024), for a total of 15 TB, and 19,508 Sentinel-2 scenes (i.e., 22 TB); and the server continue to be updated on daily basis. This corresponds to a maximum of 5 TB/year of Sentinel data downloaded, processed and stored within the Welsh NDI for the years with a full time series. Indeed, Sentinel-1A, Sentinel-1B, Sentinel-2A, Sentinel-2B sensors were all operating simultaneously for the years 2018-2021, as Sentinel-2B Level-2A's first images for Wales were available from 18th March 2017 (Copernicus, 2017; ESA, 2017) and the Sentinel-1B mission stopped delivering data on 23 December 2021 (ESA, 2022). As a consequence of overlapping orbits, Sentinel-2 data are provided every 2-5 days whilst the frequency of Sentinel-1 data acquisitions was every 1-3 days with two sensors and 2-3 days with only Sentinel-1A (Figure 5). Therefore, even after the loss of Sentinel-1B, the overlap of orbits has ensured that Sentinel-1 coverage frequency in Wales remains high. Regarding the Sentinel-2 sensors, certain areas, particularly along a northeast-south diagonal (Figure 5a), are only covered with a 5-day frequency, which is the official revisit interval with the two Sentinel-2 satellites. As a result, these areas benefit from both sensors, but not from overlapping orbits. This makes these areas vulnerable if one sensor fails, especially since Sentinel-2A is nearing the end of its planned operational lifespan after almost a decade of service (Copernicus 2024).

The use of Sentinel-1 and 2 provide capacity to monitor aspects of the physical, chemical and biological elements of the national landscape of Wales with 10-20 m resolution. This combination of data also provides a more complete and comprehensive understanding of the states and dynamics of environments by offering complementary information. Indeed, whereas optical wavelengths' interaction with surfaces is influenced by the spectral properties of the materials, which can provide information about the biochemical state of vegetation and the condition of soils and water bodies (Toming et al., 2016; Castaldi et al., 2019; Misra et al., 2020), SAR backscatter relies on the surfaces' texture, moisture, and geometric properties (Nasirzadehdizaji et al., 2019; Balenzano et al., 2021; Zeyliger et al., 2022), allowing insights into different surface conditions and topographical features often missed by optical sensors. Also, SAR operates at wavelengths not impeded by cloud cover or a lack of illumination, and therefore acquires data irrespective of weather conditions or time of day (including night-time), allowing for more consistent and frequent temporal observations than optical data. This is particularly valuable for monitoring seasonal changes, daily phenomena, and rapid environmental changes that may occur on cloudy days/seasons. Also, the Sentinel-1 SAR IW data, available in the Welsh NDI, are collected over a swath of 250 kilometers, thereby offering reliable repeated monitoring over wide areas (ESA, 2024a). Many research studies have combined time series from both SAR and optical data as this can yield richer insights on environmental conditions and changes (Schulz et al., 2021; Solórzano et al., 2021; Ghorbanian et al, 2021; Ma et al., 2021; Nuthammachot et al., 2022; Fang et al., 2023; Tang et al., 2023; Declaro and Kanae, 2024). Together, the free and open EO ARD provided by the Welsh NDI contribute to a holistic assessment and monitoring of the environment, both historical and timely.

Sentinel-1, while providing data every 2-3 days, still relies on a single sensor. This creates a significant vulnerability concerning sovereignty as the failure of Sentinel-1A could jeopardize monitoring and reporting responsibilities in Wales but also for other nations. However, despite currently being in the commissioning phase for 3 to 6 months, Sentinel-1C was launched by ESA on 5 December 2024 (ESA, 2024b). This new sensor now facilitates continuation of the dense time-series of observations (Parsonson, 2024). The data from Sentinel-1C will seamlessly integrate into the NDI, as the EODataDown system offers flexibility for searching, downloading, and processing data regardless of its origin or type. As with Sentinel-1A and B, data from Sentinel-1C will require pre-processing to achieve ARD, given that Sentinel-1 products are currently delivered only in Level-1C format by ESA. However, ESA is currently working on the development of an ARD Normalised Radar Backscatter product for Copernicus Sentinel-1 that will be compliant with CEOS specifications (Truckenbrodt et al., 2023; Pinheiro et al., 2022; Wolsza et al., 2022). When operational, and as with the Sentinel-2 Level-2A surface reflectance product (c.f., Section 3.4.1.), these will be easily integrated into the NDI. Additionally, Sentinel-2C was launched on 5 September 2024 (ESA, 2024c), and will become operational on 21 January 2025 (Copernicus, 2025) and be integrated into the NDI as well. Together, these datasets will enhance the overall monitoring capabilities of the NDI.

4.1.2. Tailored ready-to-use products and functionalities.

One of the requirements for the Welsh NDI was the provision of ready-to-use products and functionalities with which to support national policy making and reporting obligations. With this purpose, in the Welsh NDI, a series of ready-to-use products, and tools allowing the generation of ready-to-use products relevant to environmental monitoring have been made openly and freely available in the publicly shared space of the infrastructure. These include the land cover maps and associated EDs that have been generated primarily from the Sentinel-1/2 ARD for each year (from 2018 to the present) using the *Living Earth* application and *Living Wales* plugins (Figure 6).

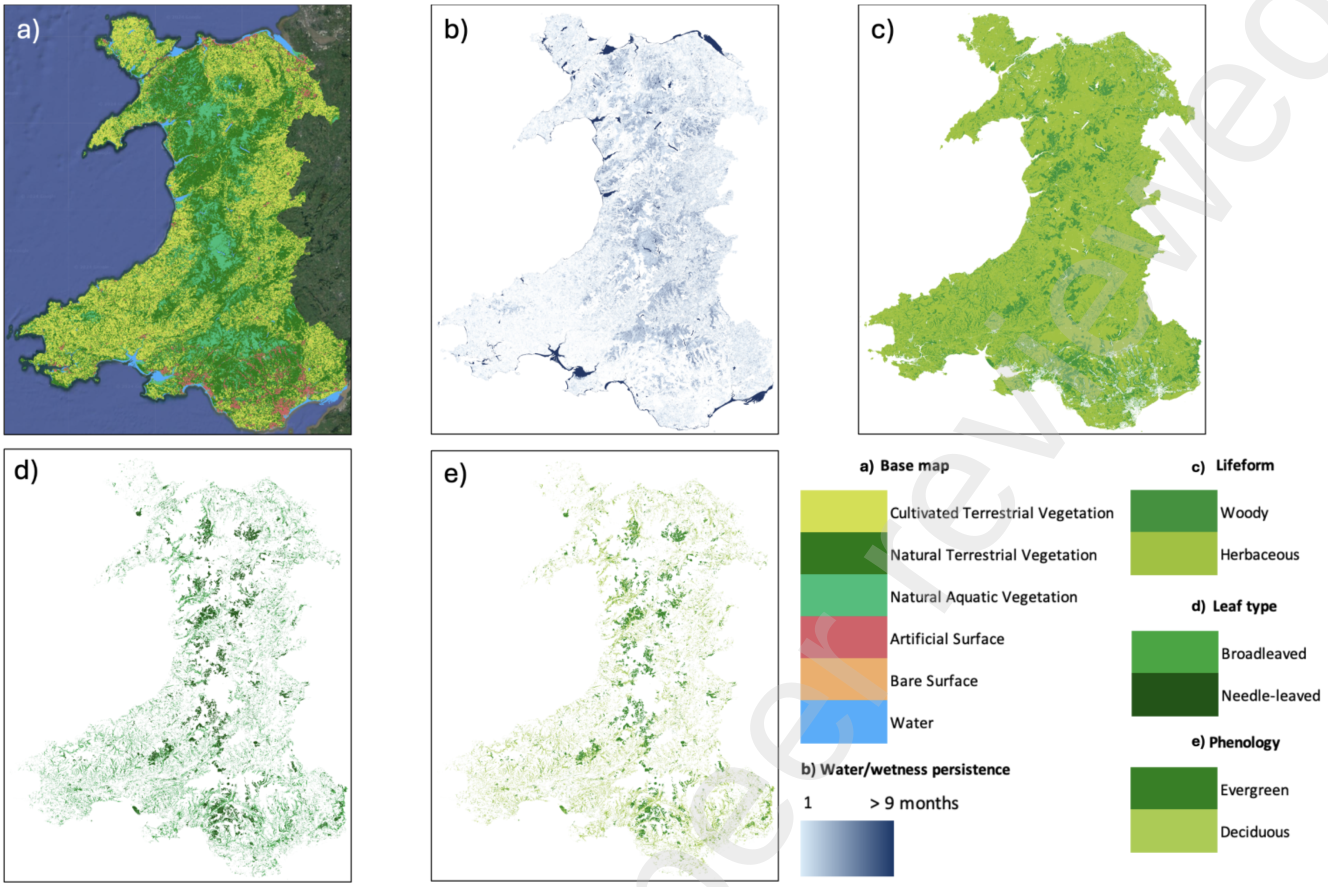

Figure 6: Annual national 10 m *Living Wales* ready-to-use products available in the Welsh NDI (here: 2023), with a) the land cover base map and b) the water/wetness persistence, c) lifeform, d) leaf type, e) phenology environmental descriptors.

As implemented, the Welsh NDI has allowed automatic generation of these products in the January following every year. For example, in January 2024, the 2023 national products were generated. After automatic generation, the products are indexed in the PostgreSQL and become available to all end-users as ready-to-use products. The *Living Earth* FAO land cover classification system embedded in the NDI and associated *Living Wales* plugins for ED retrieval have allowed the generation of annual land cover base maps and EDs with an OA of 90.2 % and > 94 % respectively. UAs and PAs exceed 80 % and often 90 % for the basemap and all EDs (Table 2).

Table 2. Accuracy assessment of the *Living Wales* 2023 land cover base map and qualitative environmental descriptors, where UA is the user's accuracy, PA the producer's accuracy, and OA the overall accuracy.

Product	Class	UA	PA	OA
Base map	Cultivated Terrestrial Vegetation	0.986	0.831	0.902
	Natural Terrestrial Vegetation	0.867	0.939	
	Natural Aquatic Vegetation	0.804	0.982	
	Artificial Surface	0.891	0.950	
	Bare Surface	0.867	0.931	
	Water	0.909	0.983	
Lifeform	Woody	0.984	0.949	0.985
	Herbaceous	0.986	0.996	

Leaf type	Broadleaved	0.972	0.934	0.941
	Needle-leaved	0.891	0.952	
Phenology	Evergreen	0.916	0.921	0.946
	Deciduous	0.961	0.958	

Together the base maps and EDs provided 186 potential class combinations for every year, thereby providing some of the evidence required by national monitoring and reporting obligations (NRW, 2022a). To facilitate the integration of these products into Welsh national affairs, an automatic translation scheme has been created to present evidence in a format that corresponds with the existing national habitat taxonomy (i.e., Phase-1; JNCC, 2010; Lucas et al., 2011, Punalekar et al., 2024). Two *Living Wales* habitat maps (i.e., detailed and broad; containing 38 and 14 habitat types respectively) have been provided on an annual basis since 2020 (Figure 7). The generation and accuracy of these maps is described and discussed in Punalekar et al. (2024). In addition to the Welsh NDI, and to support integration into Welsh national affairs, all *Living Wales* layers have also been made directly viewable on and downloadable from the *Living Wales* geoportal (https://earthtrack.aber.ac.uk/livingwales/maps.html) (Figure 7).

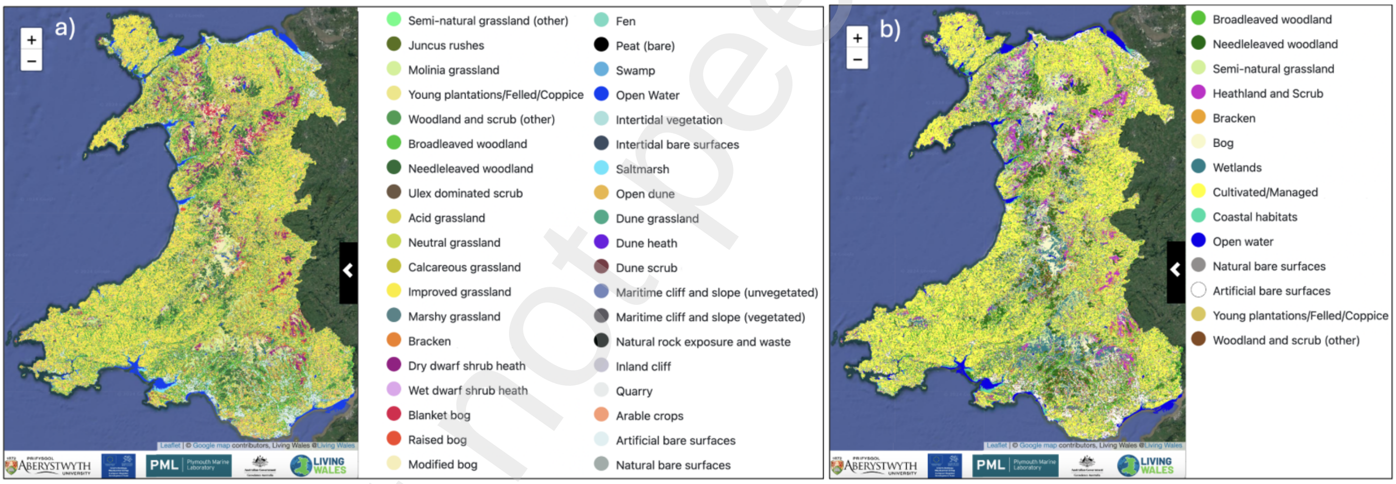

Figure 7: Annual national 10 m *Living Wales* a) detailed and b) broad habitat maps (here: 2020), as provided on the *Living Wales* geoportal. The layers are also available in the Welsh NDI.

In addition to the annual *Living Wales* products, various applications allowing the generation of ready-to-use products have been developed and integrated in the publicly shared space of the Welsh NDI, including for Near-Real Time (NRT) monitoring and report writing including the four toolboxes (flood, fire, forest and crop monitoring; Table 3). Using the Sentinel-1 ARD available in the Welsh NDI and for any area and period of interest covered by the EO ARD (see Figure 3)., the 'flood monitoring' toolbox allows historical and NRT mapping of flood extent (Figure 8a) and progression (Figure 8b) as well as assessments of frequency (Figure 8c). SAR is advantageous for flood mapping, as it operates at wavelengths not impacted by cloud cover and can acquire data for an area under all weather conditions, including heavy rain (Psomiadis, 2016; Carrasco et al., 2019). These data allow observations of open water but also moisture in the environment, allowing flood extents and dynamics to be captured (Planque et al., 2020). As shown in Table 3, this information is extremely important as, under the Environment (Wales) Act 2016 and Flood and Water Management Act 2010, Natural Resources Wales and Local Authorities in Wales are required to investigate significant local flooding incidents and publish the results of such investigations (Carmarthenshire County Council, 2023). Furthermore, the National Strategy for Flood and Coastal Erosion Risk Management in Wales (Welsh Government, 2020) aims to improve the understanding of flood risk and emphasizes the importance of accessing accurate information (including mapping) to assist decision-making and inform the public. The analysis of historical outputs (including trends) from the '*flood frequency*' application (Figure 8c) provides useful information with which to update the Flood Risk Assessment Wales Map (NRW, 2024a), understand past floods, and predict future risks for any location in Wales.

Table 3. List of the toolboxes and applications that are currently accessible in the publicly shared space of the Welsh National Digital Infrastructure, along with the key policies they pertain to.

Toolbox	Application	Objective	Key policies
Flood monitoring	*flood mapping*	Map the extent of waters for each Sentinel-1 scene available for a region and period of interest	*Environment (Wales) Act 2016*
	flood progression	Map the progression of floods between consecutive dates for a region and period of interest	*Flood and Water Management Act 2010*
	flood frequency	Map the frequency of floods for a region and period of interest	*National Strategy for Flood and Coastal Erosion Risk Management*
Fire monitoring	*burn mapping*	Map burnt areas for each Sentinel-2 scene available in a specified ROI	
	burn progression	Map the progression and recovery of burnt areas between consecutive dates	*Conservation of Habitats and Species (Wales) Regulations 2017*
	report burnt extent	Generate a report with the maximum extent of burnt area per year for a ROI, with respective date	*Heather and Grass Burning Code for Wales 2008* *Burning Management Plan*
	report burnt habitats	Generate a report of the type of habitats which were burnt for a ROI and period of interest	
Forest monitoring	*forest mapping*	Map forest extent for each year using Sentinel ARD according to Living Wales (Table A1)	*Environment (Wales) Act 2016*
	clear-fells monitoring	Map annual clear-fells in forested areas	
	mapping clear-felling dates	Map a summary of extent and date of the clear-fells	*Well-Being of Future Generations (Wales) Act 2015*
	clear-fell reporting	Automatized reporting on clear-fells for the period and region of interest	*Woodlands for Wales Strategy*
Crop monitoring	*parcel NRT monitoring*	Crop, and their growth stages, NRT monitoring at the parcel scale using Sentinel-1 ARD	*Agriculture (Wales) Act 2023*
	report crop type area	Summarizes the total area (in hectares) dedicated to each crop type on an annual basis for a selected farm	*Environment (Wales) Act 2016* *Well-Being of Future Generations (Wales) Act 2015*

	farm crop rotation	Dynamic mapping of crop rotations over multiple years at the farm scale
	parcel crop rotation	Visualizing crop rotation over multiple years at the parcel scale using Sentinel-1 ARD

In addition to natural process and risk watching and understanding, NRT monitoring also provides valuable tools for detecting illicit activities and responding promptly to mitigate environmental harm. This is, for example, the case of the '*fire monitoring*' toolbox which was added to the publicly shared space of the Welsh NDI to help governmental authorities track fires (Table 3). This toolbox utilizes the Sentinel-2 ARD, as well as the Welsh *Living Earth* habitat maps, to map (in NRT) the extent of fire scars and recovery in post-fire periods as well as report statistics (e.g., extent, affected habitats) for any area and period of interest covered by the EO ARD (see Figure 3). Fire has long played a role in the natural ecology in Wales, including upland and some lowland areas (e.g., heathlands, tussock grasses and coniferous forests) (Davies et al., 2016; Harper et al., 2018). Fire occurs naturally as a result of natural events (e.g., lightning strikes) and processes (drying), and has been used for centuries as a tool for managing agriculture and wildlife conservation. Controlled (or prescribed) burning is utilized in a variety of semi-natural habitats such as moorlands, heathlands, wetlands, grasslands, and scrub (Davies et al., 2016). However, the three-quarters of the UK peatlands have recently been reported as damaged or degraded by a range of pressures, including uncontrolled burning and wildfires. As a result, heathland and bog biodiversity has declined significantly (Burns et al., 2023). To preserve the environment, the Conservation of Habitats and Species Regulations 2017 authorize the prohibition of fires in conservation areas (Welsh Parliament, 2017). More generically, the Heather and Grass Etc. Burning (Wales) Regulations 2008 and Burning Management Plan are in place to oversee the careful planning and execution of controlled burns, regulating the conditions and timing of burning activities (National Assembly for Wales, 2008; Welsh Assembly Government, 2008).

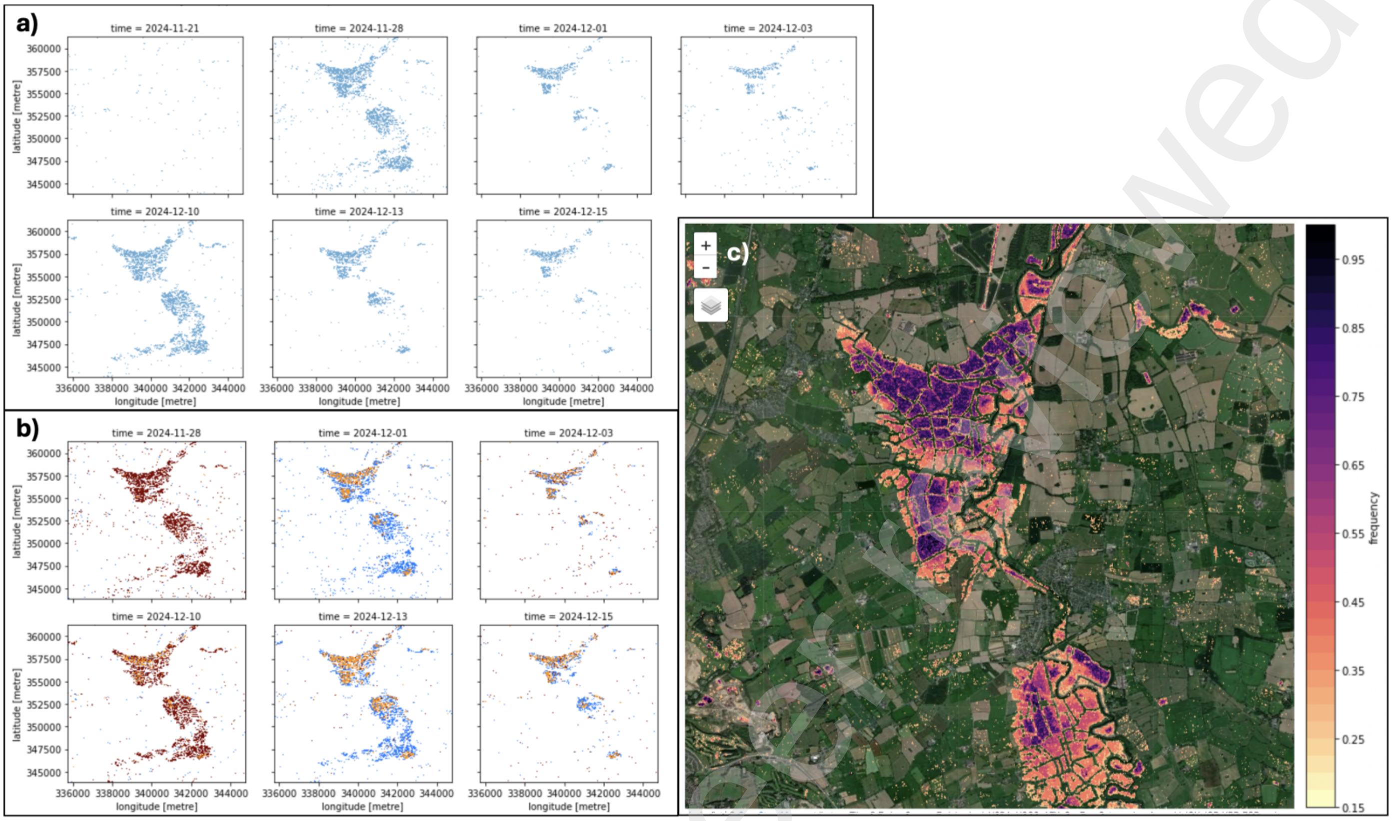

Figure 8. NRT mapping of a) flood extent (in blue) and b) progression (with newly flooded areas in red, areas which remained flooded in orange and areas where flood waters have receded in blue) for the period 20 November – 20 December 2024 around River Dee. Flood alerts were emitted on 26 November and 10 December 2024. The '*flood frequency*' application was used for that period (c). It allows overlaying of the results on a dynamic map.

Finally, the EO ARD can also be useful to assess progress towards the national and international environmental goals and targets. The '*forest monitoring*' toolbox, for example, utilizes the Sentinel-1 ARD to map annual forest extent and clear-felling dates. In 2018, Welsh Government published the latest version of Woodlands for Wales (Welsh Government, 2018). The 50-year strategy outlines Welsh Government's vision and targets for sustainably managing Wales' trees, woodlands and forest and aims to ensure high-quality and resilient woodlands. This strategy aims to contribute towards the wider goals of the *Well-being of Future Generations (Wales) Act 2015* and *Environment (Wales) Act 2016*. Currently, most managed woodlands in Wales are planted single species, single aged (over half are dominated by coniferous species), predominantly managed on a clear-fell and restock regime (NRW, 2017). However, to meet the outcomes required by the new legislative framework, Wales needs to reduce the amount of clear-felling and transition to more sustainable systems (Welsh Government, 2018). An increase in the net area of woodlands is also required. Therefore, monitoring clear-felling and the condition of forests is key in demonstrating the success of the Woodlands for Wales strategy, and consequently of the *Well-being of Future Generations (Wales) Act 2015* and *Environment (Wales) Act 2016*. Similarly, monitoring agricultural practices is key in delivering the *Agriculture (Wales) Act 2023* and *Environment (Wales) Act 2016*. Both promote sustainable farming practices that enhanced carbon storage, promote biodiversity, and improve soil health through practices such as crop rotation, cover cropping, and reduced tillage (Welsh Parliament, 2023). Therefore, the '*crop monitoring*' toolbox provide useful applications for national governance in Wales.

All these applications and toolboxes included in the current version of the Welsh NDI are not a definitive list but serve as examples demonstrating how the system can be utilized for national sovereign monitoring of the environment. The Welsh NDI is a flexible and adaptative infrastructure, and therefore is regularly being updated to meet the needs of the country and policy framework. Additionally, regular training sessions help the stakeholders to stay informed about how to best utilize these resources.

4.2. Mutualized information for homogeneous and up-to-date reporting

Currently, various governmental agencies rely on different data sources to report on similar elements, often with varying timelines, leading to inconsistencies in statistics across reports and spatial analyses. For instance, the most recent State of Nature Wales report (Smith et al., 2023) states that 90% of peatlands are in poor condition, referencing conclusions from the JNCC (2019). However, by the time this report was published, the National Peatlands Action Programme (2020-2025) had already made significant progress, restoring 3,000 hectares of peatland (Welsh Government, 2024c)—about 60% of its target to restore a minimum of 5,000 hectares (or 25% of the most modified peatlands) and ensure all peatlands with semi-natural vegetation are subject to favourable management/restoration by 2025 (NRW, 2020a). This progress will be reflected in the SoNaRR 2025 (NRW, 2024b). Also, the datasets used are not necessarily up to date. For example, despite being completed in the 1990s, the Phase 1 Habitat map is still the national reference dataset (JNCC, 2010; Lucas et al., 2011, Punalekar et al., 2024). As part of the Welsh NDI are provided open and up-to-date spatially explicit *Living Wales* land cover, EDs and habitat maps (see Section 4.1.2.) that can be used as a common and publicly accessible data source that can contribute to fulfilling a range of national reporting obligations, thereby limiting inconsistencies between reports and duplication of information. The *Environment (Wales) Act 2016*, for example, concerns various sectors (e.g., natural resources, land management, climate change) and stakeholders (e.g., public authorities, land managers, farmers). In this section, we discuss how the Welsh NDI can contribute to mutualizing data and efforts for fulfilling reporting obligations.

4.2.1. Welsh NDI for Sustainable Farming Scheme compliance checking

The Sustainable Farming Scheme (SFS) is one of the key measures introduced under the *Agriculture (Wales) Act 2023*. It includes various initiatives and incentives to encourage farmers to adopt more sustainable management practices, such as agri-environmental schemes, to improve water quality, reduce greenhouse gas emissions, and support biodiversity conservation (Welsh Government, 2022c). The SFS is being developed to replace the subsidies previously provided by the European Union through the Common Agricultural Policy (CAP) and will be structured around three layers of actions, namely those that are a) Universal and mandatory for all SFS participants; b) Optional; and c) Collaborative, which provide opportunities for participants to work with others to implement broader changes (Darragh, 2024). The universal baseline payment was tied to 17 Universal Actions, which encompass the management, maintenance, and/or creation of semi-natural habitats and woodlands, and require farms to have at least 10% under tree cover as woodland or individual trees by the end of 2029. Each year, Rural Payments Wales (RPW) selects a portion of scheme applications for inspection to ensure compliance with the scheme's regulations, including the essential baseline requirements (Welsh Parliament, 2024). In addition, Welsh Government aims to perform spot checks that utilize both physical inspections and EO methods, including remote sensing where applicable (Darragh, 2024).

During the testing phase of the Welsh NDI, it was demonstrated that the NDI can assist the Welsh Government in verifying SFS compliance by utilizing the ready-to-use products available in the publicly shared space, along with certain privately integrated data and tools. Through the modular design of the NDI framework, users have the option to upload, download and use their own data and tools in their private workspace, in addition to the ones provided in the publicly shared space. The private data/tools can be used as standalone, or with any of the tools/data available in the publicly shared space of NDI, for analysis. This feature is especially crucial when dealing with confidential/private data. With this purpose, an algorithm to translate the EO-derived *Living Wales* annual products to SFS-compatible habitat maps (c.f., Table B1) has been added by a Welsh NDI user from Welsh Government (here named 'User A') inside their personal environment, alongside a private/licensed layer (i.e., the limit of enclosed farmlands) defined and owned by the Welsh Government and run. 'User A' was able to confirm the feasibility of translating the *Living Wales* products to a SFS-compatible taxonomy when adding privately owned data (Figure 9), with the NDI structure facilitating this, and using the Welsh NDI for SFS checking.

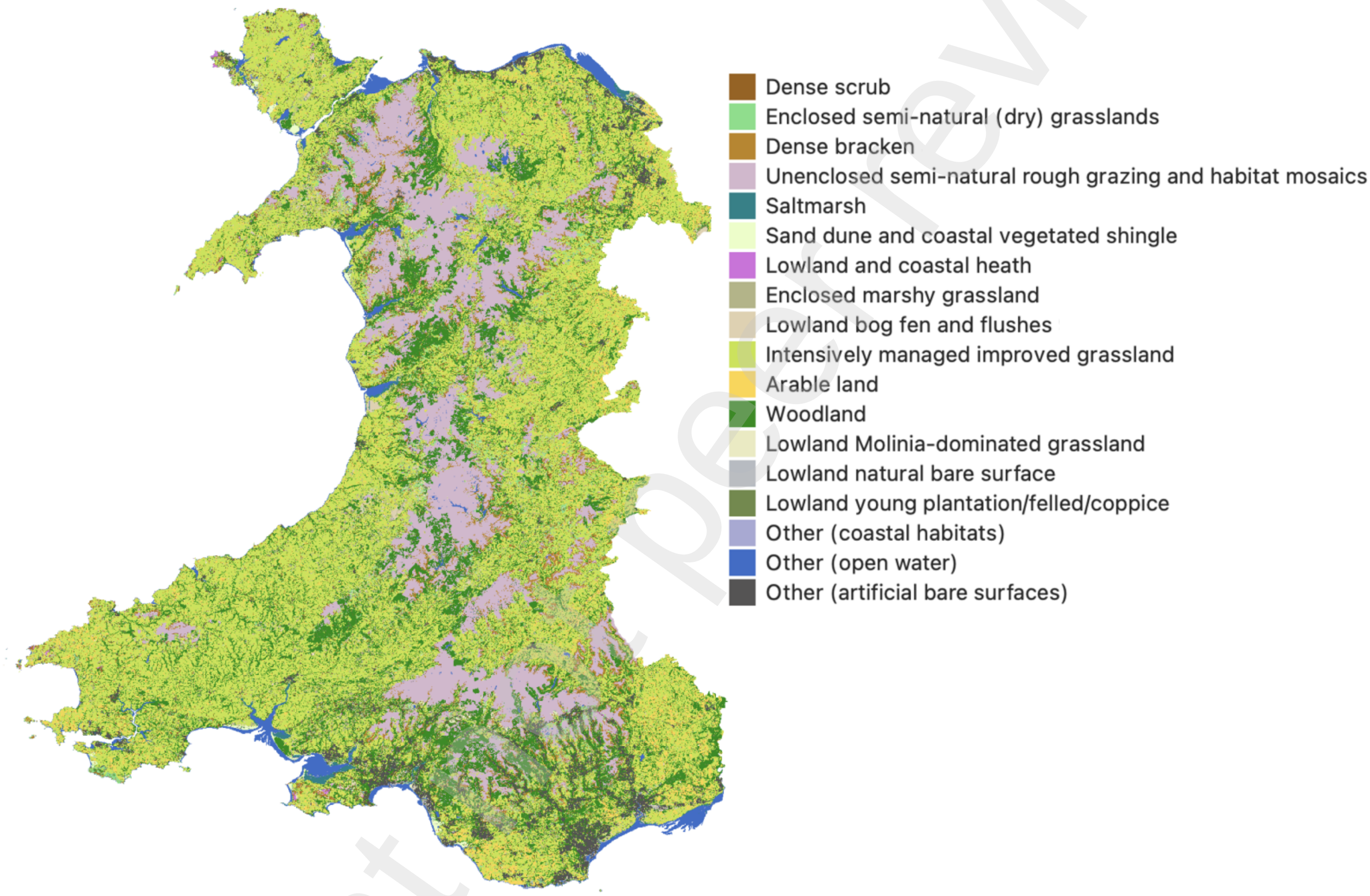

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Figure 9: Annual national 10 m SFS-compatible habitat maps (here: 2020) obtained through the Welsh NDI, by using the data available in the publicly shared space alongside privately owned data (see Table B1).

4.2.2. Welsh NDI for State of Natural Resources Reporting

In parallel with the SFS, the Welsh Government has other reporting obligations that require monitoring of the management and maintenance of semi-natural habitats (including woodlands in Wales and enclosed farmlands; NRW, 2020b). NRW is the Welsh Government sponsored organisation responsible for managing natural resources in Wales. As outlined in the *Environment (Wales) Act 2016*, NRW's mission is to promote and maintain the principles of Sustainable Management of Natural Resources (SMNR). The agency has several statutory duties related to biodiversity, including the publication of the State of Natural Resources Report (SoNaRR), area statements, and the designation of protected areas. SoNaRR evaluates the sustainable management of natural resources in Wales and identifies various opportunities for action. The report's assessments are based on the four Aims of SMNR (NRW, 2020c) and *Living Wales* annual products can serve as valuable tools for evaluating Wales's advancement in SMNR. This is particularly pertinent to Aim 2, which emphasizes the resilience of ecosystems to both expected and unforeseen changes, including habitat loss and degradation, and climate change (NRW, 2020d). During the testing phase of the Welsh NDI, and to demonstrate how the Welsh NDI can facilitate SoNaRR reporting by NRW, an algorithm to translate the EO-derived *Living Wales* annual products to SoNaRR-compatible habitat maps (c.f., Table B2) has been added by a Welsh NDI user from NRW (here named 'User B') inside their personal environment. This was undertaken and executed alongside a private/licensed layer defined and owned by the Welsh Government. 'User B' was able to confirm the feasibility of translating *Living Wales* products to a SoNaRR-compatible taxonomy when adding privately owned data (Figure 10), with this facilitated by the Welsh NDI structure.

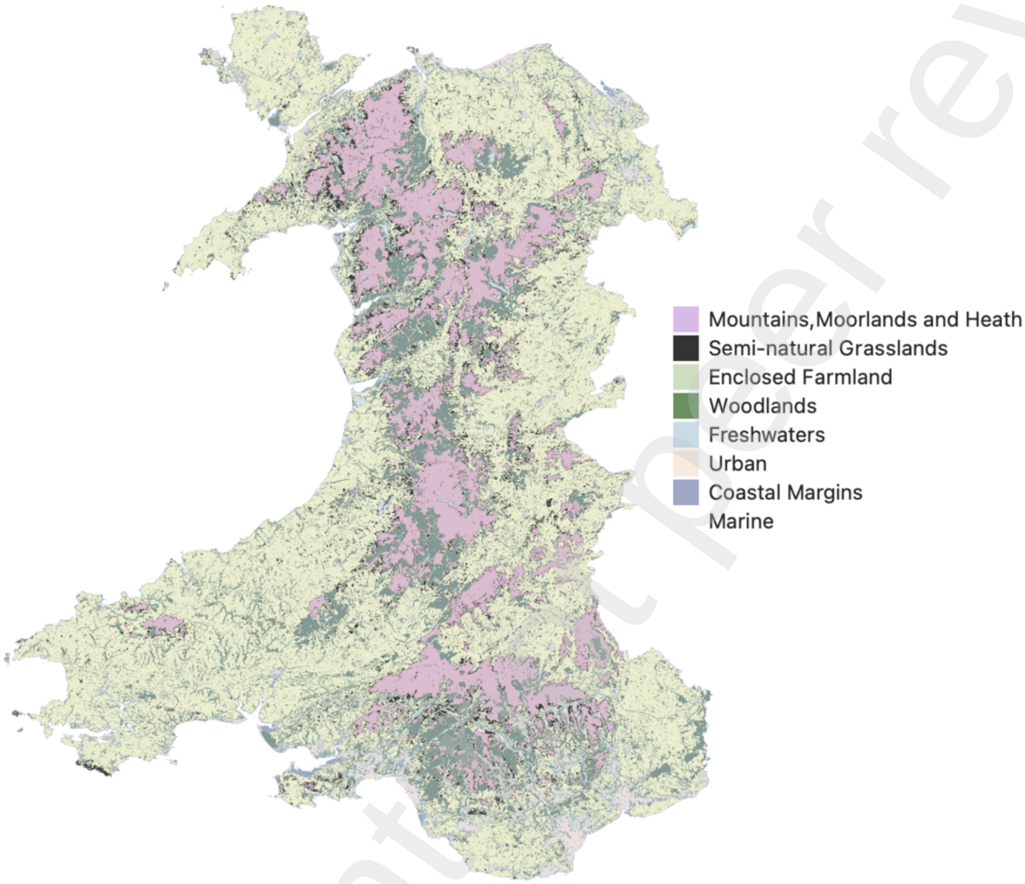

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Figure 10: Annual national 10 m SoNaRR-compatible habitat maps (here: 2020) obtained through the Welsh NDI, by using the data available in the publicly shared space alongside privately owned data (see Table B2).

NRW is an evidence-based organization dedicated to ensuring that information and actions are backed by reliable, quality-assured evidence. Time series of *Living Wales* products can provide specific evidence to address some of the critical questions needed by NRW for SoNaRR, such as: "*Has the diversity, extent, and connectivity of semi-natural habitats in Wales changed?*", "*How has land-use classification changed and what is the extent and spatial-arrangement of modified habitats?*", "*What is the extent and spatial-arrangement of qualifying habitats in protected sites across Wales?*" (NRW, 2022a). In this regard, the system is contributing to several of the cross-cutting themes of the report (e.g., Ecosystem Resilience, Biodiversity, Woodland, Coastal margins, Semi-natural grassland, Enclosed farmland).

4.3. Improving transparency and inclusivity in decision-making and payment assessments

In Wales, various legislative frameworks and schemes emphasize shared-power, co-development of plans, and collaborative decision-making, particularly in the context of land-use, environmental management, and sustainable development (Jenkins, 2018; McKinley and Ballinger, 2018; Welsh Government, 2019). Key legislations, including the *Well-being of Future Generations (Wales) Act 2015*, the *Environment (Wales) Act 2016*, and the *Agriculture (Wales) Act 2023*, encourage collaboration between government agencies, environmental organizations, local communities, and other stakeholders to achieve more sustainable and inclusive outcomes. The Rural Development Programme (RDP) for Wales was a key government initiative designed to drive the economic, social, and environmental development of rural communities throughout Wales (Welsh Government, 2022d). This programme provided funding and resources to support projects that improved rural livelihoods, encouraged sustainable agricultural practices, safeguarded the environment, and supported rural businesses, whilst at the same time prioritizing inclusivity and collaboration.

The *Living Land Management Wales* project, funded by RDP, focused on testing the application of the Welsh NDI for local environmental monitoring and planning in Monmouthshire, a county in southeastern Wales. One of the project's key objectives was to explore how the Welsh NDI could support a coordinated and collaborative approach to land-use planning at local, regional, and national levels, and involved local land managers (NRW, 2022b; Living Levels, 2023). Throughout the project, landowners in Monmouthshire worked closely with various project partners—including Monmouthshire County Council, Dŵr Cymru Welsh Water, Natural Resources Wales, and Aberystwyth University—to assess how the new technological infrastructure could be used to monitor their individual landholdings and explore what changes might be appropriate, with a view to modelling the impact of actual or proposed land-management decisions and evaluating the possible impacts of those changes in terms of yield, natural capital, ecosystem services, farm efficiency, and the proposed subsidy regimes (Living Levels, 2023). A critical component of the project involved enabling landowners to access and exchange confidential data about their holdings, which was essential for understanding, tracking, and demonstrating the impacts of their land management practices. To support this, secure user-friendly web-interfaces were developed, allowing land managers to easily access comprehensive historical and current data on their land (Figure 11). The password-protected platform was integrated with the Welsh NDI, enabling landowners to generate maps and reports using both publicly available data from the Welsh NDI and private data they have provided.

Throughout *Living Land Management Wales,* the Welsh NDI, with *Living Wales* products, has demonstrated potential for farmers and other landowners and managers to engage with advisors and governmental institutions, exchange valuable data, and receive tailored guidance on implementing sustainable practices. Such an approach was considered essential for building collaboration and trust between farmers and policymakers, especially regarding policies and payment schemes such as the SFS. Developed to replace the Common Agricultural Policy (CAP), payments with the SFS will be based on achievements, which will be assessed by monitoring and evidence. However, the SFS is being co-developed with farmers, agricultural experts, environmental organizations, and government officials, and intends to adhere fully to the principles of co-design (i.e., transparency, inclusivity, shared power and participation). In this regard, the process will be achieved by assessors, via on-site evaluations, but also by farmers themselves through self-assessment (Lyon et al., 2023). Involving farmers in data collection and reporting strengthens the credibility of the information, which in turn promotes greater acceptance of decisions (Terwel et al., 2010; Velten et al., 2018). Transparency also plays a vital role in this process, as it helps farmers understand how their land management practices influence payment evaluations, thereby enhancing trust in the fairness and long-term sustainability of the agricultural sector. In the future, the Welsh NDI aims to integrate socioeconomic and ecosystem service data with predictive modeling (NRW, 2022b). In the long term, the system will help balance competing land-use demands, enhancing communication, understanding, and collaboration between farmers/landowners and the Welsh Government. This will ultimately build trust and foster greater involvement in environmental and agricultural policies and decision-making processes.

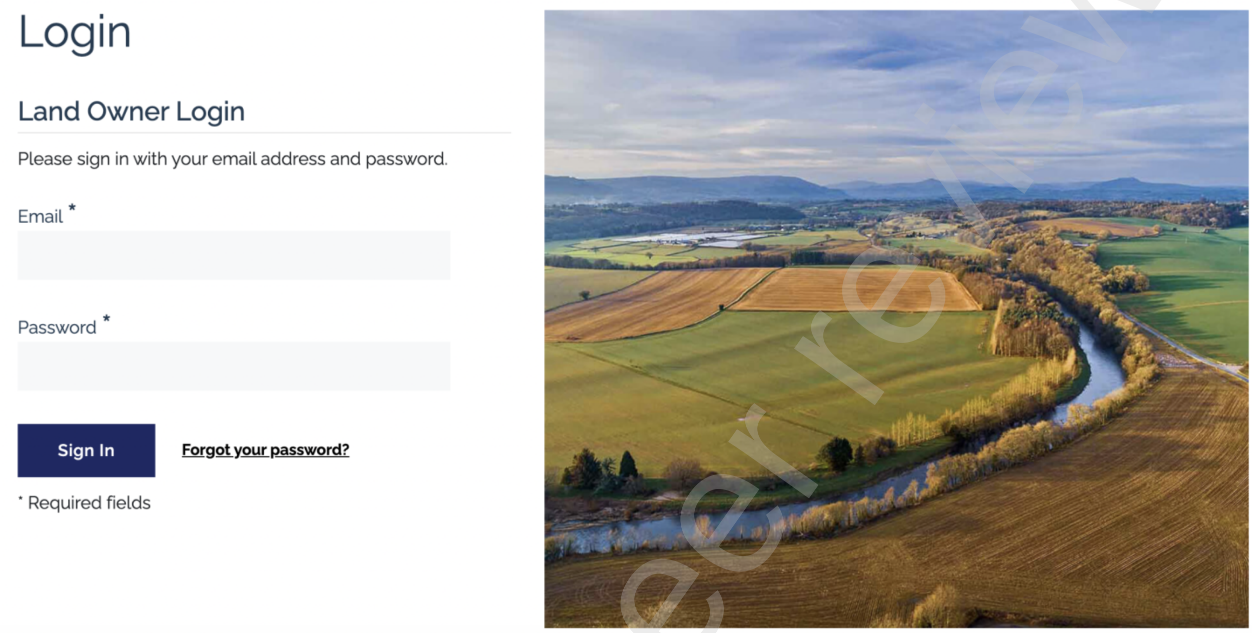

Figure 11. User-friendly password-protected *Living Land Management* web-interface enabling landowners to generate maps and reports using both publicly available data from the Welsh NDI and private/confidential data. Available from https://livingearthhub.org.

5. Conclusions

A framework that allows to build a flexible and sovereign national digital infrastructure for monitoring of the environment, managing land, and fulfilling reporting obligations was developed and introduced. The framework builds on customizable and adaptable open-source solutions such as the Open Data Cube, EODataDown, JupyterHub, and Living Earth, to ensure that countries can maintain full control over their data, technologies and decisions. In this paper, the generic capability and structure of the developed framework was tailored to meet Wales' national requirements and was successfully demonstrated and operationalized.

Data/technological sovereignty asserts a country's right to govern and control the access (including confidentiality), storage, and processing of data within its jurisdiction and is a core principle of the NDI. In Wales, to preserve complete sovereignty, the NDI was hosted on a national server, granting full control over data access and storage. The NDI also ensures that both the confidentiality of data and tools, as well as access control, are upheld. Publicly available data and tools can be shared freely on the NDI, while licensed data can be privately uploaded by users into their personal workspaces, where they can be either used independently or combined with publicly accessible resources. This setup offers a highly flexible and customized solution. Within the Welsh NDI's public domain, EO data that meet national standards have been made available, along with a variety of ready-to-use products and tools designed to support cross-disciplinary use or address specific reports and policy needs. In Wales, the system was tailored to automatically download and store CEOS EO ARD in the NDI's publicly accessible space. Freely available optical and SAR EO data collected over Wales have been used to generate up-to-date products, such as NRT information and annual land cover and habitat maps, which are also accessible through the NDI's public domain.

Together, the structure, flexibility and interoperability of the NDI, as well as the common and publicly accessible data source, have proven valuable for sovereign holistic monitoring of the environment and fulfilling a range of national reporting obligations. It allows mutualization of information by a range of organizations operating nationally or sub-nationally, thereby limiting inconsistencies between reports and duplication of information. By enhancing transparency, traceability and reproducibility, the NDI has also demonstrated its ability to foster collaboration between government agencies, environmental organizations, local communities, and other stakeholders. This collaborative approach not only helps achieve more sustainable and inclusive outcomes but also supports the principles of co-design (i.e., transparency, inclusivity, shared power and participation) while facilitating the involvement of stakeholders in environmental and agricultural policy development and decision-making.

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Appendix A. Living Wales algorithms for retrieving the Environmental Descriptors required and/or used by *Living Earth*.

Table A1. List of the Living Wales' Environmental Descriptors (EDs) and algorithms allowing their retrieval, where *i* is a scene and *N* the total number of scenes for the processed year.

ED	Variable	Algorithm
Vegetation	$vegetat\_veg\_cat$	$vegetat\_veg\_cat = f(NDVI) = \begin{cases} 1, & \max_{4 \le month \le 10}\{NDVI(month)\} \ge 0.4 \\ 0, & otherwise \end{cases}$
Aquatic	$aquatic\_wat\_cat$	$aquatic\_wat\_cat = f(water, aquaticVeg) = waterbodies + aquaticVeg$
	$waterbodies$	$waterbodies = f(wetness^{ASC}_{freq}, wetness^{DSC}_{freq}) = \begin{cases} 1, & if\ wetness^{ASC}_{freq} > 8\ OR\ wetness^{DSC}_{freq} > 8 \\ 0, & otherwise \end{cases}$
	$wetness^{ASC}_{freq}$	$wetness^{ASC}_{freq} = 12 * \frac{\sum_{i=1}^{N} wetness^{ASC}_i}{N}$
	$wetness^{DSC}_{freq}$	$wetness^{DSC}_{freq} = 12 * \frac{\sum_{i=1}^{N} wetness^{DSC}_i}{N}$
	$wetness^{ASC}_i$	$wetness^{ASC}_i = f(VH^{ASC}_i) = \begin{cases} 1, & VH^{ASC}_i < -22dB \\ 0, & VH^{ASC}_i \ge -22dB \end{cases}$
	$wetness^{DSC}_i$	$wetness^{DSC}_i = f(VH^{DSC}_i) = \begin{cases} 1, & VH^{DSC}_i < -22dB \\ 0, & VH^{DSC}_i \ge -22dB \end{cases}$
	$aquaticVeg$	$aquaticVeg = f(species) = \begin{cases} 1, & species = species_{aquatic} \\ 0, & otherwise \end{cases}$
	$species$	c.f., Appendix A in Punalekar et al. (2024)
Artificial surfaces	$artific\_urb\_cat$	$artific\_urb\_cat = f(tallness^{ASC}_{freq}, tallness^{DSC}_{freq}, NDBI_{min}) = \begin{cases} 1, & if\ tallness^{ASC}_{freq} > 8\ AND\ tallness^{DSC}_{freq} > 8\ AND\ NDBI_{min} > -0.1 \\ 0, & otherwise \end{cases}$
	$tallness^{ASC}_{freq}$	$tallness^{ASC}_{freq} = 12 * \frac{\sum_{i=1}^{N} tallness^{ASC}_i}{N}$
	$tallness^{DSC}_{freq}$	$tallness^{DSC}_{freq} = 12 * \frac{\sum_{i=1}^{N} tallness^{DSC}_i}{N}$
	$tallness^{ASC}_i$	$tallness^{ASC}_i = f(VH^{ASC}_i) = \begin{cases} 1, & VH^{ASC}_i > -15dB \\ 0, & VH^{ASC}_i \le -15dB \end{cases}$
	$tallness^{DSC}_i$	$tallness^{DSC}_i = f(VH^{DSC}_i) = \begin{cases} 1, & VH^{DSC}_i > -15dB \\ 0, & VH^{DSC}_i \le -15dB \end{cases}$
Cultivated vegetation	$cultman\_agr\_cat$	c.f., Appendix A in Punalekar et al. (2024)

Lifeform	$lifeform\_veg\_cat$	$lifeform_{veg_{cat}} = f(woody_{var}) = \begin{cases} woody, & woody_{var} \geq 1 \\ herbaceous, & otherwise \end{cases}$
	$woody_{var}$	$woody_{var} = woody_{S1} + woody_{NFI} - 2 * clearcut_{S2}$
	$woody_{S1}$	$f(tallness^{ASC}_{freq}, tallness^{DSC}_{freq}, veg) = \begin{cases} 1, & if\ tallness^{ASC}_{freq} > 8 \\ & OR\ tallness^{DSC}_{freq} > 8 \\ & AND\ vegetat\_veg\_cat = 1 \\ 0, & otherwise \end{cases}$
	$woody_{NFI}$	$woody_{NFI} = f(nfi_{woodland_{fr}}) = \begin{cases} 1, & 1 \leq nfi\_woodland\_fr \leq 4 \\ 0, & otherwise \end{cases}$
	$nfi\_woodland\_fr$	c.f, Table 1
	$clearcut_{S2}$	$clearcut_{S2} = f(NDVI) = \begin{cases} 1, & \underset{4 \leq month \leq 10}{\text{mean}} \{NDVI(month)\} \leq 0.5 \\ 0, & otherwise \end{cases}$
Leaf type/ Phenology	$leaftype\_veg\_cat$ $phenolog\_veg\_cat$	c.f., Punalekar et al. (2021)
Water/ wetness persistence	$waterper\_wat\_cat$	$waterper\_wat\_cat = f(wetness^{ASC}_{freq}, wetness^{DSC}_{freq}) = \frac{wetness^{ASC}_{freq} + wetness^{DSC}_{freq}}{2}$

Appendix B. Translation schemes for integrating Living Wales products in Welsh national monitoring and reporting obligations

Table B1. Scheme to translate Living Wales habitat map to SFS-compatible taxonomy, where X^1 indicates "in enclosure" and X^0 indicates "not in enclosure"

No	SFS Classes	Living Wales Habitat Category	Enclosure[1]
1	Dense Scrub	Ulex dominated scrub	
2	Enclosed semi-natural (dry) grasslands	Semi-natural grassland (unclassified), Acid grassland, Neutral grassland, Calcareous grassland	X^1
3	Dense Bracken	Bracken	
4	Unenclosed semi-natural rough grazing and habitat mosaics	Semi-natural grassland (unclassified), Semi-natural herbaceous vegetation (Unclassified), Juncus rushes, Molinia grassland, Young plantation/Felled/Coppice, Acid grassland, Neutral grassland, Calcareous grassland, Marsh/marshy grassland, Dry dwarf shrub heath, Wet dwarf shrub heath, Blanket sphagnum bog, Raised sphagnum bog, Modified bog, Fen, Peat - bare, Swamp, Natural rock exposure and waste, Inland cliff, Quarry, Natural bare surfaces	X^0
5	Saltmarsh	Saltmarsh, Intertidal vegetation Generic	
6	Sand dune and coastal vegetated shingle	Sand dune, Dune grassland, Dune heath, Dune scrub	
7	Lowland and coastal heath	Dry dwarf shrub heath, Wet dwarf shrub heath	X^1
8	Enclosed Marshy grassland	Juncus rushes, Marsh/marshy grassland	X^1
89	*Lowland Molinia dominated grasslands*[2]	Molinia grassland	X^1
9	Lowland bog, fen and flushes	Blanket sphagnum bog, Raised sphagnum bog, Modified bog, Fen, Peat - bare, Swamp	X^1
10	Intensively managed improved grassland	Improved grassland	
		Semi-natural herbaceous vegetation (Unclassified)	X^1
11	Arable land	Arable crops	
12	Woodland	Woodland and scrub (Unclassified), Broadleaved woodland, Needleleaved woodland	
111	*Lowland natural bare surface*	Natural rock exposure and waste, Inland cliff, Quarry, Natural bare surfaces	X^1
113	*Lowland young plantation /felled/coppice*	Young plantations/Felled/Coppice	X^1
209	Other (coastal habitats)	Intertidal Bare Generic, Maritime cliff and slope (unvegetated), Maritime cliff and slope (vegetated)	
210	Other (open water)	Open Water	

212	Other (artificial bare surfaces)	Artificial bare surfaces

[1] The limit of enclosure is defined by Welsh Government, i.e., private/license data

Table B2. Scheme to translate Living Wales products to SoNaRR-compatible taxonomy, where X^1 indicates "in enclosure" and X^0 indicates "not in enclosure"

No	SoNaRR Classes	Living Wales Habitat Category	Enclosure[1]
1	Mountains, Moorlands and Heath	Semi-natural grassland (unclassified), Semi-natural herbaceous vegetation (Unclassified), Juncus rushes, Molinia grassland, Ulex dominated scrub, Acid grassland, Marsh/marshy grassland, Blanket sphagnum bog, Raised sphagnum bog, Modified bog, Fen, Peat - bare	**X^0**
		Bracken, Dry dwarf shrub heath, Wet dwarf shrub heath, Natural rock exposure and waste, Inland cliff	
2	Semi-natural Grasslands	Semi-natural grassland (unclassified), Juncus rushes, Molinia grassland, Acid grassland, Marsh/marshy grassland	**X^1**
		Neutral grassland, Calcareous grassland	
3	Enclosed Farmland	Ulex dominated scrub, Semi-natural herbaceous vegetation (Unclassified)	**X^1**
		Improved grassland, Arable crops	
4	Woodlands	Young plantations/Felled/Coppice, Woodland and scrub (Unclassified), Broadleaved woodland, Needleleaved woodland	
5	Open water, wetlands and floodplains	Blanket sphagnum bog, Raised sphagnum bog, Modified bog, Fen, Peat - bare	**X^1**
		Swamp, Open Water	
6	Urban	Quarry, Natural bare surfaces, Artificial bare surfaces	
7	Coastal Margins	Saltmarsh, Sand dune, Dune grassland, Dune heath, Dune scrub, Maritime cliff and slope (unvegetated), Maritime cliff and slope (vegetated)	
8	Marine	Intertidal vegetation Generic, Intertidal Bare Generic	

[1] The limit of enclosure is defined by Welsh Government, i.e., private/license data

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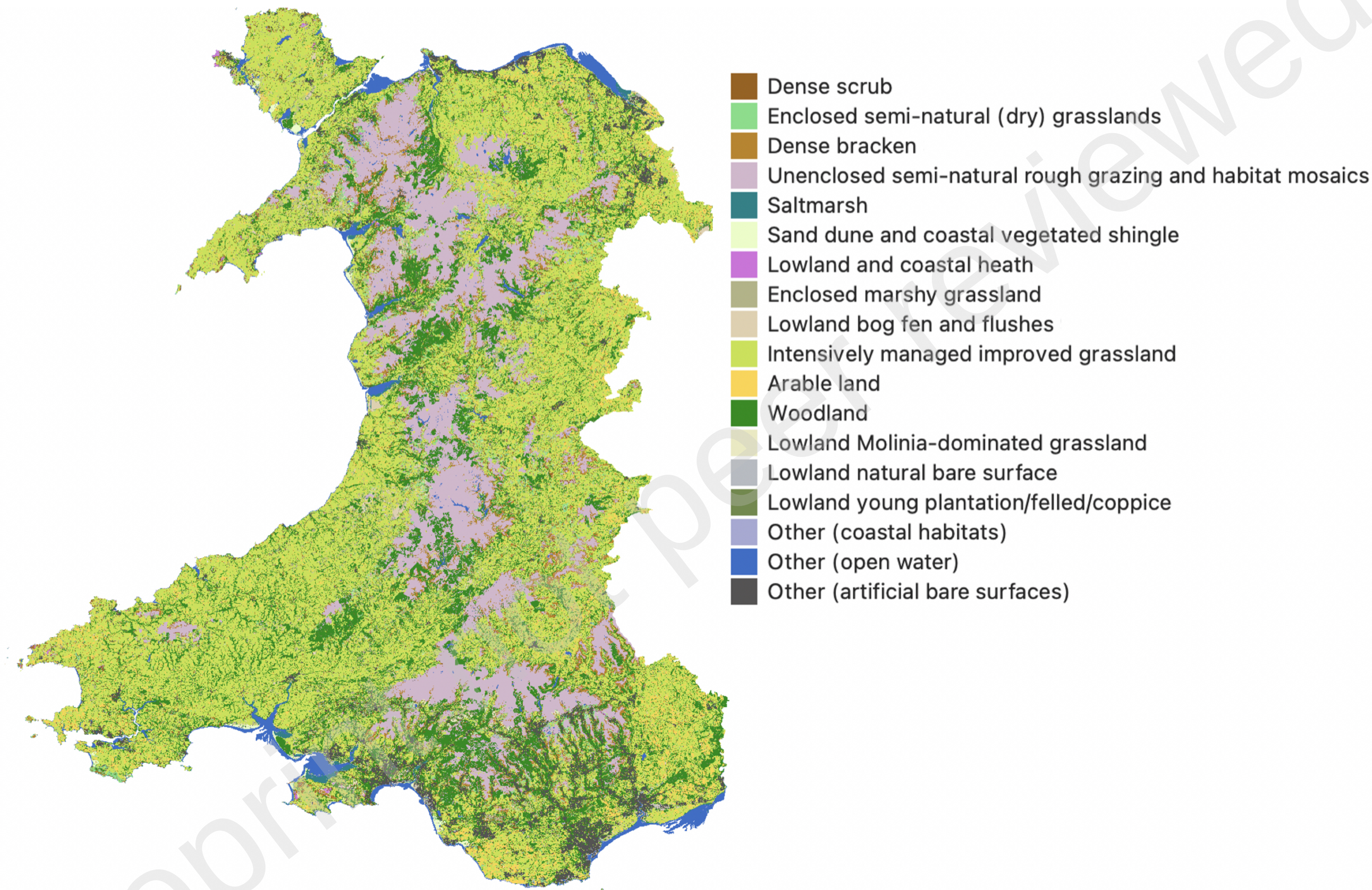
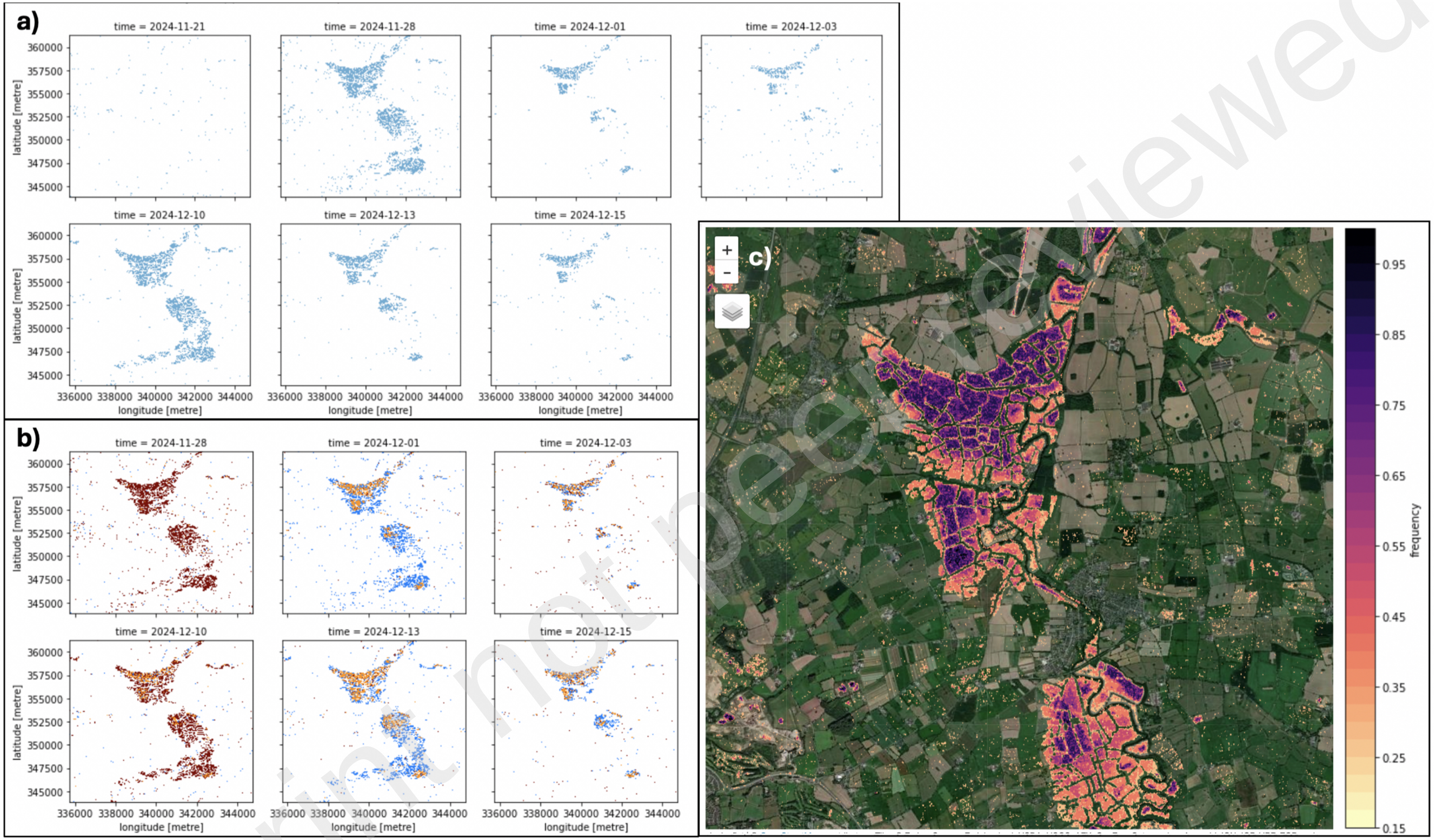

Dense scrub
Enclosed semi-natural (dry) grasslands
Dense bracken
Unenclosed semi-natural rough grazing and habitat mosaics
Saltmarsh
Sand dune and coastal vegetated shingle
Lowland and coastal heath
Enclosed marshy grassland
Lowland bog fen and flushes
Intensively managed improved grassland
Arable land
Woodland
Lowland Molinia-dominated grassland
Lowland natural bare surface
Lowland young plantation/felled/coppice
Other (coastal habitats)
Other (open water)
Other (artificial bare surfaces)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time = 2024-11-28
time = 2024-12-01
time = 2024-12-03
time = 2024-12-10
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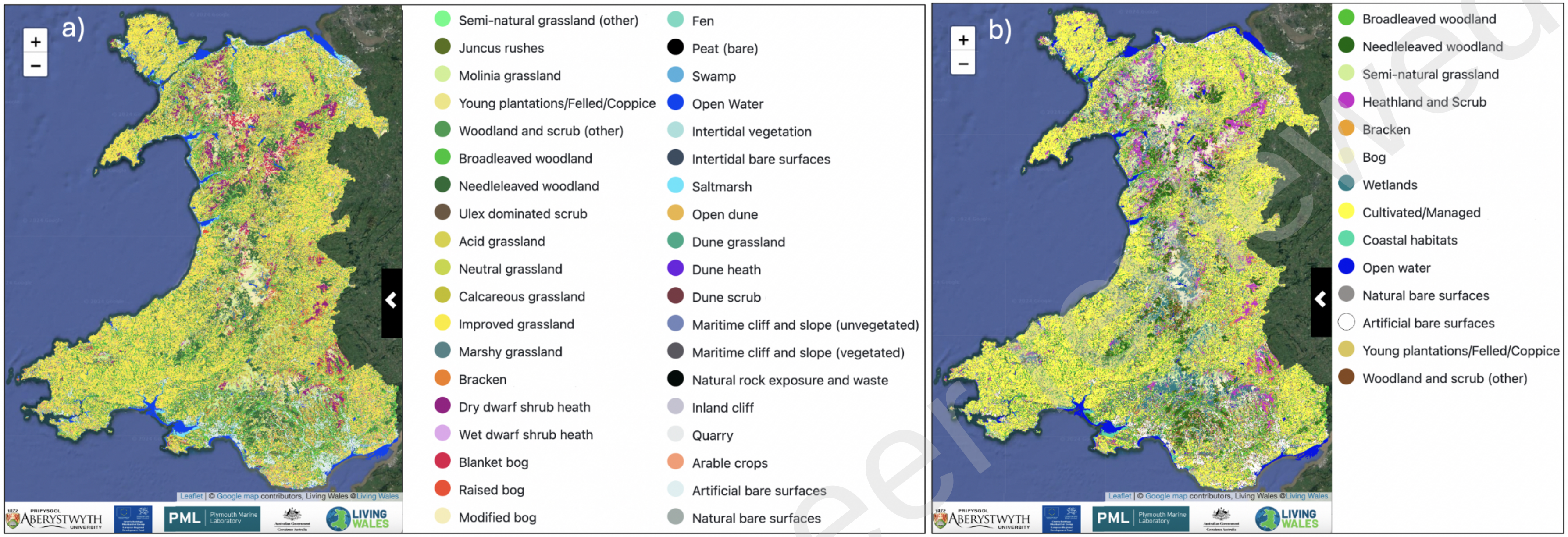
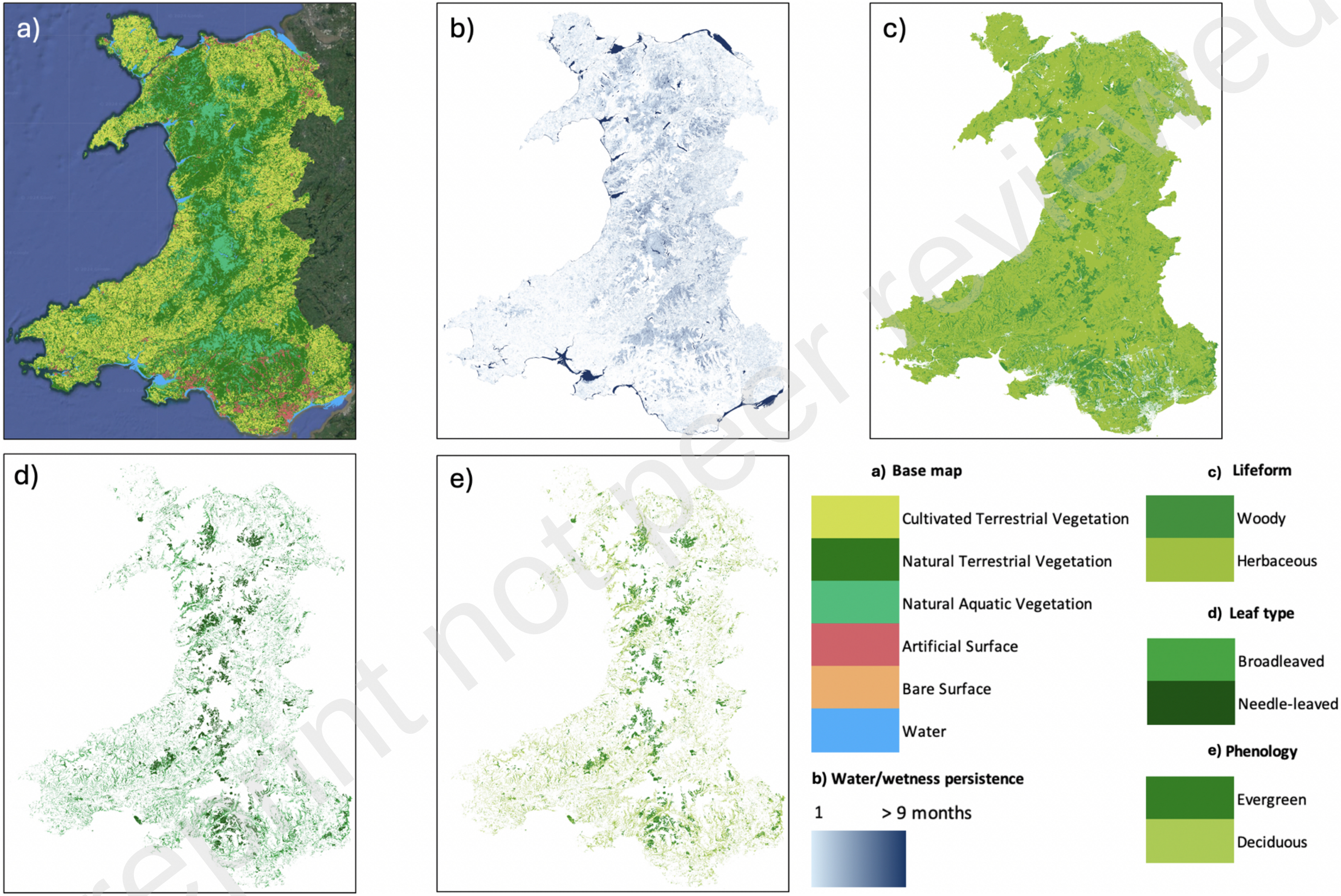
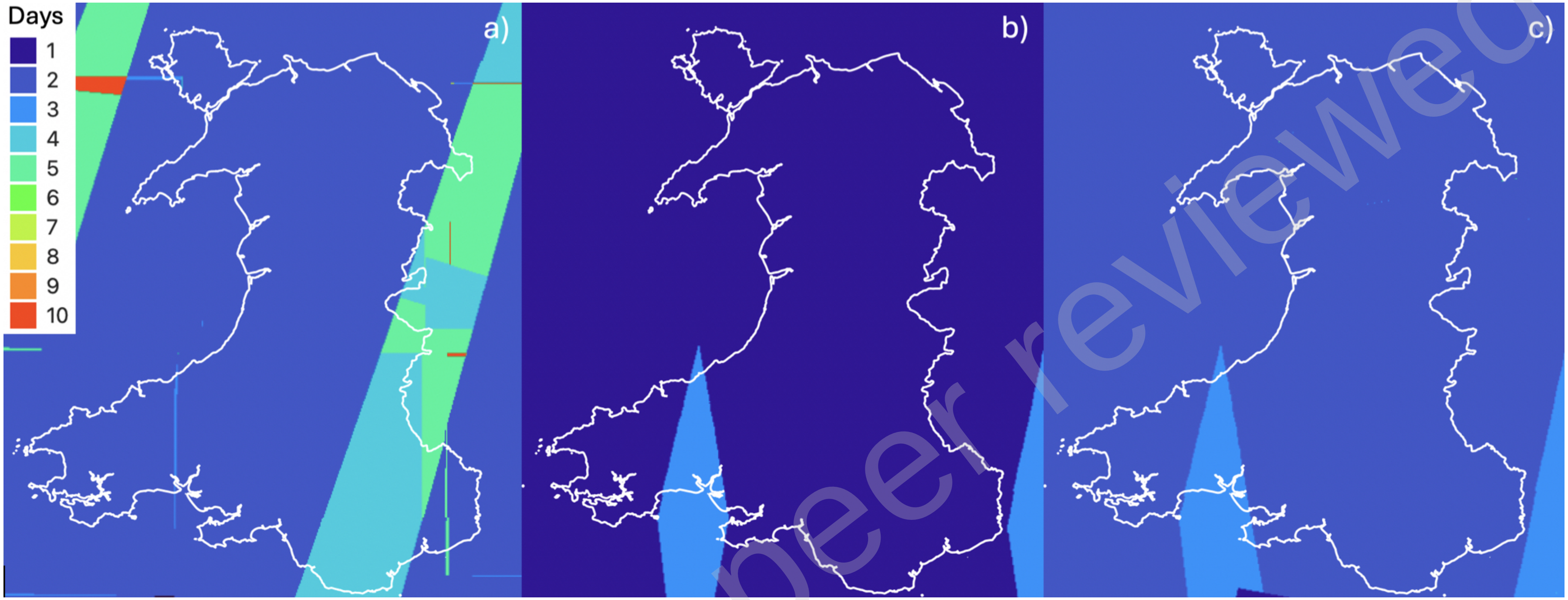
time = 2024-12-15
latitude [metre]
longitude [metre]
b)
c)
frequency


a)
Semi-natural grassland (other)
Juncus rushes
Molinia grassland
Young plantations/Felled/Coppice
Woodland and scrub (other)
Broadleaved woodland
Needleleaved woodland
Ulex dominated scrub
Acid grassland
Neutral grassland
Calcareous grassland
Improved grassland
Marshy grassland
Bracken
Dry dwarf shrub heath
Wet dwarf shrub heath
Blanket bog
Raised bog
Modified bog
Fen
Peat (bare)
Swamp
Open Water
Intertidal vegetation
Intertidal bare surfaces
Saltmarsh
Open dune
Dune grassland
Dune heath
Dune scrub
Maritime cliff and slope (unvegetated)
Maritime cliff and slope (vegetated)
Natural rock exposure and waste
Inland cliff
Quarry
Arable crops
Artificial bare surfaces
Natural bare surfaces
b)
Broadleaved woodland
Needleleaved woodland
Semi-natural grassland
Heathland and Scrub
Bracken
Bog
Wetlands
Cultivated/Managed
Coastal habitats
Open water
Natural bare surfaces
Artificial bare surfaces
Young plantations/Felled/Coppice
Woodland and scrub (other)
PML
LIVING WALES


a)
b)
c)
d)
e)
a) Base map
Cultivated Terrestrial Vegetation
Natural Terrestrial Vegetation
Natural Aquatic Vegetation
Artificial Surface
Bare Surface
Water
b) Water/wetness persistence
1
> 9 months
c) Lifeform
Woody
Herbaceous
d) Leaf type
Broadleaved
Needle-leaved
e) Phenology
Evergreen
Deciduous


Days
1
2
3
4
5
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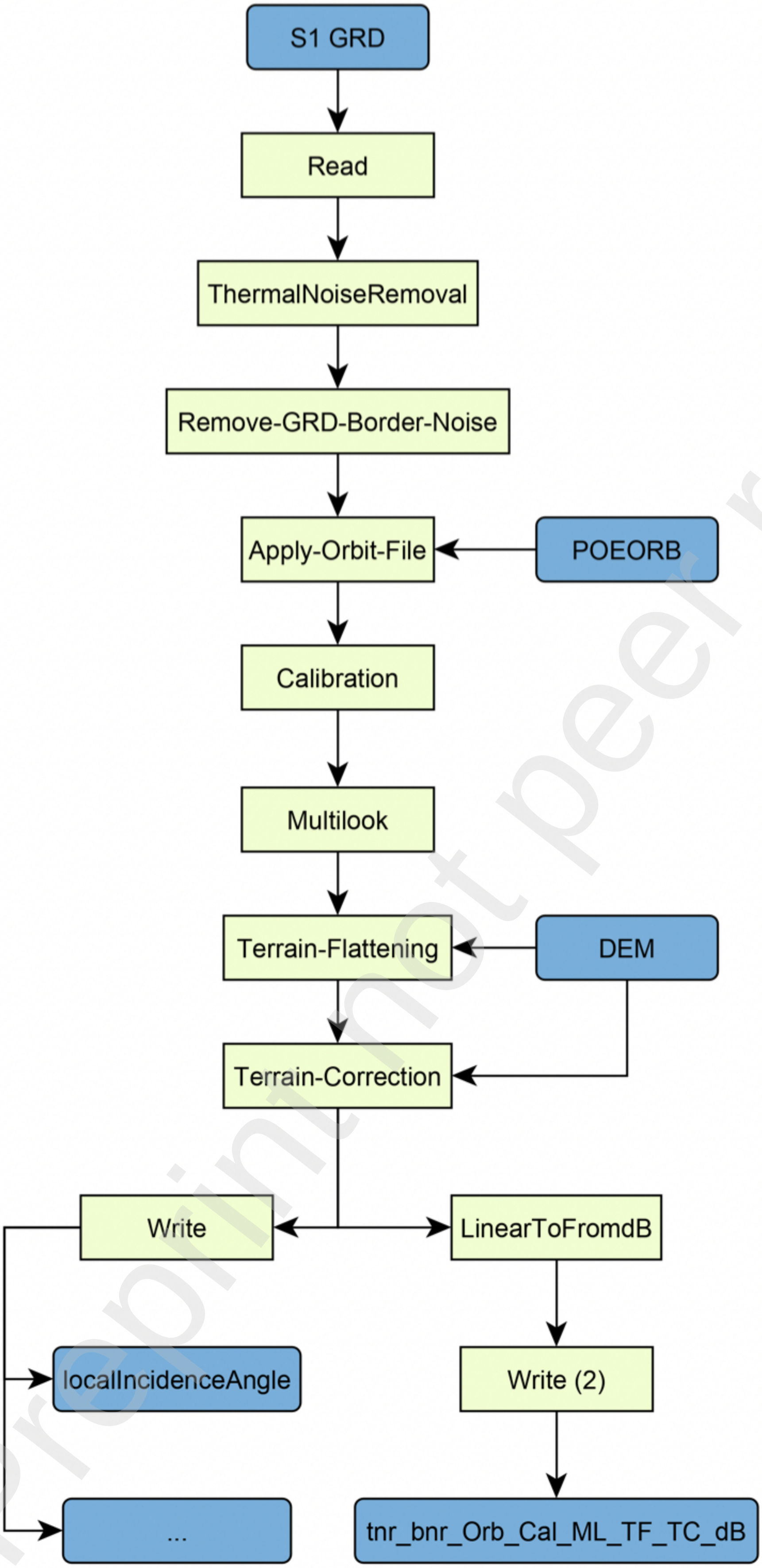
7
8
9
10
a)
b)
c)


S1 GRD
Read
ThermalNoiseRemoval
Remove-GRD-Border-Noise
Apply-Orbit-File
POEORB
Calibration
Multilook
Terrain-Flattening
DEM
Terrain-Correction
Write
LinearToFromdB
localIncidenceAngle
Write (2)
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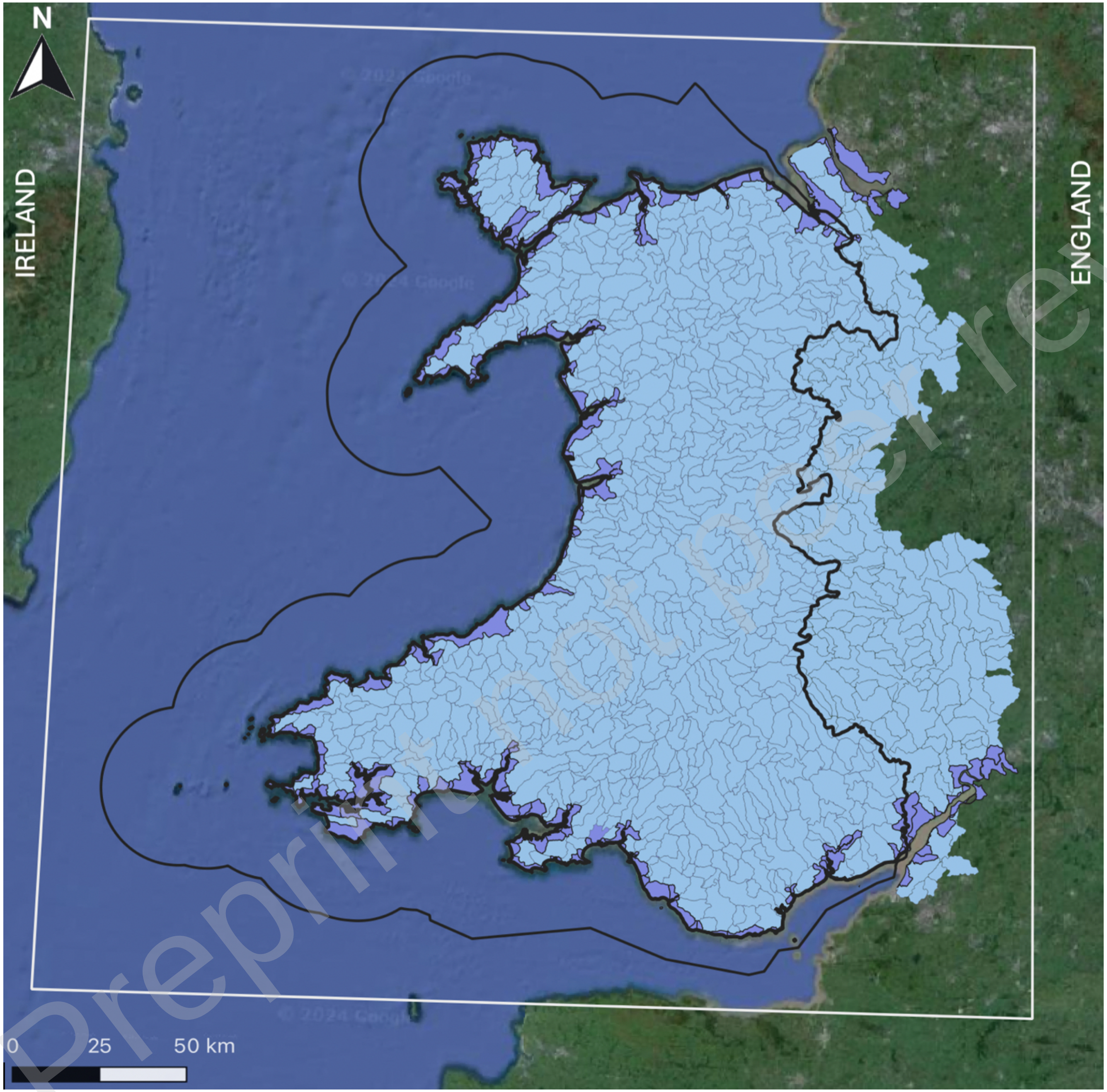
tnr_bnr_Orb_Cal_ML_TF_TC_dB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ENGLAND
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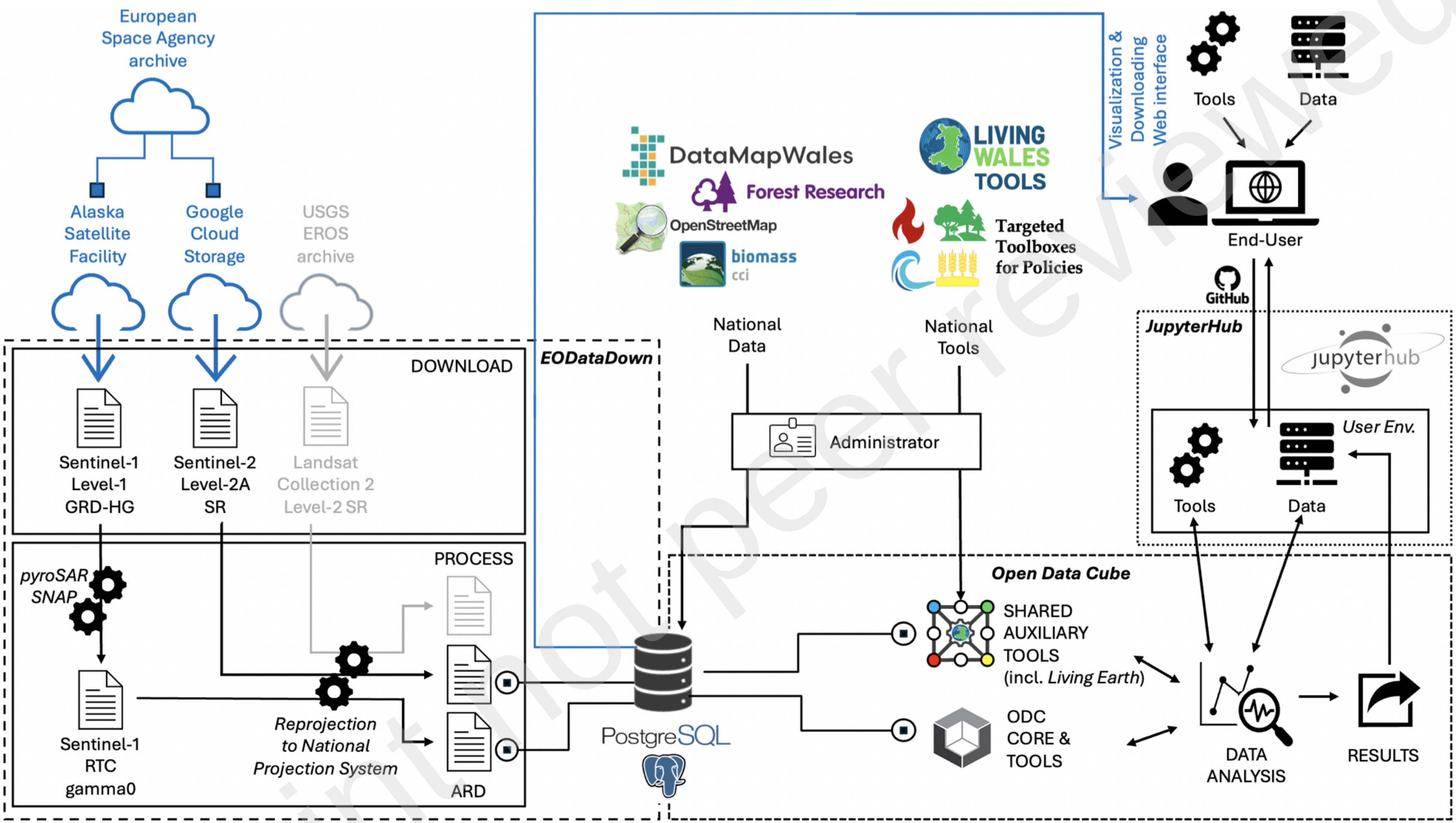
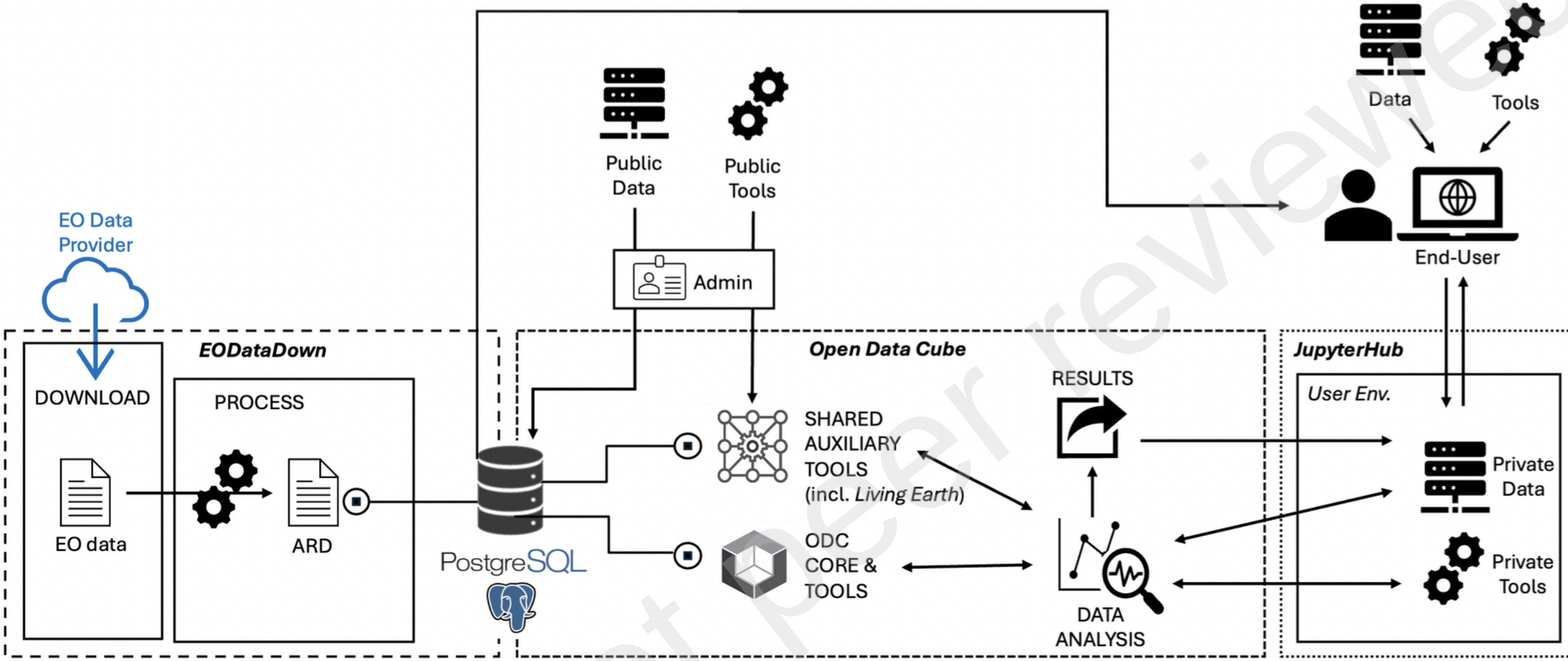
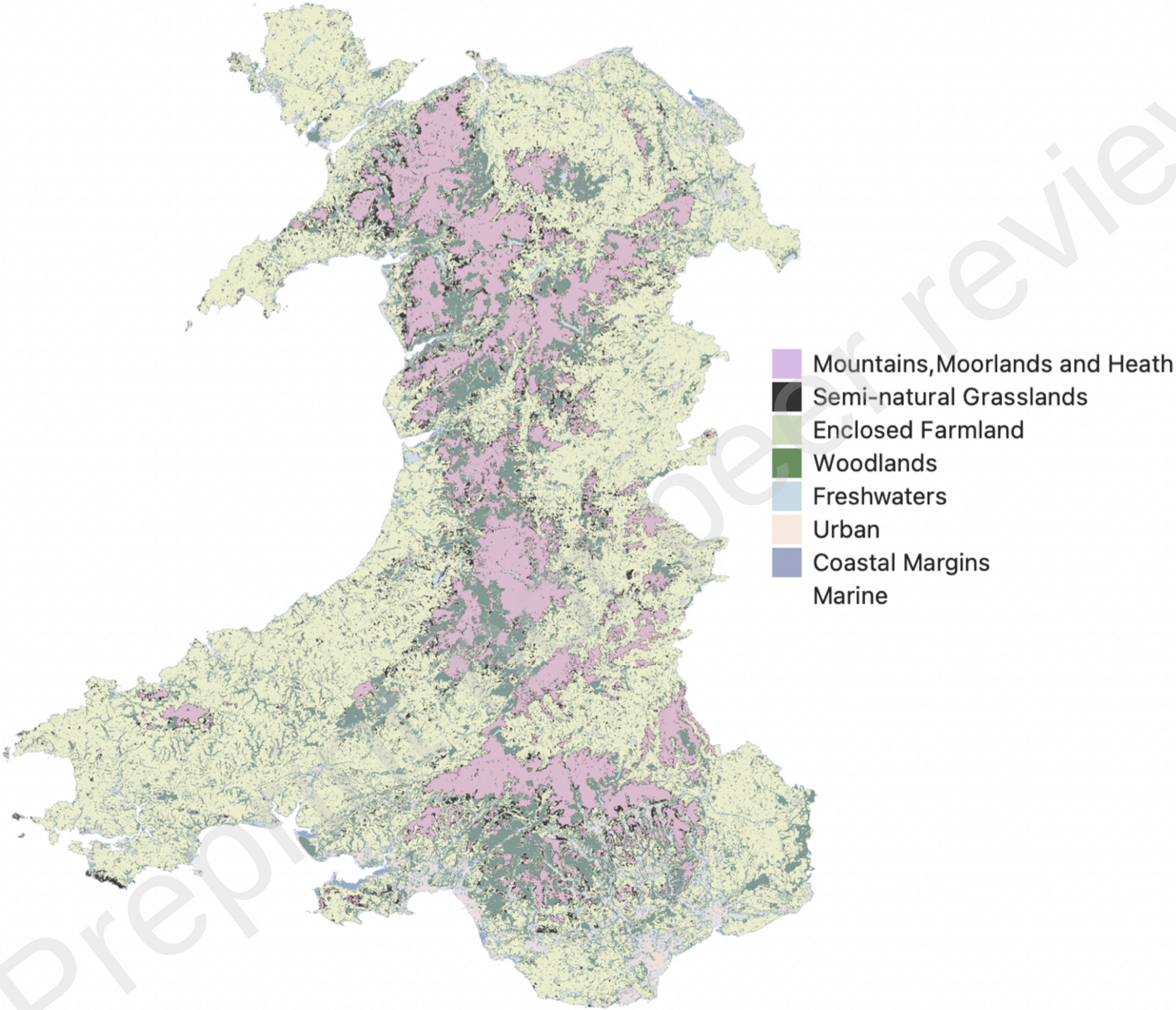


European Space Agency archive
Alaska Satellite Facility
Google Cloud Storage
USGS EROS archive
DOWNLOAD
EODataDown
Sentinel-1 Level-1 GRD-HG
Sentinel-2 Level-2A SR
Landsat Collection 2 Level-2 SR
PROCESS
pyroSAR SNAP
Sentinel-1 RTC gamma0
Reprojection to National Projection System
ARD
PostgreSQL
DataMapWales
Forest Research
OpenStreetMap
biomass cci
LIVING WALES TOOLS
Targeted Toolboxes for Policies
National Data
National Tools
Administrator
Visualization & Downloading Web interface
Tools
Data
End-User
GitHub
JupyterHub
jupyterhub
User Env.
Tools
Data
Open Data Cube
SHARED AUXILIARY TOOLS (incl. Living Earth)
ODC CORE & TOOLS
DATA ANALYSIS
RESULTS


EO Data
Provider
EODataDown
DOWNLOAD
EO data
PROCESS
ARD
PostgreSQL
Public
Data
Public
Tools
Admin
Open Data Cube
SHARED
AUXILIARY
TOOLS
(incl. *Living Earth*)
ODC
CORE &
TOOLS
RESULTS
DATA
ANALYSIS
Data
Tools
End-User
JupyterHub
User Env.
Private
Data
Private
Tools


Mountains,Moorlands and Heath
Semi-natural Grasslands
Enclosed Farmland
Woodlands
Freshwaters
Urban
Coastal Margins
Marine

Login

Land Owner Login

Please sign in with your email address and password.

Email *

Password *

Sign In

Forgot your password?

* Required fields