FAIRness Challenges in Remote Sensing Metadata: A Comparative Study Using ISO 19115-1 and ISO19115-2

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Abstract *The FAIR (Findable, Accessible, Interoperable, Reusable) principles are increasingly recognized as essential components in the dissemination and application of scientific data across various professional fields. Remote sensing imagery is crucial for environmental monitoring, as it provides vital spatiotemporal data. However, the degree to which the inherent characteristics of remote sensing data can adhere to the FAIR principles necessitates further exploration. Specifically, achieving interoperability and reusability hinges on the availability of metadata that comprehensively conveys information regarding acquisition context, sensor specifications, spatial frameworks, and processing lineage. This study investigates how the established schema of ISO 19115-1 and its imagery extension, ISO 19115-2, can facilitate the creation of metadata structures that align with FAIR principles for remote sensing images. Through an analysis of metadata standards mapping, we evaluate whether the selected metadata elements offer a structured and machine-actionable framework for detailing image-specific attributes. We assess their effectiveness in promoting semantic clarity, long-term consistency, and platform-independent integration, with a particular focus on enhancing interoperability and reusability across diverse systems and applications. Additionally, we discuss how the proposed metadata can improve the interoperable use of remote sensing images in environmental monitoring and change detection efforts. Our findings underscore the significance of metadata standards not only as documentation tools but also as facilitators of FAIR data governance. By highlighting the importance of interoperability and reusability over time and across platforms, this study contributes to the development of transparent, standardized, and application-ready geospatial data infrastructures.*

Keywords: FAIR Principles, Remote Sensing Imagery, ISO 19115

Introduction

Remote sensing imagery is essential in modern geographic information science and environmental applications. It supports critical tasks such as land cover classification, monitoring of land-use change, disaster risk management, climate studies, and agricultural production assessment(Chen et al., 2015; Thenkabail, 2011).With the continuous development of Earth Observation (EO) programs such as Landsat and Copernicus, satellite data have become increasingly voluminous and heterogeneous, posing challenges for integration, standardization, and long-term usability(Wulder et al., 2012).

The FAIR principles—Findable, Accessible, Interoperable, and Reusable—were introduced to enhance scientific data governance and improve transparency, machine-actionability, and reuse across domains. While these principles have been widely adopted in many scientific disciplines, their implementation in the EO domain remains inconsistent. For example, international platforms such as Copernicus and USGS Earth Explorer have implemented structured metadata and open-access services, whereas other national or regional platforms have largely prioritized visualization or integration functions while neglecting metadata completeness and FAIR compliance(Belward & Skøien, 2015; Giuliani et al., 2017).

To address such challenges, the ISO 19115 family of standards provides a recognized international framework for geospatial metadata. ISO 19115-1 defines the fundamental elements of geospatial metadata, including identification, extent, quality, distribution, and lineage(International Organization for Standardization, 2014), while ISO 19115-2 expands these to cover remote sensing imagery, enabling detailed descriptions of acquisition context, sensor characteristics, spatial references, and processing lineage(International Organization for Standardization, 2019). Nevertheless, systematic evaluations of the degree to which these standards align with the FAIR principles in remote sensing imagery are still lacking.

This study aims to fill this research gap by examining the applicability of ISO 19115-1 and ISO 19115-2 in the context of FAIR, using comparative analysis across representative platforms such as Copernicus Sentinel-2, USGS Landsat and SwissEnvEO. By assessing their metadata structures against the FAIR principles using criteria such as semantic clarity, cross-platform interoperability, and long-term consistency, this research identifies key strengths, existing shortcomings, and potential opportunities for advancing FAIR-compliant remote sensing data infrastructures.

Literature Review

The FAIR principle (Findable, Accessible, Interoperable, Reusable) was first proposed to improve the transparency, traceability, and long-term use value of scientific research data. Its principles emphasize that data should have clear descriptions, standardized formats that can be understood by both machines and humans, and clear authorization and source information to maximize data reuse(Wilkinson et al., 2016). Although the FAIR principles were originally proposed for scientific research data, with the vigorous development of big data and open science, FAIR has been increasingly applied to the fields of geographic information science and Earth Observation (EO).which generate large, highly heterogeneous, and highly dynamic data every day(Sudmanns et al., 2023). In the field of remote sensing, the implementation of the FAIR principle is even more important. Remote sensing imagery is widely used as a fundamental data source for applications such as vegetation and land cover mapping(Xie et al., 2008), land-use change detection and long-term monitoring(Zhu & Woodcock, 2014), and disaster risk assessment, particularly in landslide-prone areas(Casagli et al., 2017; van Westen et al., 2008). The value of such data is often limited to a one-time application, but can be continuously integrated, compared, and reused. However, remote sensing imagery itself presents several challenges: its large data volume(Drusch et al., 2012), the variety of sensors (optical, radar, thermal infrared, etc.)(Belward & Skøien, 2015), and the coverage of different spatial resolutions, bands, and temporal resolutions(Justice et al., 2015).These characteristics make ensuring standardized formats and reusability across different platforms and analytical environments a key factor in the implementation of the FAIR principles. Several international and local data platforms have developed features that align with the FAIR principles in the management of remote sensing imagery. Copernicus Sentinel-2 supports data discoverability and availability by providing standardized metadata structures, APIs, and multi-format access through the Copernicus Open Access Hub(Gascon et al., 2017). USGS Earth Explorer has long released public data on the Landsat series and provides the full acquisition context in the metadata WRS path/row, processing level, and QA band, which have become important foundations for supporting cross-generational change detection and reuse(Roy et al., 2014; Wulder et al., 2019). SwissEnvEO represents the practice of a national FAIR database, combining GeoNetwork catalog, NetCDF format, and DOI Registration, which strengthens the traceability and long-term retention of data, but there are still shortcomings in the technical details of acquisition and lineage(Giuliani et al., 2021; Giuliani et al., 2017). ken together, these implementation platforms—Copernicus Sentinel-2, USGS Earth Explorer, and SwissEnvEO—are relatively mature in Findable (F) and Accessible (A), but still show notable shortcomings in Interoperable (I) and Reusable (R)(Mons et al., 2017).

For example, satellite products for different missions may use different projection coordinate systems, distinct processing workflows, and varying quality control standards, which often lead to inconsistencies in cross-platform comparisons or long-term time-series analysis(Claverie et al., 2018). Therefore, although the FAIR principle provides an ideal conceptual framework, in the practical application of remote sensing imagery it is still necessary to adopt metadata standards, such as ISO 19115, that fully capture data sources, sensor attributes, spatial reference systems, and processing lineage to ensure compliance with all four FAIR principles.

This study therefore takes ISO 19115-1 and ISO 19115-2 as the primary reference framework and evaluates their alignment with the FAIR principles. Rather than reiterating their structures, the focus is on examining how well these standards support Findability and Accessibility, and where they fall short in Interoperability and Reusability. By doing so, the analysis not only highlights the importance of ISO metadata standards but also identifies gaps that must be addressed to advance FAIR-compliant remote sensing data infrastructures. Through such structured and machine-readable metadata, remote sensing images can not only be discovered and accessed but also preserved over the long term, reused across platforms, and supported with the semantic clarity and traceability required by the FAIR principles. This series of standards has since been widely regarded as the international benchmark for geospatial metadata and the foundation of many Spatial Data Infrastructures (SDIs). In academic research, the ISO 19115 family of standards has been widely cited as the foundation for geospatial metadata, with many GIScience projects adopting these schemas to ensure data sharing across research programs. For example, the U.S. FGDC metadata framework((FGDC), 1998), and the international GEOSS platform all align technically with ISO 19115. For researchers, following these standards not only increases the reusability of data but also ensures comparability across disciplines and domains. In practice, ISO 19115-1/-2 has been adopted by numerous countries and organizations to build national or international SDIs. In practice, most operational platforms such as Copernicus Open Access Hub, USGS Earth Explorer, and GeoNetwork still rely on ISO 19115:2003/19139 metadata profiles due to long-standing implementation and tool support. However, the transition toward ISO 19115-1:2014 and ISO 19115-2:2019 is ongoing, and systematic evaluations of how these newer standards align with the FAIR principles for remote sensing imagery remain largely absent. However, despite its structural completeness, ISO 19115 was originally designed to ensure consistency and interoperability of geospatial metadata across systems. However, in practice, while the structural framework is standardized, the lack of enforced semantic harmonization and machine-readable vocabularies has resulted in heterogeneous implementations. Consequently, metadata records can vary significantly across institutions, leading to mismatches of equivalent elements between systems. Moreover, although the standard provides structured metadata elements, aligning them precisely with FAIR principles still requires complementary frameworks and tools, such as semantic standards (e.g., RDF/OWL) or extended profiles (e.g., GeoDCAT-AP).

In addition to ISO 19115-1 and ISO 19115-2, in recent years the international community has introduced various metadata frameworks and applications to address the FAIR needs of remote sensing imagery. These frameworks are often based on ISO 19115, but they differ in their technical approaches and application scenarios, particularly in how they describe acquisition context, sensor specifications, and processing lineage. GeoNetwork is currently the most widely used open-source metadata catalog system. It natively supports ISO 19115 for geospatial metadata content, with its XML implementation defined by ISO 19139, and can be integrated with OGC's CSW (Catalog Service for the Web) to provide standardized search interfaces. In the remote sensing domain, GeoNetwork has been applied in national and international data catalogs, such as those of the European Environment Agency (EEA) and the Food and Agriculture Organization of the United Nations (FAO), to manage large-scale remote sensing imagery and environmental datasets(Nativi et al., 2017). Its strength lies in its integration with OGC services such as GeoServer, enabling metadata to dynamically link with actual imagery files (e.g., GeoTIFF or NetCDF), thus improving accessibility. However, GeoNetwork's interoperability remains primarily "structural" rather than "semantic," with cross-system semantic consistency requiring further standardization support(Arora & Chakravarty, 2021).

MIAGIS (Minimum Information About Geospatial Information System) is a recent initiative inspired by the "Minimum Information" movement in life sciences (e.g., MIAME for microarray data). It defines a lightweight set of "minimal but essential" metadata elements, drawing on ISO 19115/19139 structures and FAIR vocabularies, and informed by ESIP community guidelines. For remote sensing imagery, MIAGIS lowers the cost of metadata production and reduces the learning curve of full ISO standards, making it particularly useful for rapid sharing of derived products such as NDVI/NDWI indices or land cover classification maps. However, its simplified structure cannot fully document acquisition context, sensor parameters, or detailed processing lineage, which constrains its suitability for large-scale, cross-platform interoperability.

GeoDCAT-AP, developed by the European Commission, is a W3C DCAT application profile tailored for geospatial data. Unlike ISO 19115, GeoDCAT-AP uses RDF (Resource Description Framework) to describe metadata, integrating with the Linked Data ecosystem. As a result, remote sensing imagery can be semantically searchable and linked on the web, e.g., a Sentinel-2 image not only appears in a geospatial database but can also be linked to land cover classifications, environmental reports, or policy documents(European

Commission, 2017) . This significantly enhances reusability across domains, such as combining imagery with climate or socioeconomic data. However, implementation requires advanced knowledge of RDF and semantic web technologies, making its adoption relatively costly.

A practical example is the Swiss Data Cube (SDC). Built on the GeoNetwork catalog, it provides search and access to Landsat and Sentinel data, using ISO 19115/19139 metadata and OGC standards (WMS, WCS, CSW) to ensure interoperability. Moreover, SDC integrates with Switzerland's long-term archival system Yareta, assigning DOIs to each dataset to guarantee traceability and persistence. SDC demonstrates maturity in the Findable and Accessible dimensions, while strengthening Reusability through its lineage documentation. However, when the focus shifts to Interoperability, its performance remains mostly structural, as semantic web integration is still limited. This highlights the persistent challenges and gaps of FAIR implementation in local contexts.

In summary, GeoNetwork emphasizes standardized catalog applications, MIAGIS offers a lightweight sharing approach, GeoDCAT-AP demonstrates strong semantic interoperability potential, while Swiss Data Cube reflect the uneven progress of FAIRification across different national contexts. Collectively, these cases reveal a key research gap: the lack of systematic mapping between remote sensing imagery metadata and the FAIR principles, particularly regarding the completeness of acquisition context, sensor specifications, spatial reference, and processing lineage.

Methodology

The methodological design of this study is divided into four main steps to examine the applicability of ISO 19115-1 and ISO 19115-2 in supporting FAIR principles. First, in terms of research design and structure, this study adopts a metadata mapping approach that aligns the four major aspects of the FAIR principles (Findable, Accessible, Interoperable, and Reusable) with the relevant elements of the ISO 19115 series of standards, to evaluate their scope of coverage and practical adequacy. This design highlights both the strengths and shortcomings of the standards, providing a basis for identifying areas in need of improvement. Secondly, in terms of metadata mapping methods, this study develops a systematic mapping framework that explicitly links the specific requirements of each FAIR dimension (such as identifiers, access protocols, semantic consistency, and process steps) to the corresponding fields and modules defined in ISO 19115-1 and ISO 19115-2.Third, in the Data sources section, this study mainly refers to the schema specifications and guidelines of ISO 19115-1 and 19115-2, supplemented by actual remote sensing image metadata examples, including published metadata records from Copernicus Sentinel, USGS Landsat, SwissEnvEO to verify that the mapping analysis reflects real-world application scenarios. Finally, this study sets three evaluation criteria to examine the fitness between ISO metadata and FAIR principles: (1) semantic clarity, that is, whether the metadata field can accurately and consistently describe the remote sensing image attributes; (2) platform-independent integration, that is, whether metadata can be consistent across different platforms, databases, or systems; (3) Long-term consistency, that is, whether the metadata structure can support long-term data preservation and cross-generational reuse.

a. Study design and structure

In terms of the mapping method, this study breaks down the four aspects of the FAIR principle into specific data requirements one by one and compares the relevant elements in ISO 19115-1 and 19115-2. Specifically:

- Findable: The requirement is a unique identifier and retrievable metadata that maps to MD_Metadata.identifier, CI_Citation, MD_Keywords, EX_Extent (temporal and geographic) and MD_Resolution.
- Accessible: The requirements are standardized access protocol and authorization information, mapped to MD_Distribution and MD_DigitalTransferOptions.
- Interoperable: Requirements are cross-platform consistency and semantic consistency, mapping to MD_ReferenceSystem, MD_Scope, and MD_ContentInformation.
- Reusable: The requirement is the complete data quality, source, and processing history, mapped to DQ_DataQuality and LI_Lineage.

To ensure that the mapping is grounded in practice rather than over-theorized, this study examined metadata from Copernicus Sentinel, USGS Landsat and SwissEnvEO. These examples validate that the comparison table adequately captures acquisition context (observation time, satellite platform, environmental conditions), sensor specifications (resolution, spectral range, calibration status), spatial reference (coordinate system and projection), and processing lineage (geometric and atmospheric correction, classification steps). In this way, the mapping results not only reveal the alignment between the standards and the FAIR principles but also evaluate their applicability and limitations in practice. The detailed outcomes of this mapping and the comparative analysis across platforms are presented in the Results and Discussion section.

b. Data Sources

a. ISO standard documents and schema

This study primarily draws on ISO 19115-1:2014 – Fundamentals, which provides a core framework for geospatial metadata, covering aspects such as resource identification, spatial and temporal extent, data quality, distribution methods, and provenance. Within this framework, commonly recognized core elements include MD_Metadata, MD_Identification, MD_Distribution, MD_ReferenceSystem, DQ_DataQuality, and LI_Lineage, which together form the foundation for describing and exchanging geographic information. These elements were selected because of their prominence in ISO documentation and frequent adoption in practical implementations; nevertheless, it should be acknowledged that other elements may also be relevant in specific contexts, and this study does not claim exhaustiveness.

In addition to these core components, this study also incorporates ISO 19115-2:2019 – Extensions for Acquisition and Processing, which provides enhanced support for remote sensing imagery and gridded data. It supplements the standard with acquisition and sensor-level descriptions, such as MI_AcquisitionInformation to record the details of observation missions, MI_Instrument to describe sensor names, spectral ranges, resolutions, and calibration, and MI_Platform to annotate platform information such as satellite or aircraft attributes. Furthermore, MI_Event and MI_Operation elements capture observation events and operational processes, thereby strengthening the traceability of remote sensing data back to its source.

b. Copernicus Sentinel-2 Metadata

At the empirical data level, metadata from Copernicus Sentinel-2 was selected as the validation case in this study. This data is publicly available from the Copernicus Open Access Hub, and its metadata structure broadly addresses the requirements of the four pillars of FAIR, particularly in acquisition context, sensor specifications, spatial reference, and processing lineage. For example, in the acquisition context section, Sentinel-2 metadata includes information such as observation date, orbit number, cloud cover ratio, and solar altitude angle. In the sensor specifications section, the resolution (10 meters, 20 meters, 60 meters), band range, and calibration status of the

Multispectral Imager (MSI) are described. In the spatial reference section, EPSG codes (e.g., EPSG:32633) are used to ensure consistency with the spatial datum; In the processing lineage section, information from geometric corrections, atmospheric corrections (such as Sen2Cor processing) to the product level (L1C and L2A) are recorded. The integrity of these metadata makes it an ideal case for verifying the appropriateness of ISO element mapping.

c. USGS Landsat 8/9 Metadata

This study also refers to public metadata from USGS Landsat 8/9, which is the USGS Earth Explorer platform. Landsat metadata is characterized by its long-term stable observation data, which can support time series analysis across generations. In the acquisition context section, the Landsat metadata provides observation dates, WRS-2 orbit numbers, and environmental conditions descriptions; In the sensor specifications section, it covers the spectral characteristics and resolution of Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS). In the spatial reference section, Landsat products use UTM projection and WGS84 datum to ensure compatibility with other geographic data; In the processing lineage section, metadata documents in detail different product levels, such as Precision Terrain Correction Imagery (LITP) and L2 Scientific Products (including atmospheric correction), which provides complete traceability of the data processing process.

d. SwissEnvEO

As a FAIR-oriented national environmental database, SwissEnvEO strengthens data traceability and durability through DOI registration and the long-term preservation system (Yareta), while also adopting FAIR vocabularies to enhance semantic consistency. Its metadata demonstrates strong support for elements such as MD_Metadata.identifier, MD_Distribution, and LI_Lineage; however, descriptions of acquisition and sensor-related technical aspects (e.g., MI_AcquisitionInformation and MI_Instrument) remain relatively simplified. This indicates that its design priorities lean toward data governance and stewardship rather than comprehensive technical detail. Although SwissEnvEO positions itself within the FAIR framework, the difference lies in its emphasis on governance and long-term preservation, whereas other platforms may prioritize technical completeness or semantic interoperability.

c. Evaluation item

To evaluate the applicability of the ISO 19115 series of standards in supporting FAIR principles, this study defines three assessment criteria: semantic clarity, cross-platform interoperability, and long-term consistency. These criteria not only examine the robustness of the mapping results but also ensure that the research outcomes remain aligned with the foundational objectives of the FAIR principles.

1. Semantic Clarity

This criterion evaluates whether ISO metadata elements can consistently and unambiguously represent the properties of remote sensing imagery across different contexts. It encompasses several dimensions: (a) terminological precision, such as whether MD_ReferenceSystem explicitly references standardized EPSG codes; (b) instrument and acquisition details, for instance, whether MI_Instrument accurately specifies sensor models, spectral ranges, and calibration status; and (c) processing transparency, including whether LI_Lineage provides sufficient description of correction methods or classification algorithms. Semantic clarity is central to the Interoperable and Reusable aspects of FAIR, as ambiguity or inconsistent interpretation of metadata can lead to errors when integrating or reusing data across platforms and applications.

2. Platform-independent Integration

This criterion examines whether ISO metadata can maintain consistency and usability across different platforms and systems. In principle, standardized metadata is intended to guarantee interoperability; however, in practice, discrepancies may still arise due to variations in implementation, partial adoption of ISO fields, or differences in system-specific extensions. For example, if Sentinel-2 metadata can be seamlessly read and parsed in both GeoNetwork and GeoServer, and further compared or integrated with Landsat metadata from USGS, this demonstrates strong cross-platform interoperability. This assessment corresponds to the Interoperable dimension of FAIR and reflects the maturity of metadata not only in terms of technical standards and formats but also in the reliability of API support and software implementations.

3. Stability

This study evaluates the robustness of ISO metadata in supporting long-term preservation and cross-generational reuse. The goal is to assess whether metadata can maintain traceability, interpretability, and sustainability over decades of use.

Specifically, this involves examining whether the processing history in LI_Lineage is fully documented to ensure traceability of data transformations, whether the quality information in DQ_DataQuality remains interpretable across evolving standards and technologies, and whether identifiers and authorization information provide sustainable referencing for future access. Since remote sensing imagery is frequently applied in long-term time series analysis and environmental monitoring, ensuring metadata stability is critical to preserving the effectiveness of FAIR principles in practice.

Results and Discussion

a. Case Studies of Metadata Implementation Platforms

1. Copernicus Sentinel-2 Metadata

In the Copernicus Access to Data platform, Sentinel-2 metadata exhibits notable strengths but also important gaps when evaluated against the FAIR principles. From the Findable perspective, the platform provides robust acquisition context, including observation date and time, satellite platform (Sentinel-2A/2B), orbit number, tile ID, and cloud cover ratio. It also supports queries by spatial extent (via bounding box and EPSG code) and temporal range. These elements align with the ISO 19115-1 requirements for identification and extent, ensuring that datasets can be uniquely identified and efficiently retrieved.In terms of Accessible, Sentinel-2 products adopt the SAFE (Standard Archive Format for Europe) and offer multiple standardized access channels, such as APIs, OData, OpenSearch, and cloud processing services. Coupled with Copernicus' long-standing open and free licensing policy, this ensures broad accessibility and legal clarity for human users. However, the absence of structured fields such as MD_LegalConstraints reduces machine-readability for automated compliance checks. For Interoperable, metadata support remains limited. Although Sentinel-2 metadata is distributed across SAFE XML, STAC JSON, and OData APIs, the lack of harmonized semantic standards across these formats weakens cross-platform integration. Moreover, there is insufficient adoption of semantic web technologies (e.g., RDF/OWL), which hinders alignment with ISO's interoperability goals.Regarding Reusable, significant shortcomings remain. Current metadata provides only basic quality indicators (e.g., cloud cover ratio), while more comprehensive quality elements defined in DQ_DataQuality—such as positional accuracy, error margins, and reliability—are absent. Similarly, while product metadata specifies processing levels (e.g., Level 1C, Level 2A), the lineage descriptions in LI_Lineage are incomplete, with limited details about algorithm versions, atmospheric corrections, or processing chains. This constrains long-term traceability and reduces the scientific reproducibility of the datasets.

In summary, Sentinel-2 metadata demonstrates strong maturity in Findable and Accessible dimensions, supported by standardized identifiers, multi-channel distribution, and open licensing. However, its implementation of Interoperable and Reusable is still incomplete, particularly in data quality reporting and processing lineage. This highlights that even large-scale international satellite programs still face challenges in achieving full FAIR compliance, underscoring the need for further standard harmonization and semantic enrichment.

2. USGS Landsat 8/9 Metadata

In the USGS Earth Explorer platform, Landsat metadata provides a relatively rich description of properties and shows strong correspondence with the core elements of ISO 19115-1 and 19115-2. From the Findable perspective, metadata includes acquisition date, center and corner coordinates, and product type, which map to EX_TemporalExtent and EX_GeographicBoundingBox, enabling precise retrieval by time and location.For Accessible, metadata specifies file size and product format (corresponding to MD_Distribution and MD_Format), which allows users to understand resource size and format before downloading. In the Interoperable dimension, Landsat metadata explicitly records datum, projection zone, and WRS path/row, corresponding to MD_ReferenceSystem and MD_GridSpatialRepresentation, along with orientation and resampling methods. These elements ensure that data can be consistently interpreted across multiple platforms.In terms of Reusable, Earth Explorer metadata captures MI_Platform and MI_Instrument information (e.g., satellite number, sun elevation and azimuth) and documents resampling and product processing methods (via MI_Processing and LI_Lineage). These details enhance traceability and support long-term reuse across different applications.Nevertheless, significant gaps remain. DQ_DataQuality elements are only partially implemented: while geometric and optical attributes are well recorded, unified indicators of accuracy, error margins, and reliability are missing. Similarly, legal constraints (MD_LegalConstraints) are described only in unstructured text, limiting their machine-readability and the potential for automated FAIR compliance checks.

Overall, Landsat metadata in Earth Explorer demonstrates high compatibility with ISO 19115-1/-2, particularly in acquisition and lineage elements supporting Interoperable and Reusable. However, improvements in semantic standardization, structured quality reporting, and machine-readable authorization information are needed for full alignment with FAIR principles.

3. SwissAEnvEO

In the SwissEnvEO platform, metadata is managed through the GeoNetwork catalog system and includes several core elements aligned with ISO 19115.

From the Findable perspective, metadata provides descriptions such as categories, keywords, resource identifiers, language, and contact information. It also records dataset status (e.g., ongoing) and update frequency (continual), supporting long-term discoverability.For Accessible, SwissEnvEO adopts NetCDF as a standardized data format and provides metadata on distribution via MD_Distribution, enabling data retrieval through OGC-compliant formats and ensuring consistency with international geospatial standards.In terms of Interoperable, the metadata specifies representation type (e.g., grid), scale, and coordinate reference systems (CRS), corresponding to MD_ReferenceSystem and MD_SpatialRepresentationType. This enables structural integration with other geospatial platforms.Regarding Reusable, SwissEnvEO metadata includes lineage information indicating dataset producers, mapping to LI_Lineage and CI_ResponsibleParty. However, the descriptions are simplified and do not provide algorithm names, versioning, or detailed calibration methods. Structured data quality information (DQ_DataQuality) is also missing, leaving only indirect indicators and reducing the credibility of data in long-term comparative analysis. Furthermore, legal information is incomplete—while datasets are declared as open, the metadata lacks structured MD_LegalConstraints elements, making it difficult for automated systems to interpret licensing conditions.

Overall, SwissEnvEO performs well in the Findable and Accessible dimensions through catalog-based organization, persistent identifiers, and standardized formats. However, the implementation of Interoperable and Reusable is weakened by insufficient lineage detail, the absence of structured quality descriptions, and incomplete legal metadata. These deficiencies reduce the integrity of FAIR alignment, showing that even FAIR-oriented national platforms still face challenges in fully implementing ISO 19115.

b. Metadata Mapping Results: ISO 19115-1 and ISO 19115-2 in Relation to FAIR Principles

Table 1. ISO 19115-1 Elements vs FAIR (Examples from Different Platforms)

ISO 19115-1	Key Elements	FAIR Objective	Sentinel-2(Copernicus)	Landsat 8/9(USGS)	SwissEnvEO
Identification	MD_Metadata.identifier, CI_Citation, MD_Keywords, PT_Locale	Findable	Tile ID(T33UXP), UUID; INSPIRE keywords; EN	Scene ID(LC08_LITP_1180045_20221115); USGS thematic keywords; EN	DOI (10.xxxx);categories=land, vegetation; keywords(NDVI, Sentinel); EN/DE/FR
Extent	EX_Extent, MD_Resolution, MD_SpatialRepresentationType, MD_ReferenceSystem	Findable/Interoperable	Bounding box(lat/long); EPSG:32633; resolution 10/20/60m; Grid	Bounding box; WGS84/UTM(Zone 45N); resolution 30m; Raster Grid	Extent=Switzerland; CRS=GH1903_/LV95; Scale 1:250,000; Grid
Distribution	MD_Distribution, MD_Format, MD_DigitalTransferOptions	Accessible	SAFE format; API (OData, OpenSearch); FTP	GeoTIFF, NetCDF; FTP/HTTP	OGC WMS/WCS; NetCDF; DOI-based access
Constraints	MD_LegalConstraints	Accessible	License: free & open (Copernicus policy)	License:" USGS open data" (text note only)	License: "free use with attribution" (general statement)
Data Quality	DQ_Quality	Reusable	Cloud cover percentage	Band (cloud, snow, shadow flags)	No structured DQ; only lineage note
Lineage	LI_Lineage	Reusable	Processing levels L1C/L2A;	L1TP (terrain corrected), L2 (atmospherically corrected); QA process	"Produed by GRID-Geneva"; no algorithm details

			tool=Se n2Cor		

From the comparison in Table 1, the alignment of ISO 19115-1 elements with the FAIR principles shows significant variation across different platforms.

Findable (F): Sentinel-2 and Landsat metadata are relatively complete, with Sentinel-2 adopting UUIDs and INSPIRE keywords, and Landsat providing Scene IDs and WRS path/row identifiers to support spatiotemporal search. SwissEnvEO also enhances discoverability by assigning DOIs and multilingual keywords, extending searchability in both thematic and linguistic dimensions.

Accessible (A): Both Sentinel-2 and Landsat provide standardized distribution formats such as SAFE and GeoTIFF, along with APIs and FTP/HTTP services. SwissEnvEO supports OGC services and DOI-based access, which further improves accessibility. However, in all platforms, licensing terms remain mostly in unstructured text, limiting automated interpretation and machine-readability in FAIR contexts.

Interoperable (I): Sentinel-2 and Landsat include complete bounding box information, resolution, and projection systems, ensuring compatibility across platforms. SwissEnvEO also records CRS based on Swiss national standards (e.g., CH1903+/LV95), which supports local integration but may create barriers in broader international interoperability.

Reusable (R): Landsat provides the most comprehensive support, including QA bands for data quality and detailed lineage records for L1TP and L2 processing. Sentinel-2 offers only limited quality indicators such as cloud cover and annotated processing levels (L1C/L2A), while SwissEnvEO provides only general lineage notes on data producers without algorithmic or error-control details, reducing long-term reusability.

In summary, Landsat demonstrates the highest compliance with ISO 19115-1 in supporting FAIR principles, particularly in reusability through detailed QA and lineage information. Sentinel-2 shows strong findability and accessibility but limited reusability due to insufficient data quality and lineage detail. SwissEnvEO, in turn, emphasizes governance-oriented features such as DOIs and multilingual discoverability but lacks technical completeness in acquisition, quality, and lineage elements, underscoring that FAIR compliance remains uneven across platforms.

Table 2. ISO 19115-2 Elements vs FAIR (Examples from Different Platforms)

ISO 19115-2	Key Elements	FAIR Objective	Sentinel-2(Copernicus)	Landsat 8/9(USGS)	SwissEnvEO
Acquisition	MI_AcquisitionInformation	Reusable	Date (2023-07-21); Orbit:12345; Sun elevation:43.1°; Cloud cover:12.3%	Date (2022-11-15); WRS Path/Row: 118/45; Sun elevation:43.5°	Not recorded; only update frequency= continual
Platform	MI_Platform	Reusable	Sentinel-2A/2B	Landsat 8/9	Not specified; only lineage "Produced by GRID-Geneva
Instrument	MI_Instrument	Reusable	MSI(13 bands; 10/20/60m resolution)	OLI(0.43-2.29μm, 30m), TIRS (10-12 μm, 100m)	Not recorded
Event/Operation	MI_Event, MI_Operation	Interoperable/Reusable	Only product levels(L1C/L2A); no event detail	WRS system(row/path) enables acquisition traceability	Not recorded
Processing	MI_Processing	Reusable	Levels L1C/L2A; tool=Sen2Cor (no version)	L1TP (terrain corrected), L2 (surface reflectance); QA band	Only lineage "Produced by GRID-Geneva

From the results in Table 2, the analysis shows that the ISO 19115-2 expansion modules expose clear differences in how platforms support FAIR principles, particularly Interoperable and Reusable.

Findable (F). Sentinel-2 and Landsat both provide sufficient acquisition context to enable discovery. Sentinel-2 metadata records the acquisition date, orbit number, and cloud cover, while Landsat includes acquisition date and the WRS path/row indexing system, which allows systematic spatial search. In contrast, SwissEnvEO does not document detailed acquisition information, and only notes update frequency, limiting its capacity for temporal and spatial discovery.

Accessible (A). Accessibility is less prominent in ISO 19115-2, but related elements are indirectly reflected in platform descriptions. Landsat and Sentinel-2 metadata support standardized product structures (e.g., L1C/L2A, L1TP/L2), which aid users in retrieving appropriate datasets. SwissEnvEO, however, provides only a generic lineage statement without structured product-level accessibility metadata, reducing transparency for automated access.

Interoperable (I). Landsat performs strongly by combining acquisition records with WRS indexing, platform details (Landsat 8/9), and sensor specifications (OLI, TIRS), making integration with other datasets straightforward. Sentinel-2 metadata supports interoperability to some degree by including platform (Sentinel-2A/2B) and MSI sensor specifications, but interoperability is weakened by limited event and processing detail. SwissEnvEO offers minimal interoperability, as it does not provide standardized acquisition or sensor-level descriptions.

Reusable (R). Landsat provides the most robust support for Reusability through detailed lineage and processing information, including L1TP terrain correction, L2 surface reflectance, and QA bands. Sentinel-2 metadata partially supports reuse by documenting product levels (L1C/L2A) and processing tools (Sen2Cor), but lacks algorithm versioning and full processing lineage, reducing reproducibility. SwissEnvEO is the weakest in this respect, as lineage information is limited to the institution producing the data ("Produced by GRID-Geneva"), with no details of algorithms, calibration, or error metrics.

Among the three platforms, Landsat demonstrates the strongest compliance with ISO 19115-2 in supporting FAIR principles, particularly Interoperable and Reusable. Sentinel-2 provides basic coverage of acquisition and sensor elements but lacks lineage depth and processing transparency. SwissEnvEO highlights governance-level commitments (e.g., continual updates) but does not implement detailed ISO 19115-2 elements, underscoring the gap between high-level FAIR claims and technical metadata completeness.

Combining the results of Table 1 and Table 2, ISO 19115-1 and ISO 19115-2 provide complementary structures in supporting FAIR principles, but the degree of implementation differs across platforms. Landsat metadata demonstrates the most comprehensive coverage of both standards. It not only supports Findable and Interoperable through identifiers such as Scene ID and the WRS system, but also offers transparent lineage records and processing descriptions, giving it the strongest alignment with the Reusable dimension. Sentinel-2 shows solid coverage of ISO 19115-1 elements such as identification, extent, and distribution, and it records acquisition and instrument details under ISO 19115-2. However, its metadata remains limited in the completeness of data quality (DQ_DataQuality) and in the transparency of processing steps (MI_Processing), reducing its effectiveness for reuse and interoperability when compared with Landsat.In contrast, SwissEnvEO emphasizes Findable and Accessible through DOI registration, NetCDF formats, and OGC services, reflecting a governance-oriented approach. Nevertheless, it lacks acquisition details, sensor descriptions, and processing lineage, limiting its ability to support Reusable and Interoperable.

Overall, ISO 19115-1 establishes a robust foundation for Findable and Accessible, while ISO 19115-2 enhances support for Reusable by covering acquisition, platform, instrument, and processing lineage. Yet, in practice, most platforms only achieve partial implementation. International platforms such as Landsat and Sentinel-2 are relatively mature, but they still lack harmonized semantics and complete quality information. SwissEnvEO focuses on governance and long-term preservation but is weak in technical attributes. These findings underscore that full realization of the FAIR principles requires not only structural alignment with ISO standards but also stronger commitments to semantic clarity, quality control, and lineage transparency.

c. Comparative Results of the Three Evaluation Criteria

Table 3. Evaluation of Remote Sensing Metadata Platforms Against FAIR Criteria

Evaluation Criterion	**Definition**	**Sentinel-2(Copernicus)**	**Landsat 8/9 (USGS)**	**SwissEnvEO**
Semantic Clarity	Whether metadata elements can express data attributes accurately and unambiguously	Uses EPSG codes, UUIDs, and INSPIRE keywords; clear semantics, but lineage and license info	WRS system, UTM/Datum, and QA band provide precise semantic expression; best among platforms	Provides categories, CRS, and keywords, but lacks acquisition and sensor details

		not fully structured		
Interoperability	Whether metadata can be consistently integrated across different platforms and systems	SAFE/XML, STAC JSON, and OData API; diverse formats but lacking unified semantics; limited cross-platform parsing	GeoTIFF/NetCDF formats with WRS path/row; strongest cross-platform compatibility	NetCDF + OGC (WMS/WCS); supports interoperability, but mainly at governance level
Long-term Consistency	Whether metadata supports long-term preservation and reuse across generations	Product levels (L1C/L2A); partial lineage; lacks algorithm versions and full DQ, limiting long-term traceability	L1TP/L2 lineage + QA band; highest long-term traceability	DOI registration + Yareta preservation system; good for governance and citation, but lacks technical lineage

Table 3 presents the results of this study across three representative platforms (Sentinel-2, Landsat, and SwissEnvEO), evaluated against three criteria—semantic clarity, cross-platform interoperability, and long-term consistency. Overall, Landsat is the most comprehensive and balanced, with structured identifiers, a well-defined spatial reference system, and a high degree of traceability supported by QA bands and complete lineage records (L1TP/L2). Sentinel-2 demonstrates a high level of maturity in terms of identifiers, access protocols, and acquisition metadata, but lacks structured descriptions of licensing information, algorithm versions, and data quality metrics, which limits its potential for reuse. SwissEnvEO stands out in governance aspects, such as DOI registration and compliance with NetCDF/OGC standards but provides limited semantic detail in acquisition and sensor descriptions, weakening its technical clarity. In addition, its mechanisms for ensuring long-term consistency remain insufficiently articulated, raising uncertainty about the durability of metadata over extended periods.

d. FAIR Principles Coverage Summary

The comparative mapping results reveal that the implementation of FAIR principles across platforms remains highly unbalanced. Overall, Findable and Accessible are relatively well supported, with most platforms offering basic identifiers, spatial/temporal extent, and access mechanisms. However, significant gaps persist in Interoperable and Reusable dimensions. In particular, the lack of structured lineage, insufficient data quality reporting, and limited semantic consistency undermine cross-platform integration and long-term reuse. These findings suggest that while international initiatives have achieved maturity in basic discoverability and accessibility, advancing FAIR compliance in remote sensing metadata will require greater emphasis on harmonized semantics, transparent processing histories, and standardized quality measures.

Conclusion and Recommendation

This study systematically examined the applicability of ISO 19115-1 and ISO 19115-2 in supporting the FAIR principles for remote sensing imagery. By conducting metadata mapping and comparative analysis across three representative platforms—Copernicus Sentinel-2, USGS Landsat, and SwissEnvEO—we demonstrated that ISO metadata standards provide a robust structural foundation for FAIR-aligned data management, but their implementation remains incomplete and uneven. Overall, Landsat exhibits the most comprehensive coverage, with strong identifiers, a well-defined spatial reference system, and detailed lineage records, making it the closest to fully supporting Reusable and Interoperable dimensions. Sentinel-2 shows high maturity in identifiers, access protocols, and acquisition metadata, but its lack of structured data quality reporting and processing transparency constrains long-term reusability. SwissEnvEO, in turn, demonstrates governance-oriented strengths such as DOI registration and long-term preservation, but it omits key technical details in acquisition and sensor specifications, limiting its semantic clarity and interoperability. The findings of this study highlight that while Findable and Accessible are relatively well supported, significant gaps persist in Interoperable and Reusable dimensions, particularly in semantic harmonization, quality reporting, and lineage transparency. These results indicate that the combination of ISO standards with FAIR-based evaluation provides not only a diagnostic framework for identifying current shortcomings but also a practical roadmap for improving metadata infrastructures. Moving forward, strengthening semantic consistency through integration with semantic web standards (e.g., RDF/OWL, GeoDCAT-AP), enhancing quality and lineage documentation with algorithm versions and error metrics, and aligning national-level infrastructures with international best practices will be crucial. By leveraging the complementary strengths of ISO 19115-1/-2 and FAIR principles, the remote sensing community can design a more transparent, interoperable, and reusable metadata architecture, ultimately reinforcing the role of satellite imagery in environmental monitoring, disaster management, and evidence-based policymaking.

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