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Designing for reality: A bottom-up approach to data interoperability

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Abstract: *Problem framing:* Public science agencies in Australia face significant challenges in harmonising measurement data across diverse institutional systems and governance frameworks, leading to data fragmentation and limited accessibility. Organisations operate under distinct mandates and diverse funding models which is reflected by the various implemented data management systems and infrastructures. Despite these variations, they are unified by robust governance frameworks and comprehensive cybersecurity protocols. A shared commitment to data harmonisation and interoperability is driven by both technical capacity and motivated individuals. However, fragmented custodianship and the absence of a coordinating institution have led to siloed data efforts, limiting collaboration across research, government, and public domains.

Solution overview: To increase the interoperability of public data assets, a collaboration across Australian science agencies —CSIRO, Geoscience Australia, ANSTO, and the National Measurement Institute—coordinated their respective environmental stable isotope data assets into a coherent user experience. A co-design process united subject-matter experts from these organisations, who are custodians of stable isotope data, to create a user-centred solution which was guided by FAIR principles to balance the respective institutional requirements with the needs of both data custodians and end-users. The entire process was shaped by real user needs, proactively addressing barriers to data standardisation and accessibility, so that environmental stable isotope data can be organized and consistent across institutions and scientific domains. The bottom-up approach emphasized user needs and institutional collaboration, prioritising user needs and aligning with open data and FAIR principles rather than imposing top-down solutions. The technical solution was designed to reflect institutional capacity and data governance frameworks. Operational staff navigated institutional constraints, which highlighted the need for flexible and scalable solution design. As a result, they developed solutions that were not anchored within any single organisation.

System implementation: A flat ontology was created to translate data schemes and harmonize datasets into a common, structured data schema. It employs a 3-tiered approach of required, recommended, and optional attributes, to strengthen data quality and compatibility, implementing current reporting guidelines. This ontology acts as a practical stewardship tool for users, enhancing metadata quality ensuring the longevity and reusability of published data. A federated platform was established to streamline access to harmonised data, allowing users to search and retrieve information across diverse sources. Using the ontology to integrate published datasets from participating organisations federated data into a third-party web-based platform. The architecture employs the common ontology using APIs and connectors to interface with institutional databases and portals. Data ownership remains with each organisation, and security is managed internally to ensure only suitable data is shared publicly. By enabling efficient, secure, and user-focused data interoperability, this approach allowed multiple data sources to be seamlessly accessible through a single point while retaining institutional data management autonomy.

Conclusion: The decision-making process, connectors and translation needed, governance model established, and end-user engagement exemplifies how interoperable data systems are achievable and can unlock the full potential of scientific data. Leveraging across multiple institutional data management systems enabled the development of an open technical solution that increased the data sharing capacity across an ecosystem.

Keywords: *Data federation, FAIR data, Data governance*

1. INTRODUCTION

Harmonising data is difficult; making complex datasets comparable and compatible requires considerable effort (Cheng et al., 2024; Devaraju et al., 2021). Harmonised measurement data are compatible irrespective of the measurement procedure and when or where a measurement was made, if the pre-analytical, analytical, and post-analytical metadata are included in the harmonisation processes. Data volumes are growing at an exponential rate, with Geoscience Australia seeing a 550% increase in their geoscience data holdings from July 2018 to July 2024. The accuracy of big data tools, such as the Internet of Things, large language models (LLM), and machine learning (ML) tools, is reliant on the availability of interoperable data (Cai and Zhu 2015).

Bound by a shared responsibility, public science agencies share a common goal to ensure data generated through public investment can be leveraged for broader scientific, societal, and economic benefit (Overton et al. 2022). Central to this approach is the commitment to making data open and aligned with the FAIR principles—Findable, Accessible, Interoperable, and Reusable (Wilkinson et al. 2016)—unless specific agreements dictate otherwise. For Australia's Commonwealth science agencies, these obligations are reinforced by Commonwealth policy and organisational strategies that promote the efficient use and maximisation of data value (Australia 2022).

The challenge is to consolidate measurement data from multiple siloed repositories, each with differing levels of accessibility, while maintaining the data integrity. Efforts to harmonise data across institutions are further complicated by the existence of embedded internal data management systems with various levels of sophistication. Asymmetrical institutional investment and capacity are compounded by varying data governance frameworks, including data ownership, control and security, resulting in duplication of collection efforts. This increases data source fragmentation, ultimately limiting data accessibility and interoperability more broadly. This fragmentation poses significant challenges to the individuals responsible for achieving accessible and interoperable data.

Addressing this gap requires the development of mechanisms that enhance the visibility and accessibility of such data, while respecting the autonomy and governance frameworks of the source institutions. Ultimately, these mechanisms need to meet the needs of the individual who is the origin of data. Using environmental stable isotope data, 4 Australian Commonwealth agencies, Commonwealth Scientific and Industrial Research Organisation (CSIRO), Geoscience Australia (GA), the Australian Nuclear Science and Technology Organisation (ANSTO) and the National Measurement Institute (NMI), were able to bridge this gap, harmonising stable isotope data through co-design of a common repository, and realising a solution that centres on user-needs and integrates the broader regulatory and data policies governing public data.

2. BACKGROUND

2.1. Environmental stable isotope datasets provide an ideal case study

Environmental stable isotope data serve as an ideal context for investigating the intersection of data and institutionally driven challenges, particularly those concerning data integrity and the usability of complex datasets. The broad application of stable isotope data and substantial variation in the reporting details across scientific disciplines, organisations, and countries creates the need for data harmonisation (McCue et al. 2020; Snyder et al. 2022; Sprenger et al. 2016). Stable isotope data is collected worldwide (Bird et al. 2021; Diefendorf et al. 2010; Matiatos et al. 2021) often with geospatial metadata. International standardisation efforts (Skrzypek 2013; Skrzypek et al. 2022; Fleisher et al. 2021; Khider et al. 2019) provide metrological guidelines to support reporting consistency. There is a growing number of publicly accessible data repositories (Shipley et al. 2024; Plomp et al. 2022; IAEA 2025; IAEA/WMO 2025), owing to increased interdisciplinary collaboration across the well networked-scientific community.

Representing key collaboration nodes within Australia, CSIRO, Geoscience Australia, ANSTO and the National Measurement Institute also represent principal custodians of publicly available stable isotope data in Australia. CSIRO is Australia's national science organisation, responsible for carrying out scientific research to benefit Australian industry and the community. As a mission-driven multidisciplinary science and research organisation, the research portfolio responds to the national science priorities, using stable isotopes to characterise ecological processes and dynamics across agricultural systems, natural environments and for mineral resources. Geoscience Australia is responsible for the characterisation of Australian geology to understand natural resources for applications such as mineral exploration and groundwater management and for the provision of geoscience data and information to the public (Geoscience 2022). A strategic aim is to provide leadership in geoscientific and open data to accelerate findable, accessible, interoperable and reusable (FAIR) data across all areas of Earth science (Rossiter 2024). As such, the Geoscience Australia Data Portal provides access to and maintains the Isotopic Atlas of Australia compiling data of multiple geochronology and isotope tracer datasets (Waltenberg 2020; Fraser et al. 2020). ANSTO coordinates the International Atomic Energy Agency/World Meteorological Organisation Global Network of Isotopes in Precipitation (GNIP) in Australia with the support of the Australian Bureau of Meteorology, as well as conducting isotope-based research into water resources sustainability, environmental change, food and agriculture and the impact of contaminants. This is part of ANSTO's core function to produce and use radioisotopes and isotopic techniques for science, industry, and commerce (ANSTO 2024). NMI develops and maintains internationally recognised national measurement standards, administers the regulatory measurement frameworks, and delivers measurement products, advice and client services (DISR 2024).

Each organisation operates within a defined remit that outlines its core activities, and while these remits differ, they are governed by comparable cybersecurity protocols and public-private partnership frameworks. The nature of their data collections and systems reflect the respective organisational priorities, resulting in asynchronous infrastructure and capacity. The diversity in funding models introduces complexity into the data custodianship landscape. These models often dictate the terms of data ownership, publication rights, and conditions for reuse. Consequently, data collection, management, and analysis efforts are frequently siloed, shaped by contractual obligations and funding constraints.

Subject matter experts within each organisation are the principal data custodians who are responsible for appropriately managing data through its lifetime. They are accountable for upholding organisational policies and procedures with varying levels of support and expertise in data management best practices. As a result, their decision-making process must navigate multiple layers of well-intentioned data governance. Lacking, however, is a single institution with the responsibility to coordinate efforts. Current efforts to supply interoperable data are concentrated to where there are willing individuals. Taken together, there is a strong technical foundation and motivation to harmonise stable isotope data across organisations. The goals of this effort were to meet the needs of data custodians by increasing the usability and availability of publicly held data and create a collaborative data infrastructure for environmental stable isotope data.

3. METHODS

3.1. Co-design, facilitation, partnerships and collaboration

A co-design process brought together subject matter experts from the 4 organisations, who were willing to engage in an adaptive and responsive process, to facilitate shared understanding, decision-making, and ownership among stakeholders. Engagement with broader stakeholders was formalised in a science and user group (SAUG), consisting of both stable isotope experts and non-experts, who informed the solution design and function to be fit-for-purpose. Throughout the co-design process, use cases and user journeys were developed to articulate user barriers, incentives, and needs.

The subject matter experts were operational staff of the participating organisations, representing a diversity of experience and skillsets. As employees, the cohort were bound by their respective institutional policies and expectations. They did not have the delegation to disrupt embedded organisational data management policies or systems. However, they are individually accountable to appropriately manage data through its lifetime. As such, each person had a different interpretation of appropriate management but shared a common purpose to design and take accountability for a solution. The data sensitivities were varied across the participants, ranging from proprietary, sensitive, and confidential data to non-sensitive and non-commercial. Due to budget constraints, software developers were involved once the groups' requirements were clearly defined and articulated. The co-design process allowed freedom to design a solution based on the user's needs, unconstrained by any institutional boundary.

4. RESULTS

4.1. Fit-for-purpose governance, balancing open data

A vision and purpose statement set a guiding direction and established a foundation of trust to facilitate partnerships and collaboration between participants. A governance framework defined the needs and obligations of each organisation and user, so the data interests of all participants were respected. These two guardrails informed the design criteria and decision-making processes. This emphasised proactive personalisation while ensuring inclusivity, so that no one should be disadvantaged due to varying levels of technical sophistication.

The governance framework established trust across the stakeholders, by describing the general conditions for participation, assuring the rights and interests of data holders, and detailing how technical solutions comply with organisational requirements. Establishing the overall governance created a transparent mechanism that clarified the conditions of data access and reuse for each of the data custodians and implemented context-specific guidelines to delineate roles and responsibilities. Including the data custodians of restricted or confidential data ensured that solutions also support the interoperability of restricted data. Therefore, future collection efforts will have reuse conditions articulated from the start, accelerating access to interoperable data.

The co-design process enabled the development of an open technical solution that increased the data sharing capacity across an ecosystem. The tangible nature of the technical solution underscored the need for clear and coordinated oversight to maintain and sustain use. Terms of reference define the governance authority, including membership, roles and responsibilities, and procedures for decision-making and conflict resolution of a Steering Committee. The Steering Committee comprises representatives from all 4 contributing organisations and members the of SAUG, formalising the shared commitment to the development, maintenance, and operation of the technical solution. This bottom-up approach builds the capacity needed to sustain and further invest in development.

The technical design was guided by the shared desire to create a unifying solution, disentangling institutional rules and mechanisms, resulting in a solution that was not housed within any of these organisations. The central goal was to mitigate barriers to the standardisation of data formats, facilitating interoperability across diverse technological environments and infrastructural capacities. As a result, a two-part data strategy was implemented to standardise and integrate data.

4.2. Data standardisation

A common ontology created a standardised vocabulary to harmonise and enable translation between disparate metadata systems into a usable whole (Welti et al. 2024a). The design uses a structured, formatted file that simplifies sharing data and facilitates a simple user-experience (Figure 1), creating a systematic format of metadata attributes to give context and provide a common understanding of data across domains. The flat (denormalised) table ontology can be used as an Excel spreadsheet, comma-separated value (.csv) file or to translate between relational databases. The ontology was developed by bringing together published data held and maintained according to each organisation's data management systems. Required, recommended, and optional attribute fields improve data quality control and provide guidance, striking a balance between adopting IUPAC recommendations (Coplen 2011; Skrzypek 2013; Skrzypek et al. 2022) and accommodating legacy data with limited metadata. Using a 3-tiered approach increased the robustness and quality of metadata between imperfect datasets. The common ontology functions as a straightforward data stewardship tool for individual users so they can improve metadata quality and increase alignment to FAIR principles of data.

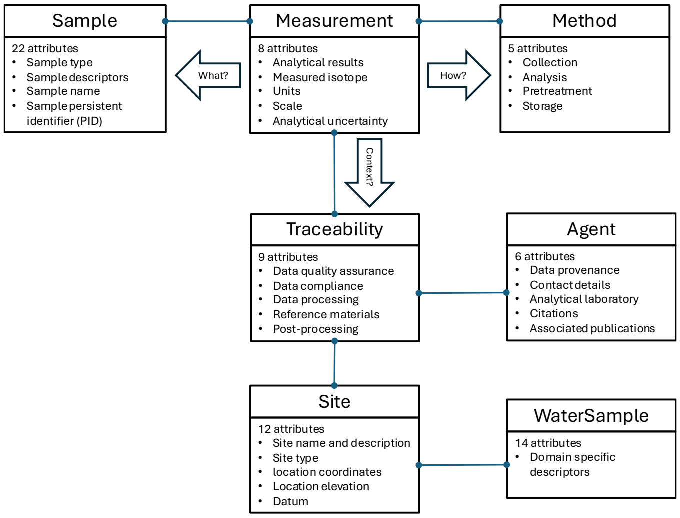

Figure 1 The conceptual model for the common ontology. The 7 attribute classes harmonise the metadata for environmental stable isotope ratio data

4.3. Data integration through a federated platform

From the user's perspective, interoperable data enables seamless searching and retrieving results across multiple data sources. A federated platform was built to provide users with a concrete and functional mechanism to realise the benefit of data interoperability (Welti et al. 2024b; isotopes.au). The decentralised federated model, the disparate data sources and infrastructures can deliver data through a shared platform using standard transfer protocol. The platform architecture implements the ontology and harmonises data without requiring substantial reworking to minimise duplication of data or effort (Figure 2). This enables data to be queried, and the results returned to users via an application programming interface (API) that can interface with several software application types, such as web user interfaces, other databases and data exchanges. Using connectors as translators, data is accessed through institutional platforms such as the CSIRO Data Access Portal (DAP) and Geoscience Australia's Data and Publications Search (eCat) and Data Discovery Portal, or through peer-reviewed publications. CSIRO, ANSTO and Geoscience Australia provide periodic copies of their data to Lithodat via the CSIRO Data Access Portal API and the Data Discovery Portal (portal.ga.gov.au) respectively, retaining ownership and control of their data connections. Data provided via web services are periodically refreshed from internal databases e.g. Suckow and Dumke 2001; Suckow 2025. Data confidentiality and security is controlled within the internal systems to ensure that only data appropriate for public dissemination is provided via the web services.

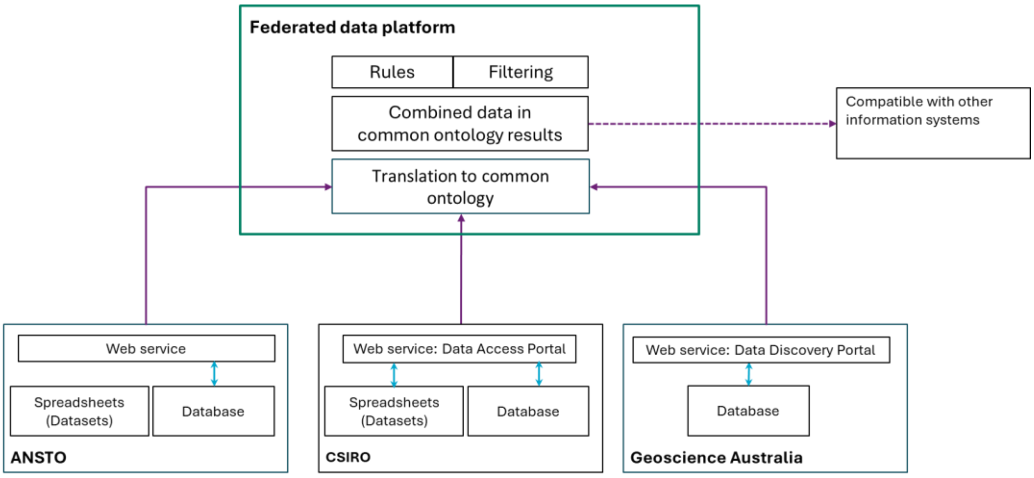

Figure 2. The federated architecture of the stable isotope data platform, Isotopes.au

The ontology and platform architecture both formalised best practices for data quality assurance, enhancing the overall data structure, without disrupting the embedded institutional systems in-place. Together these increased the implementation of FAIR principles across the entire data ecosystem. The self-assessed alignment to FAIR principles (ARDC 2025) increased to 91%, for all organisations, compared to the initial self-assessment of 88% (Geoscience Australia), 59% (ANSTO), and 45% (CSIRO). Specifically, the ontology provides a metadata schema implemented by the platform to create comprehensive machine-readable data as output, increasing the findability of data. The accessibility increased, as the data is retrievable by humans and machines through a standardised communication protocol, with authentication and authorisation where necessary. Interoperability increased by creating data outputs that are structured and machine-readable and available in an open, documented, widely used standard format. The metadata record includes URL links to related metadata, data and definitions. The reusability increased by formalising the standard Creative Commons BY 4.0 license to the data, encoded in a machine-readable format.

The existence of an external platform is an additional enabler for subject matter experts to make their data available for federation. As the platform can provide metrics of downloads at a granular level, this information can be fed back to the organisations, quantifying the wider access and value of the RD investment. Using an external platform establishes additional capacity to support the organisational goals, increasing the robustness of the data ecosystem. This in turn hopefully incentivizes organisations to further invest in systems and workflows to enable future evolution and flexible frameworks. The next challenge lies in the dissemination and adoption of the solution beyond the initial cohort, requiring deliberate strategies to ensure broader relevance, accessibility, and acceptance

5. CONCLUSIONS AND RECOMMENDATIONS

Digital transformation hinges on the accessibility of high-quality, well-curated data. This collaborative effort among 4 Commonwealth organisations exemplifies how interoperable data systems are achievable and can unlock the full potential of advanced analytical tools and modelling approaches. As individuals, data custodians are constrained by existing organisational policies and technical infrastructures. Therefore, solutions were needed that are capable of operating across systems and infrastructure with varying levels of sophistication. Rather than putting the individual at the centre, the design process addressed needs of many who shared the same values and goals, embodying the FAIR principles. The shared commitment to implement FAIR principles supported the trust needed to create the governance mechanisms so the technical solutions will empower users to create and contribute interoperable data in a way tailored to their needs. This approach fostered a form of enforced equity, acknowledging and accommodating the distinct characteristics of each agency's data ecosystem.

The user-centred and community driven approach creates a robust, repeatable model for cross-agency collaboration, which is guided by clear governance and technical alignment that can overcome the limitations of siloed systems. By starting with a manageable scope and engaging end-users early, the developed solution is flexible by necessity so that it can meet diverse data needs. The resulting system lays the groundwork for a scalable digital solution that addresses complex, cross-sector challenges while respecting the realities of operating within a multi-actor data ecosystem. The FAIR principles provided a guiding direction which focused the decision-making process away from institutional policies to realise solutions that meet the common needs of many. This focus captured an approach that was adaptive, responsive, and less restricted than what is conventionally engineered, empowering a bottom-up solution. The datafication of public spaces and decision-making processes must not overlook the users who are both the originators of data and the most directly affected by its application. Innovations that fail to incorporate user perspectives risk rejection and may erode public trust in the institutions responsible for their implementation. By fostering trust and shared ownership, the shared problem became a shared solution.

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