Food and Agriculture Organization of the United Nations

UN environment programme

World Health Organization

World Organisation for Animal Health
Founded as OIE

Quadripartite One Health Intelligence Scoping Study

◆

Final Report

Supplementary Material 3:
A Quadripartite
Global One Health
Intelligence Framework

Contents

Acknowledgements

This project was funded by the United Kingdom of Great Britain and Northern Ireland's Department of Health and Social Care (DHSC).

The project team would like to thank the Quadripartite focal points for their contributions and support: Fairouz Larfaoui (Food and Agriculture Organization of the United Nations [FAO]), Andrea Capobianco Dondona (FAO), Charlotte Hicks (United Nations Environment Programme World Conservation Monitoring Centre [UNEP-WCMC]) and Lauren Weatherdon (UNEP-WCMC), Karl Schenkel (World Health Organization [WHO]), Emilie Peron (WHO), Paula Caceres-Soto (World Organisation for Animal Health [WOAH, founded as OIE]), Daniel Donachie (WOAH) and Lina Awada (WOAH). We also thank Cat McGillycuddy (UK Health Security Agency) and Rachel Cooper (DHSC). Further we would like to acknowledge the Lead Technical Officer Madhur Dhingra (FAO) and the Oversight Steering Committee, including Keith Sumption (FAO), Oliver Morgan (WHO), Matthew Stone (WOAH) and Corli Pretorius (UNEP/UNEP-WCMC).

Our gratitude also goes to the attendees of our External Advisory Group meetings including the One Health High-Level Expert Panel, as well as participants of the One Health Intelligence Scoping Study workshops for their collaboration and support.

The project was coordinated by John Weaver (FAO) and Andrea Carvelli (FAO) and delivered by Sharon Calvin (FAO), Nigel Gibbens (FAO), Jas Mantero (FAO), Petra Muellner (FAO), Uli Muellner (WOAH), Joergen Schlundt (FAO) and Fernanda Dórea (FAO).

Abbreviations

API	Application programming interface
CITES	Convention on International Trade in Endangered Species of Wild Fauna and Flora
DGP	Digital Public Good
FAIR	Findable, Accessible, Interoperable and Reusable
FAO	Food and Agriculture Organization of the United Nations
GLEWS+	Joint FAO/WHO/WOAH Global Early Warning System for health threats and emerging risks at the human–animal–ecosystems interface
IPPC	International Plant Protection Convention
IUCN	International Union for Conservation of Nature
OHISS	One Health Intelligence Scoping Study
OHIS	One Health intelligence system
UNEP	United Nations Environment Programme
UNEP-WCMC	United Nations Environment Programme World Conservation Monitoring Centre
WHO	World Health Organization
WOAH	World Organisation for Animal Health (founded as OIE)

Glossary

All terms and definitions below are working definitions used in the context of the One Health Intelligence Scoping Study (OHISS) only and may be used differently elsewhere, including in other publications by FAO, UNEP, WHO and WOAH.

Application	An application program (application or app for short) is a computer program designed to carry out a specific function directly for an end user or, in some cases, for another application.
Data	A set of values of qualitative or quantitative variables about one or more persons, objects or activities.
Data harmonization	All efforts to combine data from different sources and provide users with a comparable view of data from different studies.
Dataset	A collection of data available for access or download in one or more representations.
Digitization	The process of converting something to digital form.
Digitalization	Digitalization is the process of transformation of digital data, such as the ability of digital technology to collect data, establish trends and support decision-making.
Early warning	The provision of early and relevant information on potential or actual disasters and their impacts.[1]
Hazard	A process, phenomenon or human activity that may result in a detrimental effect, cause loss of life, injury or other health impacts, property damage, social and economic disruption or environmental degradation.
Information system	A system designed to collect, process, store and distribute information. In this report, it is used interchangeably with *digital information system*, a specific type of information system that integrates software and hardware to enable communication and collaborative work.
Intelligence	The ability to read and respond effectively to a situation through insights and evidence. The process of intelligence is meant to provide a decision-advantage.
Interoperability	The ability of computer systems or software to exchange and make use of information with other systems. *Structural or syntactic interoperability* refers to the format of data exchange. *Semantic interoperability* is concerned with ensuring the integrity and meaning of the data across systems.
Metadata	Data about data. In this document, the term is used to refer specifically to data about a dataset or data source.
Minimum dataset	The minimum critical data values needed to execute a specific analysis or run a specific application to produce a specified output.

[1] See www.fao.org/3/x6871e/x6871e01.htm.

One Health	An integrated, unifying approach that aims to sustainably balance and optimize the health of people, animals and ecosystems. One Health recognizes that the health of humans, domestic and wild animals, plants, and the wider environment are closely linked and interdependent. Definition adopted from the One Health High-Level Expert Panel (2021).
Open source	Open source software is computer software that is released under a licence by which the copyright holder grants users the rights to use, study, change and distribute the software and its source code to anyone and for any purpose.
Pandemic Hub	World Health Organization Hub for Pandemic and Epidemic Intelligence.
Primary data	Direct measurements of occurrence of an adverse event (for instance, disease cases) in a given population.
Risk	The likelihood of the occurrence and the likely magnitude of the consequences of an adverse event during a specified period.
Secondary data	Secondary or contextual data is used to refer to indirect indicators (or indices) of health (such as vaccination coverages) or indicators used to assess disease emergence risks (for instance, measures of deforestation or livestock density). This can go as far as including data on the capacity or vulnerability of specific sectors (for example, health sector or veterinary capacity).
Structured data	Any set of data that is organized and structured in a particular way. Structured data fit into predefined models and formats, allowing applications to understand them.
Surveillance	The continuous, systematic collection, analysis and interpretation of health-related data.
Threat	A hazard, agent, event, concern or issue that poses risks to human, animal, plant or ecosystem health.
Unstructured data	Data that do not have any predefined model. These are usually qualitative data, such as free-text or images. Unstructured data can be very complex and require a lot of storage space.

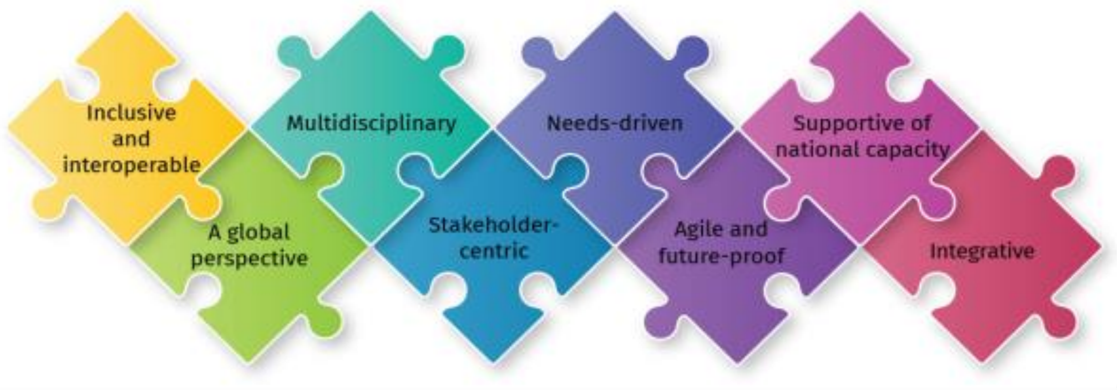
Executive summary

Strengthening global One Health intelligence will support the identification of hazards, and the identification and mitigation of risks to global health security. The One Health Intelligence Scoping Study (OHISS) aimed to identify potential opportunities for improved technical harmonization of systems to strengthen One Health intelligence, and was carried out jointly by the Food and Agriculture Organization of the United Nations (FAO), the United Nations Environment Programme (UNEP), the World Health Organization (WHO) and the World Organisation for Animal Health (WOAH, founded as OIE), henceforth called the Quadripartite. The OHISS was funded by the United Kingdom of Great Britain and Northern Ireland and coordinated by FAO, as the lead agency for the project. The scoping study was completed at the end of July 2022.

The OHISS findings highlight that the numerous international and national information systems collect a wide range of data relevant to One Health, but are not being sufficiently used for effective hazard identification, risk assessment and early warning. Considering the opportunities for collaboration and data sharing (including interoperability when relevant and possible) across health sectors identified by the OHISS, we propose an achievable, scalable and operational framework for Quadripartite-led global One Health intelligence: **the global One Health intelligence system (OHIS)**.

Based on the OHISS foundational activities, eight key requirements for Quadripartite operational One Health intelligence were identified to guide framework development (see Figure 1).

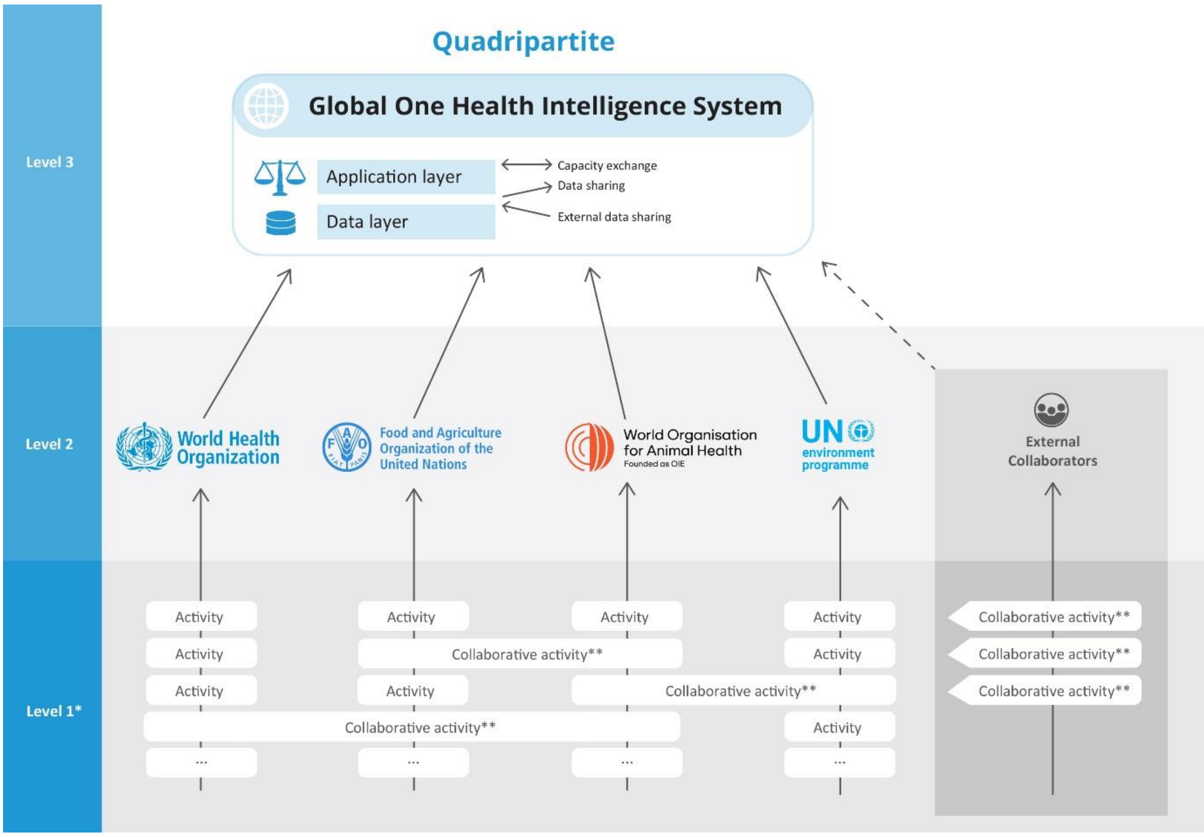
Figure 1: Requirements to create an operational global OHIS



Source: Authors' own elaboration.
Notes: **Inclusive and interoperable**: Take advantage of existing intelligence capacity from across the various relevant sectors by integrating data from multiple sources and respecting data confidentiality and governance. **Multidisciplinary**: Draw data from multiple sectors and contexts, but preserve data context and integrity. **Needs-driven**: Support intelligence systems with feedback to strengthen information and data systems. **Supportive of national capacity**: Consider the equity, needs and capacities of countries. **Global perspective**: Able to process data, information and intelligence at the global level. **Stakeholder-centric**: Meet the needs of different sectors and stakeholders to ensure ongoing support and commitment. **Agile and future-proof**: Able to quickly adapt to changing threats and evolving knowledge. **Integrative**: Support integration and cooperation among diverse initiatives.

We propose a **modular framework** to build the global OHIS, using the foundation of existing Quadripartite intelligence. Starting with ongoing activities within the Quadripartite organizations, the technical needs to support specific One Health intelligence functions and objectives are translated into specific applications. These applications are added as individual "modules" in a dedicated application layer of the framework. Modules for data storage, integration and transformation are added in an independent data layer, allowing governance and access to be defined for each application and data source independently.

Figure 2: A modular umbrella framework for global One Health intelligence led by the Quadripartite



** This may include activities at country level.*
*** This illustration is just an example, and other collaborative activities exist among other partners.*
Source: Authors' own elaboration.

Adding a One Health intelligence layer would not require a revision or rebuild of the individual systems, but would add value by amplifying individual activities and systems and supporting collaborative activities. The global OHIS creates an umbrella framework within which existing activities can drive development and their commonalities can be shared within the system, reducing current – and future – duplication of activities and processes.

The key features of the proposed global OHIS architecture are:

1. Flexible, yet controlled access: Access to data and applications can be customized and restricted where required. Access is controlled for all data and applications individually, allowing the system to preserve governance of all data ingested.
2. A dynamic **data ingestion layer**: Big data approaches can be supported through data lakes or data warehouses that store ingested and unprocessed data, as well as processed data within the system.
3. Quality documentation as a basis for collaboration: Modules in the data and application layer connect through application programming interfaces (APIs), which are thoroughly documented, so that application developers can see which data fields and functions are available. Certain APIs could also be made available to the public.
4. Efficient and FAIR (findable, accessible, interoperable, reusable) use of data: The proposed framework operates under a linked-data model, which prioritizes data reusability and allows alignment with the FAIR data principles. Data cataloguing and the advancement of consensus annotation schema for datasets will provide value not only for data in the OHIS framework, but to all collaborative One Health initiatives.
5. Functionalities of the system are added as additive components in a dedicated **application layer**.
6. An independent and considered approach to software products: The OHIS "open architecture" would be able to host applications developed in different programming languages.
7. Explicit licences, and open source code applications whenever possible, would support internal and external collaboration.
8. Customized reporting: The global OHIS would support various forms of reporting, from self-service dashboards that operate in real time to automated reports.

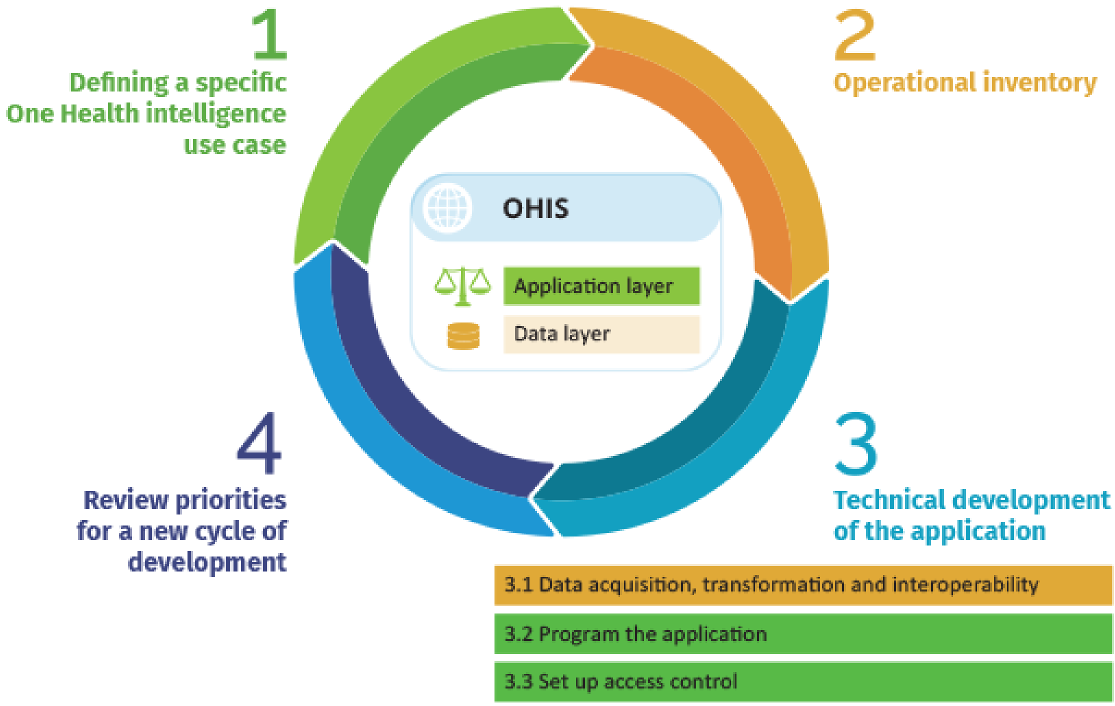
A complete description of the architecture and technical components design to support all the features listed above is provided in this full report.

Sketching the way forward: a proposed road map for building the global OHIS

The global OHIS would be developed in the first instance by gathering, collating and analysing existing information and producing new One Health intelligence for specific objectives or use cases. We propose that, in the first instance, use cases are defined from already ongoing One Health intelligence activities within the Quadripartite. This approach will provide an opportunity to strengthen and expand collaboration around these activities, and to identify similar activities that could be aligned to avoid duplication. Within use cases, mapping risk pathways and associated drivers, impacts, vulnerabilities and critical monitoring points on a subset of hazard categories will be key to identifying datasets, which could inform operational prioritization and data integration.

As more use cases/activities are incorporated into the operational framework provided by the global OHIS, existing applications can be expanded, or new applications can be designed, starting a new cycle of development. More sources of data and more functions can be added to the framework on demand. In time, the need for new One Health intelligence activities can also be identified, allowing synergistic growth between the technical framework and the Quadripartite's operational One Health intelligence priorities.

Figure 3: Iterative cycles of development of the global OHIS based on operational One Health intelligence use cases



Source: Authors' own elaboration.

The cycles of development need to happen **within an overarching framework that includes system hosting and maintenance.** The following system elements need to be put in place by the Quadripartite organizations to create the overall structure within which new development cycles can be conducted: a model for steering and stewardship that is neutral to the four organizations; maintenance processes, including funding mechanisms; processes for horizon scanning, prioritization and evaluation; models for governance and decisions regarding access to data and applications; and systematic evaluation and incorporation of stakeholder needs.

Conclusions

The intelligence activities and systems already available within the Quadripartite organizations provide a foundational structure of data and activities on which the complex demands of One Health intelligence can successfully and sustainably build. The global OHIS should not be built as a silo of data and functions, but as a flexible umbrella framework to connect existing intelligence and make it available within an environment of connectable and evolving applications.

Data-fed, needs-driven system for agile and sustainable development: Data cleaning, annotation and integration add value to the data, which is propagated as more applications can reuse them. Applications are incrementally added to the global OHIS, applying a modular approach, which ensures that the system development can start simply and adapt quickly to growing demands for complexity.

A focus on operational One Health intelligence: The focus on applications, informed directly by the decision-making needs of the system end users, ensures that the global OHIS is designed to support the daily, operational needs of One Health, aimed at mitigating threats to global health security.

The global OHIS strengthens, and is strengthened by, national capacity: Applications within the OHIS can also support countries as end users of the system. The adoption of open source applications will allow countries to reuse and adapt applications within their own resources and OHIS. The global OHIS applications that address the needs of Member Nations will incentivize continued efforts to capture accurate and timely data and information.

Introduction

People, animals and their environment are inextricably linked (One Health High-Level Expert Panel, 2021). Effective decision-making to protect the health of people, animals, plants and our ecosystems requires an intersectoral One Health approach. A holistic view of hazards and risks is particularly important to support refocusing away from response to known and active hazards, towards more proactive actions aimed at prevention and early detection. The One Health approach offers the most opportunities and benefits to improve early warning and risk assessment of global health threats, such as from epidemic and pandemic diseases (Subramanian and Payyappallimana, 2020).

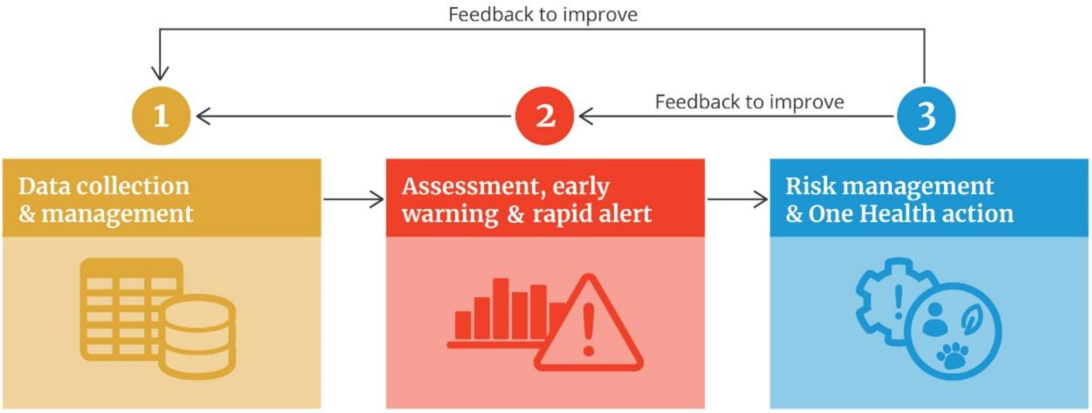
Intelligence refers to the ability to read and respond effectively to a situation through insights and evidence. The process of intelligence is meant to provide a decision-advantage (Figure 4). This recognizes that the value of intelligence lies not in the intelligence itself, but in the decisions it shapes and drives. One Health intelligence, in particular, requires gathering information from across the One Health landscape, including from across the human, animal, plant and environmental health sectors, combining it and assessing its significance, and applying it to a specific decision-making context. This can include a range of objectives; early warning, risk assessment and epidemic/pandemic prevention are considered priorities.

Figure 4: A range of activities, in varying stages of digitalization, can provide organizations with intelligence and therefore a decision-advantage

Source: Authors' own elaboration.

Effective intelligence relies on timely collection of relevant **data**, appropriate analyses to convert these data to **information** and effective communication of the insights obtained to decision-makers to inform **action** (see Figure 5)**.**

Figure 5: The One Health intelligence process



Source: Authors' own elaboration.

The intelligence process shown in Figure 5 is not unidirectional. Besides the feedback loops depicted, Steps 2 and 3 can also be fed directly by activities other than data collection, such as expert opinions, knowledge-sharing networks, results of third-party analyses, and advice and insight shared through communication and collaboration groups, including crowdsourced data and community-based information. In a well operating process, Step 3 includes risk communication and stakeholder engagement, activities that then create incentives for stakeholder participation, and strengthening the information loop in the cycle.

Several activities may provide organizations with intelligence and, as a result, a decision-advantage, as previously shown in Figure 4. A major challenge is how to unify diverse individual information systems, which may be in varying formats and in various stages of digitalization, so that an intelligible and actionable collection of insights is presented to decision-makers.

Building One Health intelligence collaboratively across the Quadripartite

The Quadripartite[2] organizations operate under the mandate of their members to perform global surveillance and intelligence activities. Working collaboratively, these organizations have advocated and provided guidance on complex issues to promote effective, multisectoral collaboration at the local, national, regional and global levels. Critical to achieving these goals is working across the boundaries of each organization to improve decision-making and support national and global stakeholders with suitable tools to drive One Health action (Bordier *et al*., 2019). As such, the Quadripartite organizations are now in a unique position to provide leadership in global One Health intelligence and evolve global One Health

[2] Comprising the Food and Agriculture Organization of the United Nations (FAO), the United Nations Environment Programme (UNEP), the World Health Organization (WHO) and the World Organisation for Animal Health (WOAH).

capability and capacity by unifying their operational One Health intelligence to provide stakeholders with information and tools to improve decision-making.

The One Health Intelligence Scoping Study (OHISS) is a Quadripartite initiative,[3] which carried out several activities (literature review, expert advisory meetings, national capacity survey, risk landscaping and a high-level assessment of intelligence systems and activities) to identify opportunities for further technical harmonization of Quadripartite partner systems, aiming to strengthen operational One Health intelligence to improve global health security and capitalize on the Quadripartite organizations' unique capabilities.

The combined findings from these activities highlighted that the many international and national information systems collect a wide range of data relevant to One Health hazards, but these are not being sufficiently used for effective early warning and risk assessment. It also demonstrated that the incorporation of data from the environmental sector has significant potential to strengthen One Health intelligence and identify risk "hotspots", and the ability to reduce risk from emerging issues.

This document reflects on the findings of the scoping study, in particular considering the opportunities identified for collaboration and data sharing (including interoperability when relevant and possible) across the various One Health sectors, and proposes an achievable, scalable and operational framework for Quadripartite-led global One Health intelligence.

[3] Requested in June 2021 by the G7 Carbis Bay Health Declaration. The OHISS was funded by the United Kingdom of Great Britain and Northern Ireland and was coordinated by FAO, as the lead agency for the project.

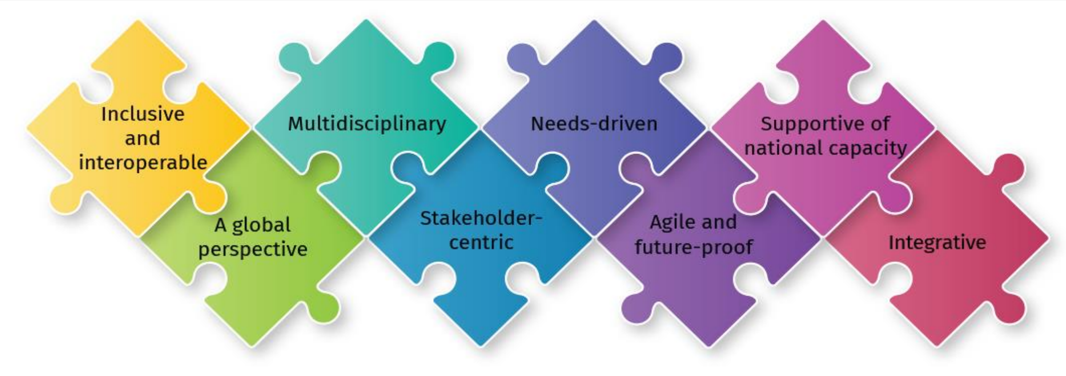
1. Operational requirements for One Health intelligence

Summary

- A system to support Quadripartite global One Health intelligence must be able to integrate activities and intelligence that already exist within the Quadripartite organizations, including those developed in collaboration with partner organizations, in order to connect, amplify and strengthen early warning and risk assessments.
- Integration across sectors needs to be driven by the common goal of One Health, while preserving an understanding of the context in which data and information are collected.
- To reach a global perspective, the system needs to connect activities at the national, regional and global levels, and to value and incorporate the needs of stakeholders at all levels.
- Those carrying out activities that collect data and information to be (re)used in the system, as well as risk managers and decision-makers (the target users of the system), are considered system stakeholders. These include the Quadripartite organizations, their members and partners, and all those working in activities to improve One Health globally.
- A flexible and modular approach is needed to ensure that the system is sustainable, able to fill identified gaps and can incorporate and adjust to the changing needs of stakeholders.

Identifying requirements is an essential component of any system design process. Eight requirements for Quadripartite operational One Health intelligence were identified through the foundational work carried out by the One Health Intelligence Scoping Study. They are described in this section.

Requirements of an OHIS



Source: Authors' own elaboration.

The OHISS highlighted the large number and diversity of activities currently conducted by FAO, UNEP, WHO and WOAH that could provide value and bring different perspectives to One Health intelligence at the global level. The existing activities result in the collection and generation of a large amount of data and information. However, these are currently distributed across many information systems, with different technical architectures and varying accessibility and audiences. As a result, the activities and the information they produce are being siloed. A degree of overlap among activities conducted across and within the Quadripartite was common. A process supporting inclusion, interoperability and awareness of ongoing activities would bring together diverse activities to reduce duplication, while maximizing the shared value of their outputs (OHIS, Requirement 1). The ability to combine information across sectors to serve a shared operational intelligence objective is critical in a future OHIS (George *et al*., 2020; Thompson and Etter, 2015). This system cannot rely solely on the digital integration of data, as discussed in more detail below, but it is an important first requirement of any system designed to support One Health intelligence in practice.

> ***Requirement 1 – Inclusive and interoperable:*** *A global OHIS must take advantage of existing intelligence capacity, leveraging existing processes and intelligence from across the various relevant sectors. This will require integrating data and information from multiple sources, across health sectors and at different resolutions. Interoperability needs to respect data confidentiality/accessibility constraints and preserve data providers' governance.*

A global system should be built on the foundation of existing intelligence; however, the specific decision-making context of One Health intelligence may differ from the original context of data collection and hence requires a multidisciplinary approach (OHIS, Requirement 2). Data collection and analyses are designed to address primary and activity-specific objectives within each organization; they are performed under different contexts with different methods, and typically lack any shared objective that would support One Health intelligence. This results in varied granularity in space and time and limited harmonization and standardization. It is, however, important that the original context is not lost, and that a global OHIS can provide decision-makers with the best possible information in a timely manner, while ensuring that data are not used or interpreted out of context. This requires a highly competent team with considerable experience and technical resources in a wide variety of technical areas, as highlighted by WHO (Morgan *et al*., 2022a), and extensively reviewed in the literature.[4] The multidisciplinary context should be explicitly captured, and differences documented to allow data alignment and reuse. The role of the Quadripartite organizations in One Health should be

[4] See Aguirre *et al*., 2021; Braks *et al*., 2019; Meurens *et al*., 2021; Queenan, Häsler and Rushton, 2016; Saylors *et al*., 2021; Schurer *et al*., 2016; Subramanian and Payyappallimana, 2020; Uelze *et al*., 2020; Zaitchik *et al*., 2016.

leveraged to contribute to global efforts to build reusable schema of data collection, codification and annotation across different One Health disciplines.

> ***Requirement 2 – Multidisciplinary:*** *Intelligence from multiple sectors arises from multiple contexts. The original context of data collection and analyses needs to be preserved in the transfer from sectoral level to an OHIS, and explicitly accounted for during One Health decision-making. A global OHIS should contribute to building a global community to create and share data schema and knowledge models for One Health.*

Different One Health-related activities will be at different stages of digitalization. Integration and recontextualization must be understood not only from the data integration sense, but as a true process of building intelligence for a defined purpose. This requires identifying the decision-making context, identifying the stakeholders responsible for those decisions and their information needs, and developing an information system tailored to support them (OHIS, Requirement 3). For example, Meurens *et al*. (2021) illustrate the need for data collection and analysis that is appropriate for decision-making in terms of scale and localization of the population of interest. An effective and fit-for-purpose system should not only digitize data and digitalize the steps of information generation that can be automated, it should also support other activities needed to transform information into intelligence, including collaboration, coordination, knowledge exchange and relationship building among different stakeholder groups (e.g. those in different sectors, or at the national, regional or global level). The need for human input as part of the information transformation process is also highlighted in the literature (Meurens *et al*., 2021; Morse, *et al*., 2014).

> ***Requirement 3 – Needs-driven:*** *An OHIS should be designed to support and strengthen the activities that feed data, information and intelligence into the system. These may be in different stages of digitalization. The needs of stakeholders carrying out these activities must be constantly fed back into the system.*

The intelligence activities conducted within the Quadripartite organizations are designed to attend to the needs of their members. Their foundation relies on the national capacity to implement data-collection and reporting processes, enhanced by other sources collected at the global or national level. Gaps in this information flow exist for many different reasons, such as lack of resources (human, technical, equipment) or lack of a supportive political environment – many of these gaps were highlighted in the literature review.[5] The architecture of a global OHIS cannot ignore these gaps, and should be designed to strengthen, and collaborate with, national and subnational authorities and partners, as appropriate (OHIS, Requirement 4). The integration of information from multiple sources – across sectors and

[5] See Fasina *et al*., 2021; Morse, *et al*., 2014; Oberin *et al*., 2022; Stevenson, Halpin and Heuer, 2021.

geographical scales – can be designed, for instance, to look for alternative sources of information where gaps exist, such as when relevant data streams may be reported by one sector but not another. This may serve as an incentive to use the system, which in turn, alongside other efforts by the Quadripartite (and third parties) to strengthen national systems, will strengthen national capacity and capabilities. As national capacity improves, global health security will be strengthened, and the additional sources of information and global intelligence can reinforce national and global One Health intelligence.

> ***Requirement 4 – Supportive of national capacity:*** *A Quadripartite approach to operational intelligence must consider the needs and capacity of Member Nations. The information system needs to support national capacity, while being designed with awareness of existing gaps. One Health intelligence at the global level will work in synergy with national capacity in a feedback loop, where national and global One Health strengthen each other.*

Activities that transform information into intelligence can occur in different sectors (for simplification, the categories of human health, animal and plant health, food safety, and environmental health are used) and at different scales (subnational, national, regional, global/Quadripartite) and with different timelines (event based, sporadic, cyclical). One Health intelligence generated at the national level can directly contribute to global One Health intelligence, but a holistic global system needs to be capable of collecting and incorporating data, information and intelligence from many other complementary sources (OHIS, Requirement 5), for example by including globally aggregated data. These sources could include data submitted as part of reporting requirements to multilateral environmental agreements, such as the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES);[6] data hosted or developed by non-governmental organizations, such as Global Forest Watch,[7] the International Union for Conservation of Nature (IUCN, 2022), the World Wide Fund for Nature,[8] and Locust Watch (FAO, 2022a); and/or data collected under mandatory global notification schemes, as in the case of the International Plant Protection Convention (IPPC, 2022a, 2022b).

> ***Requirement 5 – A global perspective:*** *Global One Health intelligence requires more than aggregation from the national to the global level. The system needs to be able to process relevant data, information and intelligence that are directly relevant to One Health intelligence at the global level. One Health intelligence at the global level will integrate data generated at various geographical levels in a web of information, as opposed to a unidirectional flow from the national to the global.*

[6] See https://cites.org/eng.
[7] See www.globalforestwatch.org.
[8] See www.worldwildlife.org.

For a global OHIS to work in synergy with national One Health initiatives, coordination within a complex web of stakeholders and user communities at various geographical levels is required. While development would be Quadripartite-led, the system users would not be restricted to the Quadripartite. All these stakeholders will have different needs and priorities. To provide deep value for each organization, the system will not only answer the big joint questions, but also be flexible enough to support the nuances and differences in operational day-to-day needs across the Quadripartite organizations and key users of the intelligence. This stakeholder-centric approach is fundamental for the success of the system and the sustainability of its components (OHIS, Requirement 6). System flexibility was a best practice highlighted throughout the literature.[9] The reuse of existing Quadripartite information and intelligence should add value to contributing stakeholders, such as the Member Nations or partner organizations, who actively provide input data into these systems.

> ***Requirement 6 – Stakeholder-centric:*** *Global One Health intelligence must respect the needs of different stakeholders, who need to find value in the system in order to stay engaged and support its long-term sustainability. Stakeholder engagement is essential for system maintenance and the quality of inputs and their usefulness in One Health practice.*

The needs of stakeholders continually evolve, as threats to health security change and emerge. The COVID-19 pandemic has accelerated global efforts towards One Health intelligence and global preparedness, and best practices are evolving in response. In parallel, the technical tools available are also being improved. The OHISS Quadripartite assessment illustrated that each of the Quadripartite organizations are undergoing significant change in how they collect, collate and manage data as part of their digitalization strategies. Global One Health intelligence must be able to evolve alongside changing objectives, technological advances and opportunities, scientific discovery, and an improved understanding of risks and their management (OHIS, Requirement 7).

> ***Requirement 7 – Agile and future-proof:*** *Global One Health is a dynamic and constantly evolving target. Global One Health intelligence can only be supported by an agile and future-proof system, capable of responding to new threats and evolving with knowledge.*

Furthermore, in a complex and evolving ecosystem, no single initiative can cover the whole spectrum of One Health intelligence globally. The Quadripartite approach to global One Health intelligence needs to consider the plethora of parallel initiatives seeking to integrate information across the One Health scene and generate intelligence for better health (OHIS, Requirement 8). It is inevitable that initiatives will overlap to differing extents; however, with

[9] See Dente *et al*., 2019; Dinesh *et al.*, 2020; Hattendorf, Bardosh and Zinsstag, 2017; Jourdain *et al*., 2019; Wahl *et al*., 2012.

the right architecture for cooperation, collaboration and integration, these initiatives can amplify efficiency and effectiveness and contribute to the same goal of global One Health. Operating under specific objectives and funding models, each initiative will be able to provide unique value to the global effort of promoting One Health.

> ***Requirement 8 – Integrative:*** *The architecture for a Quadripartite approach to operational One Health intelligence needs to support integration and cooperation with other initiatives, allowing efforts to be amplified within a distributed environment of interconnecting solutions, fostering international collaboration.*

2. Infrastructure required to support a Quadripartite One Health intelligence solution

Summary

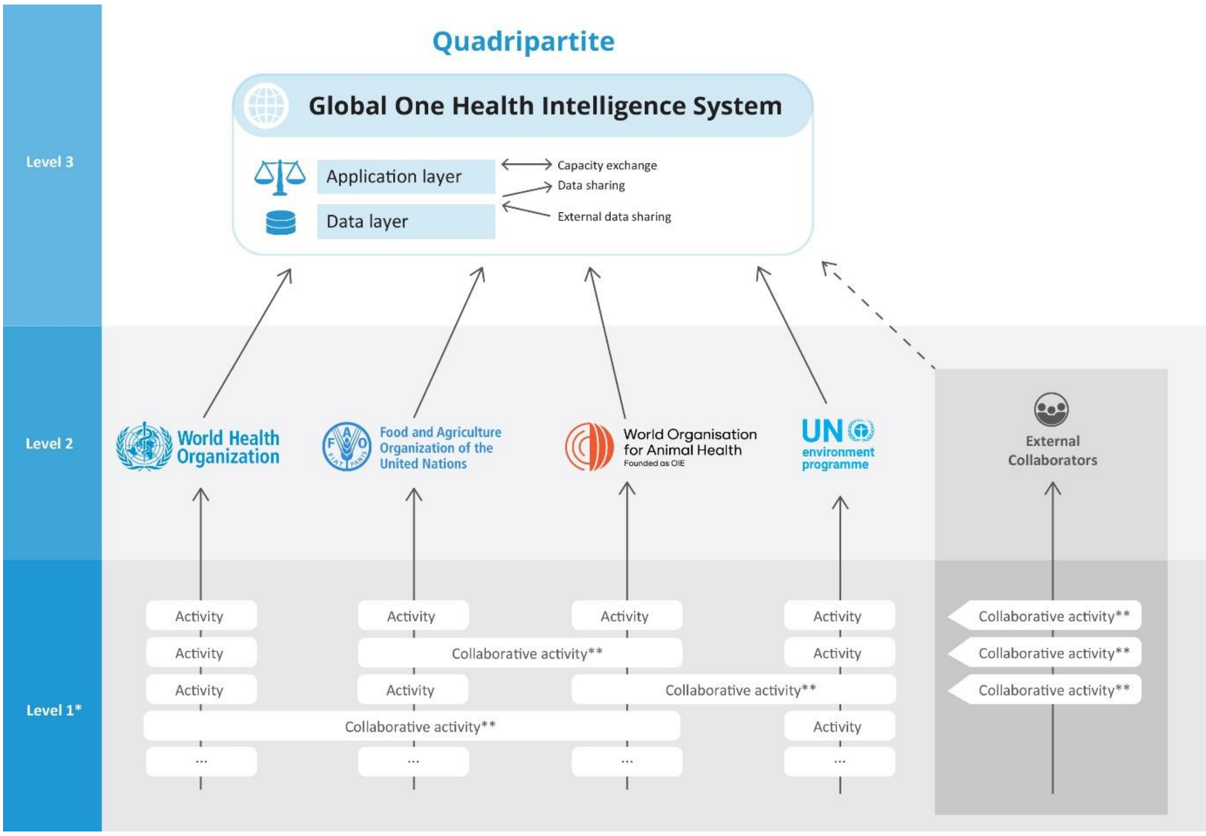
- A modular architecture to develop Quadripartite operational global One Health intelligence is proposed (the global OHIS).
- The infrastructure is designed to amplify rather than duplicate or replace existing Quadripartite efforts.
- The OHIS would work as a layer of intelligence that connects existing data, adds value to them and makes specific outputs available where needed.
- The OHIS is designed to ensure that the framework can connect to other initiatives and applications relevant to operational One Health intelligence.
- FAIR data principles are adopted.
- An access-control layer is proposed to preserve governance of the data in the system.
- Where possible, an open source approach should be used to allow capability transfer to support national and regional capacity, as well as global One Health knowledge building.

A key finding of the scoping study is that Quadripartite global One Health intelligence needs to be built on the foundations of the diverse intelligence-relevant activities already performed by the four organizations. The proposed umbrella framework aims to integrate multiple activities, including those that already exist, while supporting and preserving their governance and endorsing a joint evolution towards the common goal of operationalizing One Health intelligence. Importantly, a system capable of supporting all the workflow needs of One Health intelligence, delivering outputs that can be used in all activities that contribute to intelligence, and which can integrate data and decision needs across different sectors and governance levels, cannot be built as a single, all-encompassing architecture. A so-called monolithic system with the number of tools required to address the complexity of One Health intelligence needs would not only be challenging and resource-intensive to build and maintain, but also slow to adapt to changing needs and evolving knowledge. To preserve the governance of the individual activities and initiatives that will contribute to the system, a separation between data and applications is needed.

Starting with ongoing activities within the Quadripartite, the technical needs to support specific One Health intelligence functions and objectives are translated into specific applications. These applications are added as individual modules in a dedicated application layer of the framework. Modules for data storage, integration or interoperability, and transformation are added in an independent data layer, allowing governance and access to be defined for each application and data source independently.

This modular approach will enable agile development, allowing priority areas of integration to be tackled first. Complexity is then added progressively as more and more One Health intelligence functions are identified for inclusion in the system and the models of funding and information exchange among organizations are consolidated. The modular approach also provides flexibility to adapt to technical as well as political and economic requirements, contributing to system sustainability and the ability to adapt to changing needs and evolving knowledge. This high-level vision of a modular Quadripartite global OHIS is depicted in Figure 6.

Figure 6: A modular umbrella framework for global One Health intelligence led by the Quadripartite



** This may include activities at country level.*
*** This illustration is just an example, and other collaborative activities exist among other partners.*
Source: Authors' own elaboration.

The proposed architecture creates a framework to add connectable and reusable modules to provide One Health intelligence functionality **on top** of existing information systems. The assessments performed by the OHISS recognize ongoing efforts by all the Quadripartite organizations to modernize and improve their information systems. Adding a One Health intelligence layer would not require a revision or rebuild of the individual systems, but would add value by connecting and enhancing individual activities and systems and supporting collaborative activities. The global OHIS will not duplicate current efforts but support collaboration and integration across the four organizations. It creates an umbrella framework within which existing activities can drive development and their commonalities can be shared within the system, reducing duplication of activities and processes.

Key features incorporated in the architecture to address the specific requirements of One Health intelligence are described below. The technical details of this proposed architecture (i.e. Level 3 in Figure 6) are provided in Annex I.

Key features of the global OHIS

1. Flexible, yet controlled access

It is important that access to data and applications within the joint operational system can be customized and restricted where required. Access to the different applications and data could, for example, be managed by a dedicated identity provider. If new applications are developed, the established identity provider could be used, avoiding the inconvenience of multiple log-ins. When authorized, users log in just once to access all the OHIS applications, functionality or data they are privy to. Some applications may be accessible to the public or contain both an open and a log-in-restricted component. Importantly, while supporting joint Quadripartite activities, this will also enable each organization to use the system for their individual needs (for example, to address specific data governance requirements).

2. A dynamic data ingestion layer

The global OHIS would be able to connect to multiple data sources (as governance within specific applications allow) and be adaptable to the dynamic integration of new data. This is achieved through a data ingestion layer, which connects to different data sources and/or imports relevant data. Ingestion of data from Quadripartite organizations or external sources is possible through APIs or data connectors (though recognizing data governance issues would need to be addressed among the Quadripartite and partner organizations to facilitate access). Specific applications can also be developed to allow manual data uploads, e.g. in form of flat files for specific datasets. It is important to note that the global OHIS would be designed with the primary objective of supporting the integration of data and information already available within the Quadripartite organizations to support the One Health intelligence approach. Primary data collection is not foreseen in a first development phase; however, the modular approach will allow for future expansion and feedback on data needs.

Both raw and processed data will be retained in a storage system that supports a wide range of data formats, from structured to unstructured data. As development will first focus on existing use cases within the Quadripartite organizations, structured datasets are expected to be used first. As the system develops in complexity, however, the ingestion and storage of unprocessed data can be supported though specific technologies, such as data lakes. This will allow the system to be scalable, integrating novel data source and types as they become routinely available.

Importantly, individual applications would not directly access the data lake or warehouse. Data would be made available within the architecture through an internal API. This provides greater flexibility to share data and manage complex permissions, either on an application or data level. This acknowledges that data governance is of utmost importance and must enable a model of collaboration and trust that supports tailored access to applications and data. Through this approach, access can be restricted to different applications; and even within an application, certain data might be made available only to specific users. For example, stakeholders might be able to access their own direct outputs, be able to share these with selected others, or be able to make them openly available.

3. Quality documentation (of data and metadata) as a basis for collaboration

Good documentation is key to enable multi-use and to avoid duplication, especially of data cleaning activities. All APIs should be documented, so that application developers can see which data fields and functions are available. Certain APIs might also be made available to the public, so that other external systems or users can use the available data, for example. Efforts to make data available are already happening within the Quadripartite, e.g. in the recently modernized EMPRES-I (FAO, 2022b), the World Animal Health Information System (WOAH, 2022), the COVID-19 dashboard (WHO, 2022a) and many of UNEP and its partners' platforms, such as the UN Biodiversity Lab (United Nations, 2022). Similar initiatives are also present in plant sectors, such as the locust monitoring system (FAO, 2022a), the Fall Armyworm Monitoring and Early Warning System (FAO, 2020, 2022c) and the Pest Outbreak Alert and Response System (IPPC, 2022b). A good model for the connectivity of layers of data, accessible under a common framework, is the Hand-in-Hand Geospatial Platform (FAO, 2021).

Making data available requires consideration of associated data licence and sharing agreements and, where applicable, consultation with data providers. Where data can be made public, it can be reused by external initiatives, contributing to global intelligence outside the Quadripartite system. This collaboration-endorsing approach will also allow the global OHIS to benefit from intelligence generated outside the Quadripartite organizations, which will provide opportunities for external initiatives and organizations to develop applications that complement system functionality, for example in the context of research or national efforts.

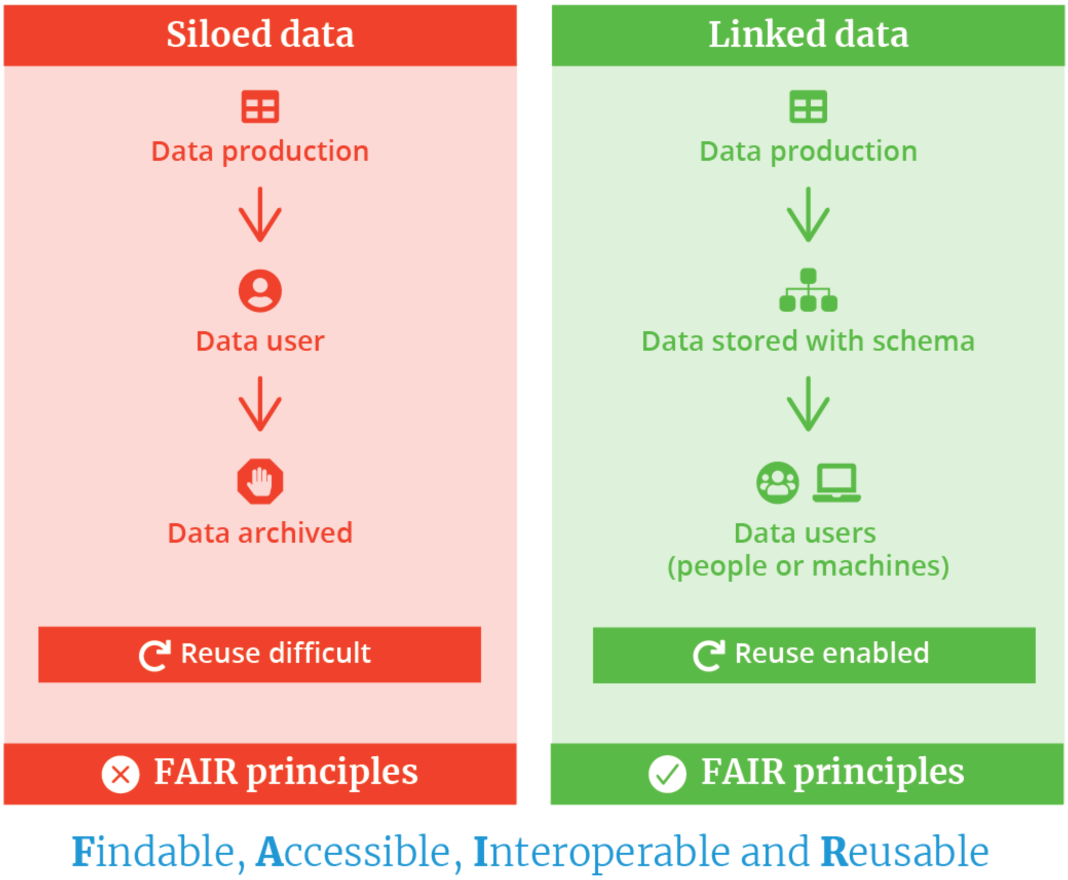
4. Efficient and FAIR use of data

One of the core functionalities of the system will be to combine different data sources so that they are preprocessed and ready to be used in different applications as required. This means data need to be cleaned and mapped against common standards, and effort is required to maintain the pipelines as datasets are updated. Data (or continuous data streams) are cleaned and/or integrated once, then made available for multiple applications.

Data cataloguing, integration and harmonization are resource demanding tasks: data models (schema) or knowledge models (ontologies) need to be built, data and metadata need to be mapped or annotated according to these available models, and the models themselves need to be kept up to date. These steps are critical in ensuring that the information is provided with well-defined meaning, enabling computers and people to work in cooperation. Recognition of the need for such data harmonization efforts is increasing in the academic and public sectors, (Thompson and Etter, 2015; Zinsstag *et al*., 2018), but global leadership is needed to ensure that the efforts of diverse initiatives are channelled towards a common goal. The Quadripartite organizations are in a unique position to lead this effort, for the direct benefit of their members and the global community.

The framework will operate under a linked-data model (Figure 7), which prioritizes reusability of data (by authorized users) and allows alignment with the FAIR data principles (Force 11, 2016). Recommendations to align with the FAIR principles were also clear in the literature review carried out by OHISS (Dinesh *et al.*, 2020; Timme *et al*., 2020).

Figure 7: Linked-data model



Source: Authors' own elaboration.
Note: Data are stored with all the context needed for both humans and machines to reuse the information. Data and metadata are annotated so that data are findable, accessible, interoperable and reusable (FAIR).

When a dataset is added to the system, specific **metadata** is assigned to the dataset to make it **findable**. This means that both humans using the system and applications within the system can identify which datasets are relevant to each question.

Importantly, these metadata should include explicit licences that define the permissions for data reusability. Note, this does not imply a requirement that data should be open, only that the governance of the data should be explicit. This will allow data to be more easily accessible for multiple purposes and contexts, either for multiple applications (and use scenarios) within the OHIS framework or by external applications or collaborators.

The ability of humans and machines to interpret the data within these datasets is called, in the technical setting, accessibility. Accessibility by humans is ensured by proper documentation of data fields, and use of data dictionaries. Machines accessing the data (e.g. automated applications, such as mapping or data visualization tools) need to be able to follow the structure and coding used in the dataset. In the FAIR data model, both data and metadata are annotated with specific schema (models specifying the structure of the data) or ontologies (knowledge models specifying the structure and semantic meaning of data terms). The adoption of FAIR data principles in the global OHIS will support global efforts to develop data schema and ontologies for One Health intelligence. Quadripartite members and the global One Health community will benefit not only from the data available in the global OHIS (for those with access) and the intelligence generated by the system, but also from the data harmonization models provided for reuse.

Interoperability is achieved by creating compatible linkages between the data structure and meaning of different datasets (for example, through harmonizing hazard categorization and naming across different datasets).

5. Different system functionalities are added as additive components in a dedicated application layer

Applications (or apps) are programs designed to carry out a specific function (for example, visualize a level of risk or provide aberration detection). In the global OHIS, these can be for a specific data analysis function, a predictive model or a dashboard visualizing the occurrence of adverse events, vulnerabilities or capabilities. Building individual targeted applications allows different use scenarios to be incorporated, offers direct value to different stakeholder groups, supports the flexibility to expand and modify the functionality, and allows the global OHIS to rapidly adopt to future requirements as they arise, for example during a significant outbreak.

6. An independent and considered approach to software products

Importantly, an architecture containing independent applications will support the use of different software depending on user preferences or demands. The OHIS "open architecture" would host applications developed in different programming languages.

Currently, each Quadripartite organization and other partners have different software tools that are used and supported in-house and provide value for different purposes. It would be unrealistic and inappropriate to force the short-term use of a single technology. The proposed system design is flexible and inclusive, making the system independent of specific suppliers or technologies. Supplier dependency could pose a risk for long-term sustainability and will need to be carefully managed. There are advantages to proposing preferred technologies in the long-term if the Quadripartite organizations so wish; for example, less applications and programming languages used means lower maintenance and upgrade efforts.

Examples of different languages that could be added to the framework in accordance with project or operational preferences include:

- R or Python for statistical computing and models, enhanced by JavaScript for data visualizations, including geographical data visualization through specific libraries;
- proprietary tools for data visualization (Tableau, Qlik, Power BI);

- cellular phone apps for Android or iPhone, e.g. using React Native or Ionic;
- native websites built with HTML, CSS, JavaScript; and
- software applications built with Java, C++, PhP or similar.

Applications within the global OHIS connect to the underlaying data using internal APIs. This separates the functional application layer from the data connected, creating **independency**. Therefore, specific representations of the data can be shared flexibly across multiple applications and formats, e.g. some results may be shared as reports, others may be made available via web interface or cellular phone apps.

7. Explicit licences, with open source code, support internal and external collaboration

The adoption of explicit licences to govern reuse should be considered when referring to the reusability of software components. Every application should have specified licences for reuse of its software codes. The inclusion of proprietary application modules can be accommodated in the system, and access to their codes can be protected where needed.

When possible, applications should adopt open source licences. This is in line with the United Nations view that "[t]*o unlock a more equitable world, a global effort is needed to encourage and invest in the creation of digital public goods: open source software, open data, open artificial intelligence models, open standards and open content*" (United Nations, no date).

If an open source licence is applied, it typically means that the source code of an application needs to be disclosed and made available for reuse. Functionalities of the global OHIS could easily be shared with others. This would further support reproducibility and enable users to research the programming code and methods used, and contribute to ongoing application development, for example through research collaborations. To adapt to stakeholder requirements, different types of open licences can be used, allowing specific definition of how codes can be reused, linked or redistributed. The use of copyleft licences ensures that users can reuse codes and/or redistribute the software, as long as the same rights are preserved in derivative works. Examples of copyleft, open source licences are the Creative Commons Attribution Share-Alike licence[10] and GNU General Public Licence.[11] Numerous environmental data sources and information systems are aligning with the "digital public goods" approach; for example, data from the Projecting Responses of Ecological Diversity In Changing Terrestrial Systems (PREDICTS) database and the code to produce the Biodiversity Intactness Index are publicly available, and the PREDICTS database is licensed under the Creative Commons-NonCommercial 2.0 (CC BY-NC 2.0).

[10] Available from https://creativecommons.org/licenses/by-sa/4.0/.
[11] Available from www.gnu.org/licenses/gpl-3.0.html.

Open source codes, written in an open source language highly accessible to One Health stakeholders, provide several key advantages, including the ability for the Quadripartite to reuse data analysis codes already existing in the public domain as a starting point (Organisation for Economic Co-operation and Development, 2020). When applications are shared under open source licences, the use of the open source statistical programming environment R is proposed (The R Foundation, 2021). This framework can accommodate the application of other languages, such as those suggested above. The use of R is encouraged given its wide use in the health and research domains and ability to connect with other approaches and software. R is rapidly become the language of choice in One Health and epidemiology data science. See, for instance, the recently published *Epidemiologist R Handbook* (Batra *et al.*, 2021). R is also used to develop applications in the Epiverse, a global consortium that designs and builds software tools to power pandemic response (data.org, no date). It is also the key technology for the R Epidemics Consortium (RECON, 2022), an international not-for-profit, NGO that aims to create the next generation of analytical tools to inform the response to disease outbreaks, health emergencies and humanitarian crises. A good example application is the epitweetr tool (European Centre for Disease Prevention and Control, 2022). R was explicitly chosen as the computing platform to make the tool as broadly available as possible, as it is free, open source and runs on any modern operating system.

The development of an OHIS with the features described so far, prioritizing data reusability (by authorized users), applications and using open source codes when possible, contributes to the creation of **digital public goods**, as mentioned above. It also complies with several of the **open science** principles endorsed by the United Nations to meet the Sustainable Development Goals (United Nations Educational Scientific and Cultural Organization, 2022). Following the example of the Humanitarian Data Exchange (United Nations Office for the Coordination of Humanitarian Affairs, 2022), the proposed framework for the global OHIS supports data sharing across the organizations, relies on open source software and follows a modular approach to provide an agile software development process.

Quadripartite stakeholders can reuse the codes, reducing the need to duplicate efforts. Users will be able to benefit directly from the system outputs based on data available within the global OHIS. Quadripartite stakeholders may also hold very detailed data that is not channelled (for technical or governance reasons) into the global OHIS. With an open source application, they can reproduce applications at the national level, for instance.

Through this approach, applications within the global OHIS can be enhanced by the collective global expertise, and external stakeholders can suggest improvements to the applications' code, or contribute new applications. This will allow improved linkages between research and operations to help advance capabilities and foster joint funding applications and collaboration with other initiatives, groups and activities, such as Preventing Zoonotic Disease Emergence (PREZODE, 2022), the WHO Hub for Pandemic and Epidemic Intelligence (WHO, 2021), the

Epidemic Intelligence from Open Sources initiative (WHO, 2022b) or the various projects in the Ending Pandemics collection.[12]

8. Customized reporting

Reporting One Health intelligence will require customization in accordance with user needs and expectations. Flexible reporting should be at the heart of the global OHIS and will allow various forms of reporting, from self-service dashboards that operate in real time to automated reports (e.g. created with R Markdown). Priority applications may have more advanced reporting functionality than those built for fewer users or targeted at non-priority objectives.

- **Off-the shelf-reporting tools** (such as Tableau, Qlik, Power BI) offer a quick way to create standard dashboards or reports with a lower degree of customized features or interfaces. There is no specialist programming knowledge required to use these tools and APIs, and data sources can be connected once access has been granted. These tools will typically be used outside the system, either as separate cloud systems or desktop applications.
- **Scripted reporting** (such as R Shiny, Markdown, Python Dash, JavaScript) offer analysts, researchers or data scientist tools to create more advanced, specialist "code-first" reporting. Reports are custom-coded, and the approach offers greater flexibility than the off-the-shelf tools. These tools can be used to build specialist reporting, e.g. for epidemiological or genomic analysis, or when there are specific reporting needs. Users might export specific formatted reports through a dashboard interface using self-service report generation. An alternative option is scheduled reports that are sent to a distribution list at certain time intervals or when events happen. This requires a tool for report scheduling with an integrated data pipeline to prepare the required data for the reports.

[12] See https://endingpandemics.org/.

3. The way forward: a proposed blueprint and road map for the development and implementation of the global One Health intelligence system

Summary

- To enable the development of the global OHIS, an approach to break down the overall goal of “improved operational One Health intelligence” into concrete, attainable subtasks is outlined.
- The suggested approach is **data-fed** but **needs-driven**. The system will provide applied value from the start, and progressively but sustainably grow in complexity, continuously widening its coverage of the many One Health intelligence needs.
- From a technical perspective, development can start based on a single simple application. Identification of this “pilot application” will require specification and prioritization of the One Health intelligence needs across the organizations, coupled with an inventory of technical and governance details for the data sources available to support the application’s objectives.
- A road map for implementation of the global OHIS is proposed.

The global OHIS would be developed by breaking down the overarching goal of “gathering existing and producing new One Health intelligence” into specific objectives or **use cases.** These use cases would then be translated into user requirements for one specific application within the system. Technical and operational specifications are application specific and cover user information, including their different levels of access, the specific technical functions needed to support their intelligence work, any capacity building required, the required data, and how they will be cleaned and validated.

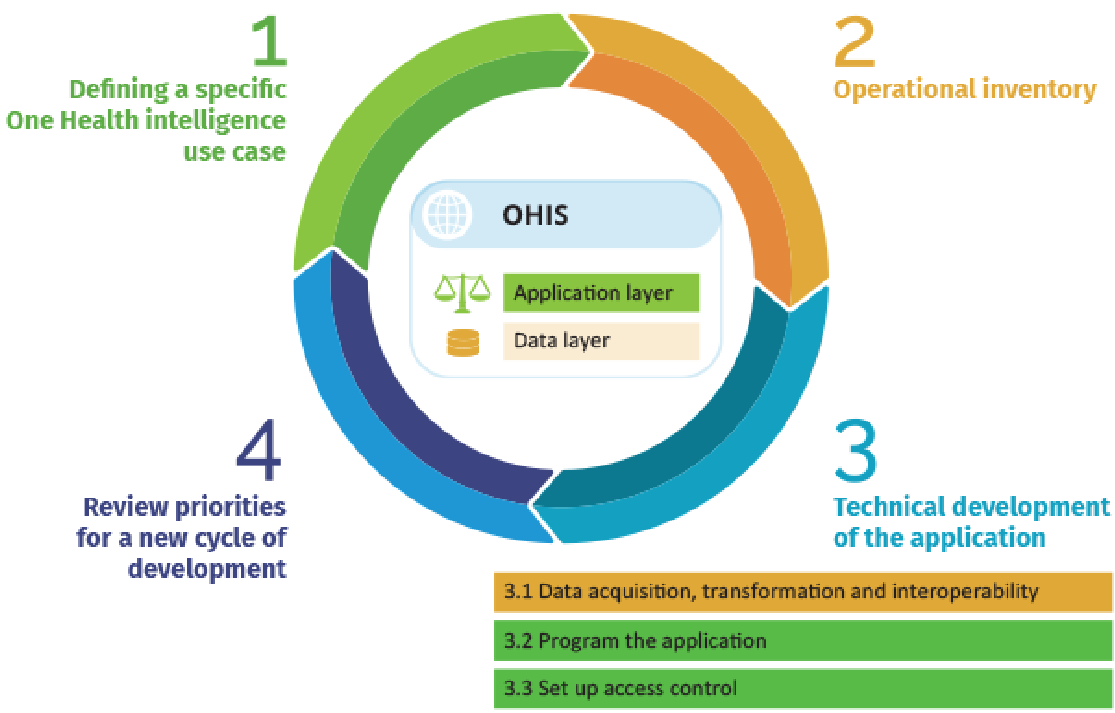
Based on the results of the Quadripartite assessment, it is suggested that use cases are defined from the current One Health intelligence activities in the Quadripartite in the first instance, using this as an opportunity to also strengthen and expand the collaboration around these activities, and to identify similar activities that could be aligned to avoid duplication. A use case is a description of the ways in which a typical user interacts with a system or product. This may include establishing success scenarios, failure scenarios and any critical variations or exceptions.

As more use cases/activities are brought into the operational One Health intelligence work supported by the global OHIS, existing applications can be expanded or new applications can be designed, starting a new cycle of development. More data sources and functions can be added to the framework on demand. In time, the need for new One Health intelligence activities will also be identified, allowing synergistic growth between the technical framework and Quadripartite's operational One Health intelligence priorities.

A: Blueprint for stepwise application development

A standardized four-step process for application development within the global OHIS (Figure 8) is proposed. This **needs-driven approach** is repeated every time an application is designed and developed.

Figure 8: Iterative cycles of development of the global OHIS based on operational One Health intelligence use cases



Source: Authors' own elaboration.

Step 1: Defining a specific One Health intelligence use case

To move from the OHISS foundation work towards system development, the first and most fundamental step is defining a set of initial system goals i.e. how will the system be used, by whom and what do these users expect to get from the system. This should relate to the risk questions that need to be answered by users, and can be informed by the identification and analysis of One Health hazards. Specifying these goals through the documentation of "user requirements" is an essential step in software engineering, hence the development of specific use cases is recommended. Existing One Health intelligence activities within the Quadripartite organizations could be prioritized as the first use cases, as is suggested below in section B.[13]

Use cases will allow the user requirements to be defined for a single application within the global OHIS. Owing to the modular approach proposed, development can be carried out one application at a time, and complexity and functionality can be added to the system progressively rather than requiring a long lead in time until the system can be functional. This will also make system development more realistic, reduce project risks and align better with current project funding mechanisms for the Quadripartite organizations, which can lead to considerable ebb and flow of resources and are often tied to a specific objective or project.

Here, application refers to one single function expected from the system. For example, this could be a data visualization application, combining data on events or risk indicators relevant to a single hazard in space, time, or both. Another example could be an **aberration detection application** for early warning, in which data about specific events or risk indicators are transformed into a time series and monitored continuously to generate alerts of unexpected trends or increases. Complex applications, requiring more complex analyses, more challenging data integration operations, or more intricate structures of interaction between human insight and information generation from data can also be developed, such as **risk maps** or **risk analysis platforms**. It is worth noting that not all applications need to be data or computationally intensive, some can simply serve to support communication within expert networks or have a rapid alert, repository or networking function. Another consideration for applications is building on opportunities for joint development that could feed into joint work programmes or inform policy/project implementation; for example, analyses using CITES or IUCN Redlist data may feed back into the work of partner organizations on conservation planning or prioritizing where to target health/sanitary measures in relation to wildlife trade.

Step 2: Operational inventory within the Quadripartite

The number of One Health-relevant activities within the Quadripartite organizations provide a great foundation on which to develop applications for the global OHIS. The scoping study showed that there is a high risk of considerable overlap and duplication among some activities, and that data are often collected, functionalities siloed and not made available for

[13] Some exploratory discussions and work around use cases has been initiated under the OHISS, to begin exploring available data and the opportunities and challenges in combining data. These include looking at existing One Health activities (such as the Joint FAO/WHO/WOAH Global Early Warning System for health threats and emerging risks at the human–animal–ecosystems interface [GLEWS+]), as well as other One Health hazards (e.g. Nipah virus, water scarcity and land-use change due to agricultural expansion).

reuse. For every new use case identified for the global OHIS, an in-depth inventory of existing activities within the Quadripartite organizations is recommended, focusing specifically on their linkages to the use case. This process is an opportunity to bring together the relevant users, data and platforms.

Step 3: Technical development of the application

Step 3.1 Data acquisition, transformation and interoperability

Development should begin by making use of the existing data, information and intelligence already available to the Quadripartite. Data availability is not the same as data accessibility. Making data accessible within the global OHIS will require a dedicated and complex effort of data connection, transfer and integration – including resolving both data governance and technical challenges of integration. Data connectors can be set up to link to data already available to the Quadripartite organizations, which can contribute to the chosen application.

To inform the technical work to establish data connectors for the data sources identified as being relevant for the application, a technical assessment will need to consider the details below, as a minimum. If the details are not well documented in the metadata, this limitation will need to be addressed.

- Data reporting and recording workflow and timelines, including an assessment of data gaps.
- Context and supporting data. For disease events, these are often called "epidemiological context" and include, for example, target population and population coverage, geographical granularity, and timeliness of the data. Context for environmental data may include details such as geographical coverage, resolution, timescales, frequency of update or species/ecosystems covered.
- Data dictionaries, data formats and any coding systems used. Where consensus annotation schema are not already available, those should be developed, as efforts to promote data interoperability globally need the support of leading international organizations. This will be a continuing effort, progressively addressing data complexity as the system grows.
- Technical specification of how data would be connected to the global OHIS, including format of current data storage, options for data connection and transfer.
- Governance information including who has access to the data currently, feasibility of permission to connect data to the global OHIS, which applications and which users would be permitted to access the data.

Prioritization is critical at the data layer. Consideration is required of which datasets add more value to the system, considering both the benefits (how many applications they could support, how they relate to risk identification and management activities, how valuable the data and insights are for decision-making) and the costs (how difficult or feasible data transfer and integration is, how much effort would be required to maintain data pipelines). A focus on minimum information tables (the minimum amount of information needed for an application to deliver meaningful results) is required to make quick gains in the first instance and to avoid wasteful duplication of effort. This simplicity will also contribute to building integration and interoperability among additional datasets as they are brought into the system. A curated and actively maintained minimum dataset, annotated according to consensus schema, will support the ad hoc development of applications during emergencies.

Step 3.2 Program the application

Having data in the system does not provide any decision-advantage to stakeholders until it is set out how these will be used and how the application outputs can be actively connected with the decisions to be made. By specifying the decision points where intelligence will be needed, it is then possible to identify the sources of evidence needed and a suitable analytical approach. This will in turn determine what analyses are needed to transform data into information, and how and in which format this information should be combined and presented to the system user to make it digestible and actionable. This may be an iterative process with Step 3.1, as a clearer definition of how data can be used, and the analytical approach will help refine exactly which data to integrate.

Beyond data integration and harmonization, there are a number of challenges to consider when it comes to using data to inform analyses or applications: accounting for differences in granularity, time periods and geographic areas covered by different datasets; different spatial resolutions; different methods and definitions used, etc. For instance, global datasets tend to have lower resolutions and include less detail than national datasets; some types of data may be updated frequently, while other types of data in the application may be updated only every few years.

In this step, the application is programmed to attend to all the user requirements identified, from the analytical approach to functionalities such as multi-device support or the expected frequency of data updates.

Step 3.3 Set up access control

In the technical details provided in Annex I, a separation between the data layer and the application layer is suggested to allow access control to be defined both at the application level and the data level. The user requirements should specify all system users, their role and access permissions.

Step 4: Review priorities for a new cycle of development

Having one prioritized application initially will allow development of all components of the modular system architecture proposed. In a first step, these components are set up with the minimum complexity needed to deliver the pilot application.

For the application development a "bootstrapping" approach is suggested if possible. This is a set of software templates that provide a basis for groups of applications, e.g. customized dashboards. The template then provides a starting point with a default stylesheet, navigation, templated data visualizations and data connectors. This would mean that development of other applications of the same type does not need to start from scratch and there is already a process in place. This will allow building of a harmonized look and feel for the global OHIS user interfaces, allowing users to interact confidently with the system without having to learn how to use each application from scratch. This will contribute to the system achieving a high usability and sustainability.

As more and more applications are added to the system, more complexity is added as needed. More components can also be added, such as those that enable communication with external systems or support sustainability of data pipelines. Access is restricted in the first instance for simplicity; however, in the longer-term, wider (if not open) access should be supported whenever possible. As more applications are developed, the data layer components are expanded to serve the new functionality needed. Eventually, public APIs and data sharing options are brought into the system to endorse collaboration with third-party initiatives or other systems, such as those led by the Pandemic Hub, Members Nations or external collaborators.

This approach will provide a strong system foundation, as core building blocks can easily be added, which provide immediate operational gains but are not too complex to maintain. Minimizing system maintenance demands and maximizing user engagement will enable long-term usability and sustainability.

B: Road map for implementation

A road map for achieving the global OHIS could start with the Joint FAO/WHO/WOAH Global Early Warning System (GLEWS+) as a pilot application (see Box 1). GLEWS+ is a collaborative activity involving three of the four Quadripartite organizations. It contributes to One Health intelligence with the specific objective of exchanging intersectoral early warning and situation awareness information. The main technical application used is a platform for alert message exchange and documentation of validated signals. To date, GLEWS+ has not included UNEP, but further development within the OHIS framework could bring in UNEP, adding the ecosystem health perspective for additional sensitivity and reliability. Any further development of a GLEWS+ application within the global OHIS would need be guided by the GLEWS+ team. Taking this approach would allow the technical development to be facilitated by an existing structure of users and already-defined operational details, thereby ensuring high relevance and usability. Bringing UNEP into a network that is already in use to share information about health threats and emerging risks at the human–animal–plant-ecosystems interface will also provide an immediate use case for the integration of information on environmental dimensions into delivering enhanced operational One Health intelligence.

Many other Quadripartite information systems were identified during the OHISS. In a next step, they could be subjected to a prioritization exercise to select the next use cases for development of the global OHIS. For example, WHO's Epidemic Intelligence from Open Sources (EIOS) could become a use case, and would bring in Quadripartite expertise, expanding epidemic intelligence using an intersectoral One Health approach.

Prioritization could also develop use cases focusing on target hazards, not only information systems. Initial target hazards might include:

- Disease/hazard-specific tools for risk monitoring, forecasting and decision support: The Rift Valley Fever Decision Support Tool, developed by FAO, builds capacity for early warning and forecasting at the country level. The tool could serve as an example to guide the development of similar tools focusing on other vector-borne diseases, such as Zika virus or Nipah virus. The tool is also being used as an example to develop decision support for avian influenza prevention and control. The Quadripartite collaboration would widen the data available to feed analytical models, as well as contributing expertise from the different health sectors – animal health, public health and environmental health. In the future, all the data processed, cleaned and integrated into tools such as these, along with the programmed modules, could be made available for other applications (respecting any access restrictions).
- Antimicrobial resistance: WOAH reported an initiative to keep track of antimicrobial use, which is already also being supported by FAO and WHO. These organizations all conduct activities monitoring antimicrobial use and resistance. This expertise could be connected and further amplified by including UNEP expertise and environmental monitoring activities.
- Environmental health: Environmental health hazards, such as air pollution, water scarcity, environmental degradation and land use change, pose direct and indirect risks for the emergence and spread of health hazards in plants, animals and humans. A use case could support mapping the risk landscape and establishing critical monitoring points for such health hazards, with direct inclusion of information from the environmental health monitoring activities of UNEP and its partners.

A prioritization of Quadripartite activities as use cases for the global OHIS should be performed, balancing the cost of development (resources needed to transfer and integrate data, and to program and maintain the application) against the expected benefit to global operational One Health intelligence. Development will be facilitated by starting from use cases that lead to simple applications, and progressively increasing complexity to tools that require more challenging data integration and more complex analyses. Applications that would benefit a large number of users and activities, or whose function is considered a priority for advancing operational One Health intelligence, should be prioritized for their value to the Quadripartite organizations and their members.

As more and more of the current Quadripartite activities start operating under the global OHIS framework, or their current frameworks are linked to the global OHIS, gaps in operational One Health intelligence (objectives and decision needs not yet fulfilled) will become evident. At this point, new information workflows can be designed directly under the global OHIS umbrella.

Box 1: Proposed pilot use case: The Joint FAO/WHO/WOAH Global Early Warning System for health threats and emerging risks at the human–animal–ecosystems interface (GLEWS+)

Background: GLEWS+ provides a use case that is already collaborative across three of the Quadripartite organizations. Involving UNEP would foster understanding of how ecosystem health can be included in its early warning and intelligence for better global health.

User requirements: While already strong in its One Health intelligence role, using GLEWS+ as a pilot would allow development to begin with an application that has simple requirements. No databases would need to be integrated, as the focal points only need to have access to their own data, from which they collaboratively exchange warnings as well as relevant epidemiological/contextual information.

Application: Initially, reflecting the current functionality, the application can be a message board where focal points can enter alerts that are then delivered in a timely manner to the right people within the collaborating agencies. All users can respond and communicate about the alert, and past alerts and messages are documented. Further development still based on this use case is then possible by improving the communication platform to also support the transfer of epidemiological/contextual data, under specific access rules.

Access control: GLEWS+ would be simple in its requirement, as application “owners” and “users” are identical. Unlike many data analysis tools (which are developed within the organizations to serve external stakeholders), the design of a GLEWS+ functionality within the global OHIS would be informed by Quadripartite representatives that are direct users of the application and can be guided by established operational processes.

Benefits: Following the proposed approach, the system would first be built to support the current GLEWS+ network and, in time, the intelligence work performed itself would be improved. New operational requirements from the GLEWS+ team can be added to the system, reflecting, for instance, their perception of how risk landscape data could be added to the global OHIS to support even earlier signal detection. At the same time, data and functionalities added to the global OHIS by other use cases could enable the GLEWS+ team to expand their browsing, analyses and/or sharing of epidemiological data.

C: Guiding considerations for system set-up

The cycles of development detailed above need to happen within an overarching framework that includes system hosting and maintenance. The following system elements need to be discussed by the Quadripartite organizations and put in place to create the governance and operational structure within which new development cycles can be conducted:

Hosting

Hosting arrangements typically include:

- Cloud hosting – could be provided by Amazon Web Services, Microsoft Azure, Google Cloud Platform or similar providers. The Quadripartite organization's cloud hosting policies need to be taken into consideration. Sustainability criteria of participating organizations should be taken into account when selecting providers, e.g. to avoid long-term vendor lock-in. Further alternatives need to be made available for countries with strong preferences in their cloud hosting, e.g. those who may prefer local data centres.
- Service level agreements (SLAs) – to be confirmed with information technology (IT) partner. This guarantees support services dependent on the severity level of the issue raised (e.g. low, medium, severe) and would include system monitoring, backups and recovery, redundancy, patching or system upgrades.

Potentially, existing hosting arrangements by Quadripartite organizations can be used or specific systems components can be hosted in a distributed model. For example, some of the apps can be hosted by Quadripartite organizations, others externally, or the data layer can be hosted separately to the application layer. Detailed specifications can be decided based on Quadripartite organization preferences.

Maintenance

Having a common operational OHIS across the four Quadripartite organizations has many advantages, including, for instance, focusing funds on a common resource, rather than diluting efforts into multiple overlapping and siloed systems. System development starts from the vantage point of the existing intelligence-supporting activities within the four organizations, and the value generated by the system becomes amplified within the network. It also means that internal and external resources can be channelled into a single initiative that is not subject to the same funding gaps that so often cause innovative initiatives to perish in time. This requires establishment of a joint global OHIS funding/resourcing model.

Building the global OHIS on the foundation of existing activities ensures that no unnecessary costs are added through duplication of efforts. Engagement of stakeholders is sustained by the value added to data delivered to the system and the ability to reuse applications. In turn, this engagement strengthens the system in a positive feedback loop.

All the above points promote the sustainability of the global OHIS once developed, but the costs of ongoing management, maintenance and user support must be acknowledged and planned for. The system will demand human and technical resources to keep the data connectors and the system itself up-to-date, e.g. as data evolves or system updates become available. This, plus the administrative maintenance and running overheads, which include administrative hosting, communication and dissemination, will result in ongoing costs. A plan for system maintenance should therefore be established, including a regular maintenance plan and a road map for ongoing updates and upgrades.

Governance

The governance of all intelligence-supporting activities within the Quadripartite organizations and their partners, as well as of the data generated by these activities, must be preserved. Within the global OHIS there will be a need to discuss access at the Quadripartite and the global level for applications in which data are integrated. Some general governance rules need to be set in place for the global OHIS. As access can be negotiated at the application and even the data level, there needs to be a general set of rules governing how these decisions are to be made for every application. The agreed set of governance rules should be documented. The handbook from the WOAH-supported Global Burden of Animal Diseases (2020) initiative is a useful example of such a practice.

A monitoring and evaluation system should be set up to report on strengths and weaknesses of the system and/or its applications. This can then be used to guide ongoing improvements and for funding purposes. In addition, systematic and regular system evaluations, including user acceptability surveys should be conducted.

Systematic incorporation of stakeholder needs

The proposed architecture was motivated by making the system “future-resilient”, that is, able to adapt, recover quickly from challenges and evolve with new knowledge and new technology.

The needs of the Quadripartite organizations and other stakeholders are also constantly changing and must adapt to new challenges and opportunities. There is pressure on all organizations to deliver One Health outcomes and support pandemic preparedness and early warning, in addition to their business-as-usual activities. The modular approach proposed makes the system dynamically adaptable and supports user-centricity. New functionality can be added in the application layer and new types of data can be integrated into the system as they become available.

For the system to respond to new needs, **a systematic process of identifying and prioritizing needs must be put in place**; this could include regular focus groups, user or member surveys, expert consultations or other mechanisms. Needs should be converted into operational priorities for the system's continuing development and improvement, and a set of overarching strategic objectives.

The following key elements of the framework must be proactively identified and addressed.

System custodianship and funding: The modular framework proposed will allow many of the framework administration and technical details to be managed at an application level, distributing the responsibilities and "overhead" costs among the Quadripartite organizations. No single operational structure is imposed for the entire framework, and the different needs and constraints from each organization can be investigated and accommodated per application. The overall technical infrastructure needs clear governance arrangements and a funding and maintenance model.

In considering hosting and maintenance, any specific criteria and restrictions for web service imposed by the Quadripartite organizations to providers need to be defined, so that a cloud hosting provider can be chosen. As SLA will also have to be established between the provider and the Quadripartite organizations or their delegate. An SLA guarantees support services dependent on the severity level of the issue raised (e.g. low, medium, severe), and would include system monitoring, backups and recovery, redundancy, patching or system upgrades.

Steering board and technical/external advisory group: Each OHIS application would have its own focal points within the organizations, who can serve as a management group for the application, deciding on the users and their level of access, desired functions, evaluation and capacity building. The focal points should be associated with specific roles within the organizations, not specific individuals, to ensure system sustainability. At the overall framework level, a global OHIS steering committee should be defined. The steering committee will need to ensure that the respective organizations commit to sharing the data, expertise and other resources that will be required to deliver a global OHIS, including organizational policies. The global OHIS steering committee will also need to agree on priorities and investments. Therefore, the committee composition should both consider the administrative decisions needed at the Quadripartite organizations level and include a technical team of One Health intelligence specialists. This team will be responsible for overseeing the long-term system development, maintenance, evaluation and mechanisms to regularly capture and prioritize the needs of the organizations and their members.

List of prioritized applications: The OHISS identified One Health activities currently conducted by the Quadripartite organizations that can serve as the foundation for the framework. GLEWS+ was specifically suggested as a pilot application. It is critical to establish a list of prioritized applications so that development can continue. Use cases for more complex data integration, analyses and visualization tasks should be encouraged, allowing development of modules with high potential of reusability and high added value to the framework. In time, a systematic process to identify gaps in operational One Health intelligence and design new activities should be established.

The development model suggested would also allow the global OHIS to become an umbrella platform to host reusable applications. In that sense, individual Quadripartite organizations could also take the initiative of developing modules of the OHIS that are a priority for them, but not for other or all Quadripartite partners. The steering committee could judge whether the umbrella framework can support development and host the modules, in exchange for the value they add to the overall framework.

Inventory of data and mechanisms to share and connect existing data platforms: It is recommended that data are brought to the OHIS on demand, and are not held in the system, as required by applications, and are based on minimum information tables so that these data can be annotated to ensure FAIR-ness and reusability. However, some general data integration mechanisms can be investigated, in parallel to the development of applications, as part of the overall framework development. Some priority datasets and data elements for a consensus annotation schema should be identified. Data storage over time (maintenance) is an important element of system sustainability. Commitment to data availability is an important dimension of the data sharing discussion.

Robust integration of environmental considerations and data: To date, the integration of environmental, including biodiversity and ecosystem service considerations, within One Health intelligence has been limited. The OHISS identified key ecosystem and environmental hazards relevant to One Health, considered available data and information systems, and undertook initial exploration of how environmental factors and information could be combined into One Health use cases. Some examples of the potential value offered by better integration of environmental, ecosystem or contextual information include the use of information, such as the Biodiversity Intactness Index, IUCN Redlist species ranges, or climate change projections, to inform future projections of likely disease outbreaks or declines in nutrition/food security at national or subnational level in order to proactively identify and monitor locations of risk and plan for mitigation measures (Carlson *et al.*, 2022); and the opportunity to explore combinations of air quality data (near real time) and water availability data with other environmental and health datasets. The value of integrating UNEP and environmental sector information and users in existing tools and applications such as GLEWS+ has been discussed, and this would also apply to strengthening health-related analyses and linkages within UNEP platforms, such as the World Environment Situation Room, and the UN Biodiversity Lab. Further technical work is needed to ensure that environmental opportunities are integrated in a robust and targeted manner. The refinement of existing One Health intelligence activities and the collaborative development of new applications within the OHIS should also allow for sufficient background research and development of appropriate workflows to ensure robust and comprehensive integration between human, animal, plant and ecosystem health intelligence.

Risk and change register: These cover identification of corporate risks for the approaches taken and are typically documented in a risk management log, covering risk status, impact, probability of occurrence, impacts, response strategy and contingency plan.

General risks include:

- clearances required from certain organizations for products developed as part of the OHIS;
- technologies becoming obsolete;
- access to data becoming restricted due to confidentiality, security or other concerns;
- disincentives/incentives for contributing information/reporting on One Health concerns; and
- unclear roles and responsibilities and lack of engagement and resources (at the institutional or individual level).

Risks should be assessed at the start of the project and re-assessed on an ongoing basis to detect risks as early as possible and to put in place strategies for unexpected events. Changes should be managed and documented in a change management log, covering status, priority, owner, expected resolution or action steps of any changes identified.

Security in data sharing may be problematic. The Quadripartite organizations will need to support OHIS security, and the steering committee should have a mechanism to respond to any data breach emergencies. Note that the development model proposed, which starts from simple data and simple applications, and includes increasing complexity over time, will allow such issues to evolve organically within the steering *modus operandi*.

Global need for collaboration: The global OHIS presented in this document is designed as an ecosystem of linked data and applications, supporting various models of connectivity. The opportunity and importance of ensuring connectivity between the global OHIS and other health intelligence systems is highlighted. The global OHIS will process data and information from a broad range of knowledge areas that support the early identification and management of emerging health threats. External initiatives should be able to:

i. Consume data integrated and cleaned within the framework, respecting data governance rules for each source.

ii. Use the applications (functionalities) made available. When governance allows, these applications will be made available in open source formats, so that other initiatives can reuse or even improve them (suggest improvements in the code).

iii. Contribute to the collective knowledge used in the system to improve integration and analysis of data in the multidisciplinary One Health context.

Conclusions

The intelligence activities and systems already available in the Quadripartite organizations provide a foundational structure of data and activities on which the complex demands of One Health intelligence can successfully and sustainably build. The global OHIS is not to be built as a silo of data and function, but as a flexible umbrella framework to connect and add value to existing intelligence and make it available within an environment of connectable and evolving applications.

Data-fed, needs-driven system with agile and sustainable development

In the proposed global OHIS framework, the linked-data model is used to preserve data context (meaning) and maximize interoperability among data within the distributed environment of the Quadripartite organizations. Data cleaning, annotation and integration add value to the data. This added value is then propagated and amplified as more and more applications can reuse these data (respecting the original data access rules).

Applications to analyse data and produce outputs that support decision-making are added to OHIS in a modular architecture, which ensures that the system development can start simple, and adapt quickly to growing demands for complexity and the evolving needs of the organizations. Agile cycles of development are proposed based on one application at a time.

A focus on operational One Health intelligence

The focus on applications, informed directly by the decision-making needs of the system end users, ensures that the OHIS is designed to support the daily, operational needs of One Health. These include demands from the Quadripartite agencies at the global level, but also support to Member Nations and their national capacity to produce One Health or sector-specific intelligence.

The global OHIS is powered by the intelligence-supporting activities already available in the Quadripartite organizations and their partnerships. With the added value brought by UNEP, FAO and other partners in terms of environmental and contextual data and expertise, in the areas of forestry, ecosystem services, pollution, etc., applications supported by the OHIS can go beyond infectious/zoonotic diseases, and can also focus on other One Health hazards, such as vulnerabilities and early drivers of disease emergence. This will improve global capacity to detect and respond to emerging threats early.

The global OHIS is purposefully designed as a network of interconnected modules to accommodate the complexity and diversity of the Quadripartite organizations' operating environments. Applications can be as simple as the generation of descriptive reports, or as complex as predictive models with automated alert functions.

Support to One Health intelligence at the national level

Applications within the OHIS can directly support countries as potential end users of the system. The adoption of open source applications will enable countries to reuse and adapt OHIS applications within their own OHIS. Alternatively confidential country-specific access can be provided through the systems' access layer, similar to the UN Biodiversity Lab Workspaces,[14] which provides countries and stakeholders with a secure area, common data repository and collaborative work environment for decision-making, monitoring and reporting. Applications from the global OHIS that directly meet the needs of Member Nations will also incentivize their continued efforts to collect and feed the system with accurate data and information in order to better understand their data and compare them with data from other countries, or consider them from a global perspective. Success of the OHIS at the global level depends on functioning One Health systems at the national and regional levels. Members should be supported to establish their own One Health systems and One Health intelligence services.

The global OHIS is developed to support and enhance, not duplicate other Quadripartite organization initiatives

The proposed framework supports various models of connectivity to these existing initiatives. We suggest a review of existing Quadripartite organization initiatives to identify which could be supported, linked or even transferred to the global OHIS. Frameworks such as the joint Global Early Warning System (GLEWS+), for instance, can operate as a dedicated application within the Quadripartite organizations' operational intelligence.

Integrating existing initiatives under one umbrella would **unify diverse individual activities**, so that an integrated sample of insights can be presented to decision-makers. It would further ensure that funding for maintenance is channelled to one structure and support cost-efficient development and maintenance.

It is not proposed that the OHIS serves as one central silo where all initiatives are concentrated**.** The global OHIS should be built as an ecosystem of linked data and applications, which can amplify and support a variety of diverse activities.

The global OHIS needs to operate in the context of an accelerated environment of One Health intelligence, and to find its niche next to other key Quadripartite organization initiatives, such as the WHO (2021) Hub for Pandemic and Epidemic Intelligence (Pandemic Hub), which also supports the linked-data model. The OHIS flexible framework is designed for collaboration and linking with other activities. The global OHIS aligns with the requirement for tools that can be cross- and down-scaled identified in the recent Pandemic Hub Forum (Morgan, *et al.*, 2022b).

[14] More information available at https://unbiodiversitylab.org/unbl-workspaces.

This similarly applies to collaboration with the One Health High-Level Expert Panel to ensure the academic standards set by the Panel are operationalized in the OHIS framework.

The global OHIS enables collaboration and connectivity outside the Quadripartite organizations

In the framework proposed, several formats of connectivity and collaboration are enabled. External initiatives can:

- Reuse/link data, which can be provided in the global OHIS as public, open data when data governance allows. This will maximize the value of the data cleaned and integrated within the framework.
- Develop additional applications empowered by the system data. This will allow the OHIS to develop alongside the global growth and evolution of One Health knowledge.
- Reuse applications developed within the global OHIS in open source formats (when this is possible) and even improve them.
- Contribute to collective knowledge needed to preserve data contexts, while allowing interoperability in the multidisciplinary One Health context.

The modular approach proposed enables the application layer to dynamically evolve alongside advances in analytics for intelligence. This includes advances in areas such as genomic surveillance (Timme *et al.*, 2020; WHO, 2022c) or machine learning (Ho, 2022). Knowledge models used in the data layer (ontologies) can evolve to incorporate new knowledge.

As the operational implementation of One Health intelligence progresses, the system's performance should be evaluated.

A unique opportunity to improve global One Health

The OHISS proposed a framework for operational One Health intelligence, building on the foundation of the Quadripartite organizations. The framework is flexible to attend to the needs of the complex web of stakeholders involved, while recognizing the operational barriers that this complexity imposes to system implementation. Not all these barriers can be addressed with the technical architecture alone, but their resolution is imperative to the success of its implementation. The OHIS provides the Quadripartite organizations with a unique opportunity to develop joint operational One Health intelligence, allowing rapid progress towards each organization's One Health goals in the short term and a shared framework to support global health into the future. The global OHIS supports the draft *Quadripartite One Health Joint Plan of Action* (One Health Quadripartite, 2022), specifically in the delivery of the Pathway 3: Data, evidence and knowledge, which will have a cross-cutting impact across all areas.

References

Aguirre, A.A., Gore, M.L., Kammer-Kerwick, M., Curtin, K.M., Heyns, A., Preiser, W. & Shelley, L.I. 2021. Opportunities for transdisciplinary science to mitigate biosecurity risks from the intersectionality of illegal wildlife trade with emerging zoonotic pathogens. *Frontiers in Ecology and Evolution*, 9: 7.

Batra, N., Spina, A., Blomquist, P., Campbell, F., Laurenson-Schafer, H., Florence, I., Fischer, N. *et al*. 2021. *The Epidemiologist R Handbook*.

Bordier, M., Delavenne, C., Nguyen, D.T.T., Goutard, F.L. & Hendrikx, P. 2019. One Health surveillance: A matrix to evaluate multisectoral collaboration. *Frontiers in Veterinary Science*, 6: 109.

Braks, M., Giglio, G., Tomassone, L., Sprong, H. & Leslie, T. 2019. Making vector-borne disease surveillance work: New opportunities from the SDG perspectives. *Frontiers in Veterinary Science*, 6: 232.

Carlson, C.J., Albery, G.F., Merow, C., Trisos, C.H., Zipfel, C.M., Eskew, E.A., Olival, K.J., Ross, N. & Bansal, S. 2022. Climate change increases cross-species viral transmission risk. *Nature*, 607(7919): 555–562.

Data.org. No date. Epiverse: Distributed Pandemic Tools Program. Cited 8 December 2022. https://data.org/initiatives/epiverse/

Dente, M.G., Riccardo, F., Bolici, F., Colella, N.A., Jovanovic, V., Drakulovic, M., Vasic, M. *et al*. 2019. Implementation of the One Health approach to fight arbovirus infections in the Mediterranean and Black Sea Region: Assessing integrated surveillance in Serbia, Tunisia and Georgia. *Zoonoses and Public Health*, 66(3): 276–287.

Dinesh, A.S., Mathur, V., Ansil, B.R., Chandru, V., Chellam, R., Vanak, A.T., Ramakrishnan, U. & Rajagopal, P. 2020. Health heatmap of India: An open data platform. *Journal of the Indian Institute of Science*, 100: 701–716.

European Centre for Disease Prevention and Control. 2022. epitweetr, R package, Version 2.0.3 2022. Cited 8 December 2022. www.ecdc.europa.eu/en/publications-data/epitweetr-tool

Fasina, F.O., Fasanmi, O.G., Makonnen, Y.J., Bebay, C., Bett, B. & Roesel, K. 2021. The One Health landscape in sub-Saharan African countries. *One Health*, 13: 100325.

Food and Agriculture Organization of the United Nations. 2020. *Fall Armyworm Monitoring and Early Warning System (FAMEWS)*. Guidance note 10. Rome, Food and Agriculture Organization of the United Nations.

Food and Agriculture Organization of the United Nations. 2021. Hand-In-Hand Geospatial Platform. Cited 8 December 2022. www.fao.org/hih-geospatial-platform/en/

Food and Agriculture Organization of the United Nations. 2022a. Locust Hub. Cited 8 December 2022. https://locust-hub-hqfao.hub.arcgis.com/

Food and Agriculture Organization of the United Nations. 2022b. EMPRES-i, Global Animals Disease Information System. Cited 8 December 2022. https://empres-i.apps.fao.org/

Food and Agriculture Organization of the United Nations. 2022c. FAMEWS global platform, Global Action for Fall Armyworm Control*.* Cited 8 December 2022. www.fao.org/fall-armyworm/monitoring-tools/famews-global-platform/en/

Force 11. 2016. The FAIR Data Principles. Cited 8 December 2022. https://force11.org/info/the-fair-data-principles/

George, J., Häsler, B., Mremi, I., Sindato, C., Mboera, L., Rweyemamu, M. & Mlangwa, J. 2020. A systematic review on integration mechanisms in human and animal health surveillance systems with a view to addressing global health security threats. *One Health Outlook*, 2: 11.

Global Burden of Animal Diseases. 2020. *Data Governance Handbook for GBADs*.

Hattendorf, J., Bardosh, K.L. & Zinsstag, J. 2017. One Health and its practical implications for surveillance of endemic zoonotic diseases in resource limited settings. *Acta Tropica*, 165: 268–273.

Ho, C.W.-L. 2022. Operationalizing "One Health" as "One Digital Health" through a global framework that emphasizes fair and equitable sharing of benefits from the use of artificial intelligence and related digital technologies*. Frontiers in Public Health*, 10: 768977.

International Plant Protection Convention. 2022a. *Official pest report.*

International Plant Protection Convention. 2022b. *Recommendations for an Effective Pest Outbreak Alert and Response System.* Rome, Food and Agriculture Organization of the United Nations on behalf of the Secretariat of the International Plant Protection Convention.

International Union for Conservation of Nature. 2022. IUCN Open Project Portal. Cited 8 December 2022. https://open.iucn.org/

Jourdain, F., Samy, A.M., Hamidi, A., Bouattour, A., Alten, B., Faraj, C., Roiz, D. *et al*. 2019. Towards harmonisation of entomological surveillance in the Mediterranean area. *PLOS Neglected Tropical Diseases*, 13(6): 28.

One Health High-Level Expert Panel. 2021. *One Health High-Level Expert Panel Annual Report 2021*. Food and Agriculture Organization of the United Nations, World Organisation for Animal Health, United Nations Environment Programme and World Health Organization.

Meurens, F., Dunoyer, C., Fourichon, C., Gerdts, V., Haddad, N., Kortekaas, J., Lewandowska, M. *et al*. 2021. Animal board invited review: Risks of zoonotic disease emergence at the interface of wildlife and livestock systems. *Animal*, 15(6): 100241.

Morgan, O.W., Abdelmalik, P., Perez-Gutierrez, E., Socé Fall, I., Kato, M., Hamblion, E., Matsui, T. *et al*. 2022a. How better pandemic and epidemic intelligence will prepare the world for future threats. *Nature Medicine*, 28: 1526–1528.

Morgan, O., Redies, I., Leiva Rioja, Z.B., Brownstein, J., George, D., Golding, J., Hanefield, J. *et al*. 2022b. Innovations in public health surveillance: Updates from a forum convened by the WHO Hub for Pandemic and Epidemic Intelligence, 2 and 3 February 2022. *Eurosurveillance*, 27(15): 2200302.

Morse, S.S. 2014. Public health disease surveillance networks. *Microbiology Spectrum*, 2(1).

Oberin, M., Badger, S., Faverjon, C., Cameron, A. & Bannister-Tyrrell, M. 2022. Electronic information systems for One Health surveillance of antimicrobial resistance: A systematic scoping review. *BMJ Global Health*, 7(1).

One Health Quadripartite. 2022. *Draft One Health Joint Plan of Action (2022–2026)*. Food and Agriculture Organization of the United Nations, United Nations Environment Programme, World Health Organization and World Organisation for Animal Health.

Organisation for Economic Co-operation and Development. 2020. *Why open science is critical to combatting COVID-19*. Cited 27 May 2022. www.oecd.org/coronavirus/policy-responses/why-open-science-is-critical-to-combatting-covid-19-cd6ab2f9/

Preventing Zoonotic Diseases Emergence. 2022. PREZODE. Cited 8 December 2022. https://prezode.org/

Queenan, K., Häsler, B. & Rushton, J. 2016. A One Health approach to antimicrobial resistance surveillance: Is there a business case for it? *International Journal of Antimicrobial Agents*, 48(4): 422–427.

R Epidemics consortium. 2022. RECON. Cited 8 December 2022. www.repidemicsconsortium.org/

Saylors, K., Wolking, D.J., Hagan, E., Martinez, S., Francisco, L., Euren, J., Olson, S.H. *et al*. 2021. Socializing One Health: An innovative strategy to investigate social and behavioral risks of emerging viral threats. *One Health Outlook*, 3(1): 11.

Schurer, J.M, Mosites, E., Li, C., Meschke, S. & Rabinowitz, P. 2016. Community-based surveillance of zoonotic parasites in a 'One Health' world: A systematic review. *One Health*, 2: 166–174.

Stevenson, M., Halpin, K. & Heuer, C. 2021. Emerging and endemic zoonotic diseases: Surveillance and diagnostics. *Revue Scientifique et Technique*, 40(1): 119–129.

Subramanian, S.M. & Payyappallimana, U. 2020. Environment, biodiversity, and planetary health: Links between natural systems and human health. In R. Haring, I. Kickbusch, D. Ganten, & M. Moeti, eds. *Handbook of Global Health*, 1–14. Cham, Switzerland, Springer.

Thompson, P.N. & Etter, E. 2015. Epidemiological surveillance methods for vector-borne diseases. *Revue Scientifique et Technique*, 34(1): 235–247.

The R Foundation. 2021. A language and environment for statistical computing. Cited 8 December 2022. https://www.R-project.org/

Timme, R.E., Wolfgang, W.J., Balkey, M., Venkata, S.L.G., Randolph, R., Allard, M. & Strain, E. 2020. Optimizing open data to support one health: Best practices to ensure interoperability of genomic data from bacterial pathogens. *One Health Outlook*, 2(1): 20.

Uelze, L., Grützke, J., Borowiak, M., Hammerl, J.A., Juraschek, K., Deneke, C., Tausch, S.H. & Malorny, B. 2020. Typing methods based on whole genome sequencing data. *One Health Outlook*, 2: 3.

United Nations. No date. *The United Nations Secretary-General's Roadmap for Digital Cooperation: Promoting Digital Public Goods*.

United Nations. 2022. UN Biodiversity Lab. Cited 8 December 2022. https://unbiodiversitylab.org/

United Nations Educational Scientific and Cultural Organization. 2022. Open Science. Cited 8 December 2022. www.unesco.org/en/natural-sciences/open-science

United Nations Office for the Coordination of Humanitarian Affairs. 2022. The Humanitarian Data Exchange (HDX). Cited 8 December 2022. https://data.humdata.org/

Wahl, T.G., Burdakov, A.V., Oukharov, A.O. & Zhilokov, A.K. 2012. Electronic integrated disease surveillance system and pathogen asset control system. *Onderstepoort Journal of Veterinary Research*, 79(2): 455.

World Health Organization. 2021. *WHO Hub for Pandemic and Epidemic Intelligence. Better Data. Better Analytics. Better Decisions.*

World Health Organization. 2022a. WHO Coronavirus (COVID-19) Dashboard. Cited 8 December 2022. https://covid19.who.int/

World Health Organization. 2022b. Epidemic Intelligence from Open Sources (EIOS). Cited 8 December 2022. www.who.int/initiatives/eios

World Health Organization. 2022c. *Global genomic surveillance strategy for pathogens with pandemic and epidemic potential, 2022–2032*. Geneva, World Health Organization.

World Organisation for Animal Health. 2022. World Animal Health Information System (WAHIS). Cited 8 December 2022. https://wahis.woah.org/#/home

Zaitchik, B.F., Hayden, M.H., Villela, D.A., Lord, C.C., Kitron, U.D., Carvajal, J.J., Câmara, D.C. & dos Reis, I.C. 2016. Climate information for arbovirus risk monitoring: Opportunities and challenges. *Bulletin of the American Meteorological Society*, 97(5): ES107–ES111.

Zinsstag, J., Crump, L., Schelling, E., Hattendorf, J., Maidane, Y.O., Ali, K.O., Muhummed, A. *et al*. 2018. Climate change and One Health. *FEMS Microbiology Letters*, 365(11).

Annex I
Technical specification of the components proposed for an IT system to support Quadripartite One Health intelligence

Further details of the proposed modular architecture to build the global OHIS and meet the requirements laid out are shown in Figure A1. The following details of the system components are required.

System components

Data ingestion

The data ingestion component of the systems consists of a series of data connectors to external validated systems. Data connectors could connect to external APIs and pull data from other systems – the data transfer into the OHIS would pull data of interest into the system at defined intervals, e.g. new, modified or removed records would be transferred every x minutes/hours/days. Alternatively, the global OHIS could make an API available for other systems to push data to. Other data connectors could include flat file transfer (e.g. via file transfer protocol) or direct database connectors, e.g. to Oracle, Microsoft or open source databases. The type of connector to be used will depend on what is available or easiest to implement with a particular external data system.

A data connection is not a "one time" action. Once a data connector is established, it needs to be maintained and monitored. Technical and human resources are needed to keep the connection active.

Additional applications could be developed to allow manual data uploads, e.g. in the form of flat files for specific datasets.

Data storage system

Data retrieved from the data ingestion component would be stored in a data lake or data warehouse. Data lakes are data repositories that are capable of storing vast amounts of raw data (e.g. source system data, sensor, or social data) and can then be used for analytical purposes. More traditional data warehouses store data in structured or hierarchical formats, whereas data lakes follow a flat structure that usually stores data in object "blobs" or "files". This allows storage of raw data (coming from the **data ingestion** component) alongside processed data coming from the **data transformation** into the system to be used in the app layer for analytical purposes.

The type of data storage system to be used would be determined by the type of data and data volume expected, either a data lake architecture or a more hierarchical data warehousing system could be suitable, or a mixture of both.

The global OHIS should have its own primary data storage system but it is acknowledged that secondary linked-data storage systems will likely be required due to country-specific data requirements, i.e. if certain data is not allowed to be stored offshore. In this case, specific solutions to integrate those external data systems would need to be established.

Data transformation

When data are retrieved from multiple sources they typically need to be cleaned to be used in analytical tools, e.g. for report generation of data visualizations. This includes the removal or conversion of invalid records that are outside the expected range, clarification of whether values in certain fields represent zero or missing data (e.g. when NULL, empty, NA or 0 values are received), or validation and transformation of measuring units (e.g. lbs versus kg). Data cleaning and normalization activities are typically scripted based on rules. It is advisable to set up logging to monitor which records are processed, removed or converted.

Once individual datasets are cleaned and validated, they also need to be integrated if multiple sources of data are needed to provide specific analyses and visualization. There are two main types of interoperability that need to be addressed:

- Structural or **syntactic interoperability** refers to compatibility of data formats. Standardization of data types includes, for instance, the alignment of the format and use of date fields for things like "date of onset/occurrence of an event", "date of observation", reporting and format to display dates. For data types that can have a large number of categories, such as disease names, conditions, symptoms and species, harmonization among datasets is more challenging. When data standards are already used, syntactic interoperability can be addressed with data transformation based on **data dictionary** or **mapping tables**.
- **Semantic interoperability**, on the other hand, is concerned with ensuring the integrity and meaning of the data across systems. Semantic interoperability is particularly important in One Health in order to allow data reuse across sectors while preserving the original context of the data. The linked-data model will be adopted to maximize data usability and reusability.

The **linked-data model** is based on the use of semantic technologies to annotate data with all the necessary information to preserve its context and allow accessibility of the content and meaning by both humans and machines. Several terminology catalogues already exist in health and epidemiology. **Ontologies** can incorporate these existing resources and reuse their knowledge. In an ontology, a specific programming language (web ontology language – OWL) is used to incorporate the listing of concepts needed to read the data and explicitly map all "relationships" between concepts (semantics), creating a knowledge model for the specific context of data integration – One Health intelligence in this case. This knowledge model can incorporate relationships at various granularity levels, from data about specific individuals and locations, to high-level aggregated data at the population level. Ontologies are themselves interoperable, and several already-developed relevant ontologies can be incorporated into this layer of the system.

Semantic tools are an essential part of making data FAIR – findable, accessible, interoperable and reusable (Force 11, 2016). Explicitly modelling relationships between concepts allows interoperability to be adopted under different accessibility constraints and the different depths of interoperability needed. Datasets which already adopt specific terminologies/standards can be mapped to a common language, allowing **interoperability** within the system and **accessibility** of the datasets in various applications. Raw datasets which are not processed and normalized within the system can be tagged by adding semantic annotation to their metadata. Metadata is used here to refer to all the information about the dataset, as opposed to the data values themselves. Explicit annotation of metadata will allow applications to identify all datasets that may be relevant to specific questions (**findable** datasets). The ontology can also be used to annotate the specific governance rules for each dataset, making datasets **reusable**.

Private and public APIs

The individual applications would not directly access the data lake or warehouse. Data would be made available within the architecture through an internal API. This provides more flexibility to share data and manage permissions, either on an application or data level. Data access can be restricted to different applications; and even within an application, certain data could be made available only to specific users.

All APIs should be documented, so that application developers can see which data fields and functions are available. Certain APIs could also be made available to the public, so that other external systems or users can make use of the available data, for example.

APIs are typically built in the Representational State Transfer (REST) style. REST describes a set or architectural constraints for building and integrating application software, organizing information exchange between an information provider and information user. The information is transferred via Hypertext Transfer Protocol (HTTP), an application-layer protocol for transmitting hypermedia documents using a specific data format. For data exchange in web applications, the most common used format is JSON (JavaScript Object Notation). JSON is extensively used in web applications, with the benefit of storing data in text format that is also human-readable. JSON can also be used to semantically tag data, offering compliance to the linked-data model (JSON-LD) proposed above. REST APIs can also be used in conjunction with role-based access control to allow access to certain restricted data (e.g. the data owner can grant access).

Application layer

Functionalities and use cases are bundled in different applications. This modular structure enables more granular access control and flexibility to adopt and expand certain functionality. Dedicated applications could be made available, for example, to support data access through search and data export functionality, to carry out specific analytical tasks, or to provide dashboards and reports. Also, an administrative application should be made available to provide an interface to manage data transformation, data storage and data ingestion activities. This can also serve to provide access to the tools used for interoperability and data harmonization, such as terminologies, mapping tables or graphical representations of the ontology.

Applications can also be developed to allow non-IT personnel to manage data transformations in certain areas. Certain system functions should be made available to monitor the data transformation, storage and ingestion activities, e.g. to check on server performance, backups or the data processed.

Identity provider

Identity providers are a well-established method to grant single-sign-on access for users across multiple software applications. User credentials are stored at a central location and the identity provider organizes which applications a user can access and which permission level each user has within an application. There are two aspects an identity provider looks after – authentication and authorization. Authentication confirms that users are who they claim they are, while authorization grants permissions to access certain resources.

Identity providers enable a universal log-in experience. When a user is initially logged in, they do not need to log in again to access other applications they also have access to. An identity provider typically acts behind the scenes – a user can go to the web address of a specific application, then the application authenticates the user against the identity provider: either a log-in screen is served or users are instantly logged in.

Access layer

As described above, the identity provider component will negotiate access and allow management of different levels of access to data and applications by different groups of users.

From the organizational perspective, this means that there should be a standardized process for users to request access, and the agencies hosting and maintaining the global OHIS will have to define the specific data governance principles that should be imposed to organize and grant access.

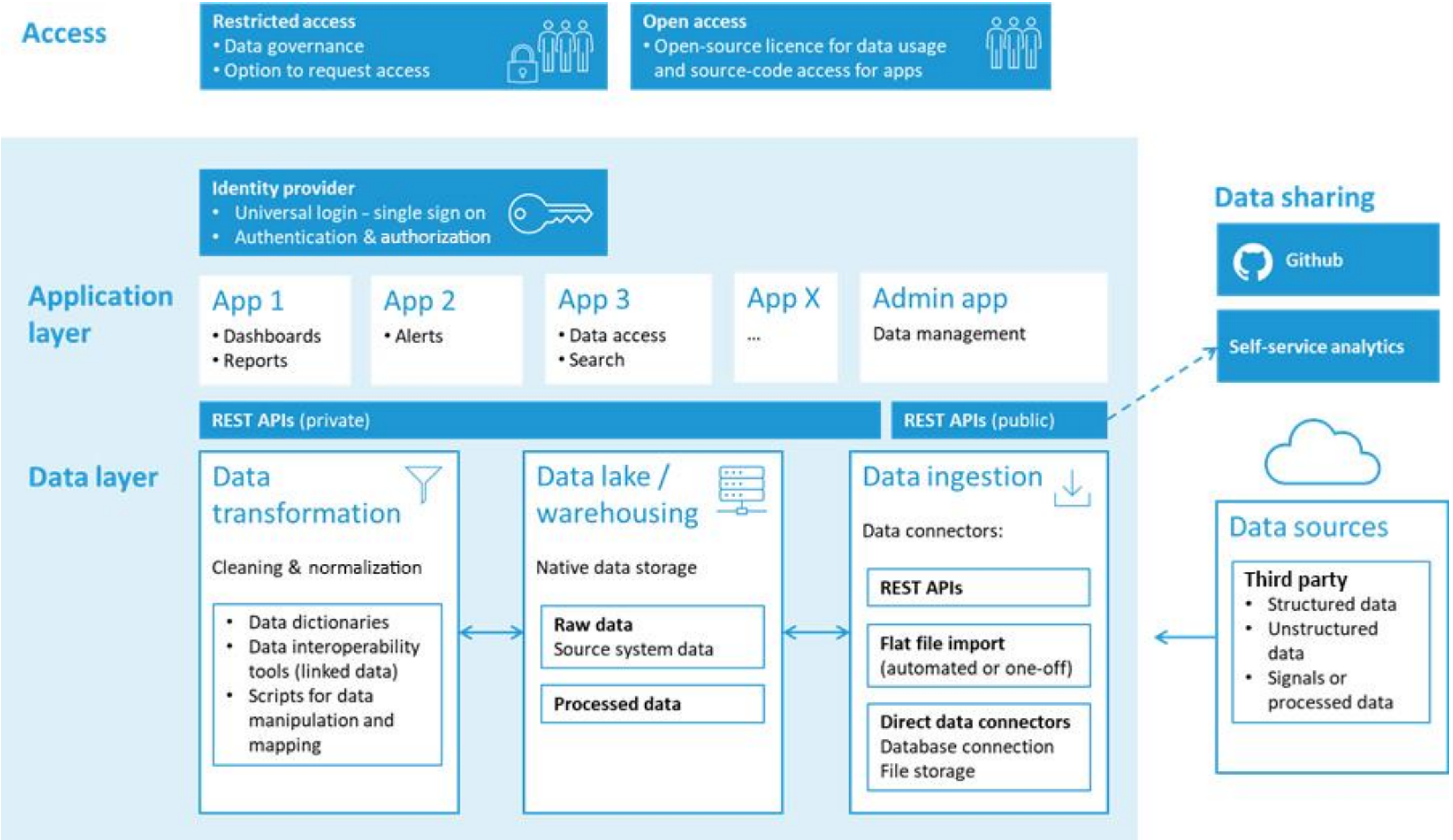
From the technical perspective, this means that, where possible, data and applications can also be made accessible **without log-in** and this will not compromise the access restrictions that need to be applied to other parts of the system.

Providing access without log-in is only one aspect of providing open access. The complementary aspect, which is also defined in the FAIR data principles as “reusability”, refers to associating explicit reuse permission licences to **both** data and software. If an open source licence is applied, it typically means that the source code of an application needs to be disclosed and made available for reuse. This would enable users to research the programming code and methods used, and potentially also to contribute to the ongoing application development.

Data sharing

The architecture proposed also supports different options for data sharing, so that external users can access, extract and use the underlaying data with external tools and in context of different scenarios, e.g. for research or science communication. Common ways to share data are either via a public REST API that others can access, or data publishing to a public GitHub (or similar type) repository. The objective would be that external parties can then either extract data on a one-off basis or programmatically access the publicly available data.

Figure A1: Overview of the modular architecture proposed to build a Quadripartite global OHIS



Source: Authors' own elaboration.