World Economic Forum

Food and Water Systems in the Intelligent Age

WHITE PAPER

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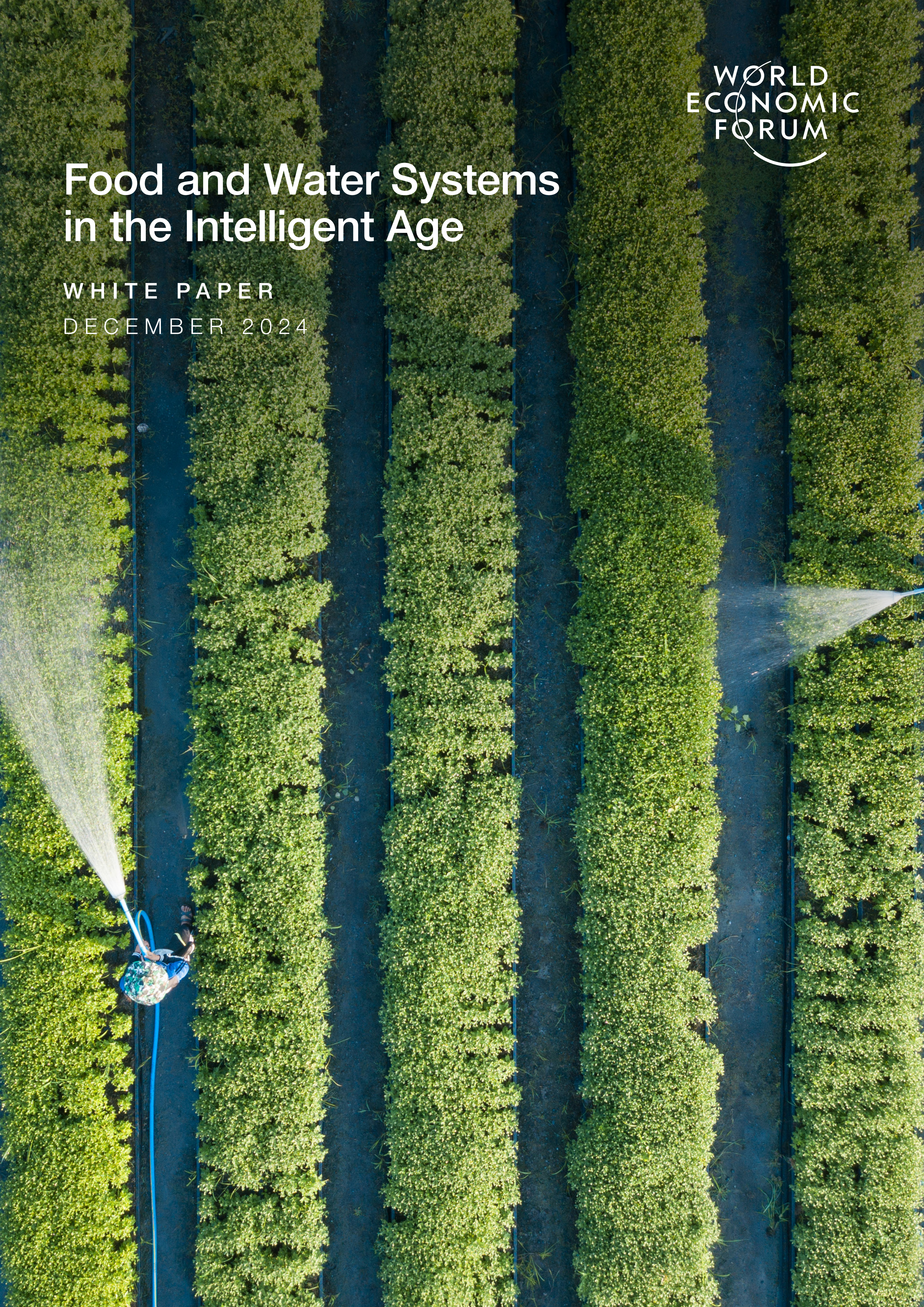

Images: Getty Images

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Executive summary

An integrated view of data for both food and water can drive improved decision-making and sustained solutions in every geography.

Food systems represent 72% of water withdrawals worldwide. Current production and consumption trends are not sustainable, as global food production is projected to increase by 70%, intensifying pressure on already-stressed water resources.

Connecting data from food and water systems is essential for scaling sustainable interventions in these interlinked areas. While several frameworks recognize the overlap between datasets, integrating them to create a platform for robust decision-making remains a challenge. This white paper outlines connections between water and food, the impacts of aggregated data, the role of artificial intelligence (AI) and a data stack framework to inform and improve decision making. This approach can also promote collaboration between stakeholders and spur innovation within the interlinked systems.

The successful application of the food-water stack framework requires a diverse set of data sources – captured manually or through technologies such as remote sensing and internet of things (IoT) – and includes macro-level information such as water availability, weather forecasts, salinity levels and land use patterns. The data is assessed in combination with information about the physical infrastructure in a location, and the technology available to create an analysis that can then be distilled and communicated to the relevant stakeholders through tools like AI chatbots. The white paper outlines three cases that illustrate how the stack framework can bring together stakeholders for more sustainable management of water resources.

The food-water stack, at scale, offers an opportunity to elevate the role of water as an impact multiplier in food (to the same level as carbon and other emissions). With the challenges in food and water systems only growing more complex, the time to act is now. The stack methodology offers a clear pathway to better decision-making, resilience and sustainability for generations to come. The Global Future Council on Food and Water Security recommends the following actions to implement the stack at country level:

- **Develop efficient and collective data infrastructures**. When incorporating proprietary information, common data-sharing protocols, as well as contours around privacy, access and monetization, need to be developed.

- **Intentionally co-create the stack with end users** to ensure that the stack applies to different contexts and includes necessary data for sufficiently tailored, scenario-specific applications.

- **Design the food-water data stack to respond to local circumstances.** While some high-level characteristics of food and water systems are similar across the world, they often possess specific features unique to the country and region. Localization guarantees ownership and commitment to improving implementation over the long term.

- **Ensure open access to the stack**. Use a coordinating mechanism to host the stack and convene communities of local and global stakeholders on its use, management and governance.

- **Harness nature markets and innovative financing to multiply benefits**. Various sources of financing can be used to develop and maintain the stack, and, in the long run, collective analysis from the stack can demonstrate the benefits of its use by linking water and food to climate and nature finance.

- **Convene a multi-ministerial and multistakeholder coordinating mechanism** to coordinate the development of the stack, including key issue areas to focus on.

- **Integrate food and water outcomes into national action plans**, including climate and social development targets, the national food systems pathways developed from the United Nations (UN) Food Systems Summit, national biodiversity strategies and action plans (NBSAPs), water roadmaps, AI and digital policies, and more.

- **Collaborate across industry to drive implementation**. Working with private actors and users in the food and water sectors will drive rapid adoption, while facilitating the solution safely into real world scenarios.

- **Future-proof for improved resilience and decision-making on new innovation**. While developing the stack, account for future decisions in food, including the use of water in alternative proteins or AI.

Introduction

Emerging technological advances, data solutions and innovation present a unique opportunity to secure food and water systems and facilitate large-scale transition.

Ensuring lasting, sustainable food and water systems is critical to maintaining a functioning society. A fundamental enabler of food systems, water is increasingly becoming an at-risk resource, with the food system representing 72% of water withdrawals worldwide.[1] Water and food security are inextricably linked, and estimates suggest that an additional 80 million people will be at risk of hunger by 2050 due to water risks influenced by climate change.[2] The current trends and practices in production and consumption are not sustainable, with climate change exacerbating existing issues. It is projected that global food production will increase by 70%, intensifying pressures on land, water, labour, nutrients and energy.[3] For the first time in history, the hydrological cycle is out of balance from decades of mismanagement and undervaluation of water resources.[4] While demand for food and water rises, water resources become even more scarce or unpredictable.

Emerging technological advances, data solutions and innovation present a unique opportunity to secure food and water systems and facilitate large-scale transition. The limited availability of clean water means that to ensure better food and water security and improve decision-making, data and evidence from these two sectors need to be more effectively integrated. Data-driven decision-making is essential to support stakeholders in selecting water-smart methods and incentivize sustainable production and consumption choices that reduce water use per nutritional unit.[5]

The Global Future Council (GFC) on Food and Water Security provides necessary strategic foresight as well as insight into the interconnected impacts of food and water systems, harnessing the power of innovation and technology as a catalyst for change.[6] Comprised of leaders with expertise in food, water, technology, policy and finance, the GFC recommends the implementation of an evidence-based framework to inform decision-makers on the inherent link between food and water security. It additionally supplies guidance on the potential use of innovation in effectively navigating these issue areas. Data stacks – which consolidate and synthesize diverse datasets on one integrated platform and use emerging technologies like artificial intelligence (AI) to inform recommendations – are one way of creating a data-driven decision-making framework. Currently, much of the data is either low-quality, unused or outdated. The stack, when adopted, can allow for better data sourcing, integration and interoperability. This paper presents this framework, case studies and key recommendations for stakeholders to adopt an intelligent decision-making tool, enabling them to capitalize on the latest developments in technologies.

> **With open access to data, artificial intelligence and predictive analytics, we have the tools we need to co-design resilient and fair food and water systems and create real change. The food-water stack created by the Global Future Council on Food and Water Security provides an integrated view for leveraging the latest in tech and AI to food and water decision-making in the 21st century, and secure a thriving future for people everywhere and our planet.**
>
> Usha Rao-Monari and Ranveer Chandra, Co-Chairs of the Global Future Council on Food and Water Security

BOX 1 | Global Commission on the Economics of Water

The recent report by the Global Commission on the Economics of Water (GCEW) highlights the critical importance of water in food and land systems. “Green water”, or water contained within plants and soils, is a crucial but often forgotten part of the global hydrological cycle. Plants absorb soil moisture, and in turn release water vapour into the atmosphere, which then falls as precipitation, emphasizing the transboundary nature of the water cycle and the influence of agricultural development and deforestation in one geography on drought or water scarcity in another. This broadens our understanding of water flows and highlights the need for a new way to value, manage and govern our freshwater resources across industries (including in food systems).

The GCEW report also highlights the costs of water inaction/injustice and the need to adopt water system justice values when dealing with water. Such values undergird the mission-based approach promoted in the report.

Mission One of the GCEW articulates the importance of improving water management in food systems to secure future resources for people and planet. Through a focus on irrigation efficiency, coupled with a farmer-led approach to regenerative agriculture supported by the entire food value chain, it’s possible to improve water management while delivering food security and adequate nutrition outcomes, and protecting the livelihoods of farmers. Just partnerships and just financing are needed to scale these solutions globally, and new technology like AI can support this development. Mission Four, however, recognizes the possibilities linked to AI while acknowledging its shortfalls, not least the required water consumption for its operations. Water’s integral role in the global economy, food systems and beyond, must be considered by decision-makers and valued in operations and policies accordingly. Harnessing the latest technology in a sustainable way can support a more data-informed future.

Source: Global Commission on the Economics of Water. (2024). *The Economics of Water: Valuing the Hydrological Cycle as a Global Common Good*.

1 A food-water stack for data-driven decision-making

At scale, the food-water stack enables better decision-making and long-term sustainability, elevating water's role as an impact multiplier on the climate agenda.

In a world facing increasing food security and water sustainability challenges, the food-water stack emerges as a transformative tool designed to drive impactful change through better decision-making. As these challenges intensify, the need for accurate data and coordination in food and water systems is more urgent than ever. The inefficiencies caused by fragmented decision-making and a lack of reliable data prompt delays that affect the lives of millions of people. This tool fills the gap by enabling real-time data integration and predictive analytics.

The primary goal of the stack is to empower stakeholders with actionable insights. By aggregating and analysing data from diverse sources, the stack offers a comprehensive view of the food and water systems, enabling more informed and timely decision-making. Establishing a common data framework, the stack can enhance coordination among stakeholders across the food and water value chain, from farmers to policy-makers.

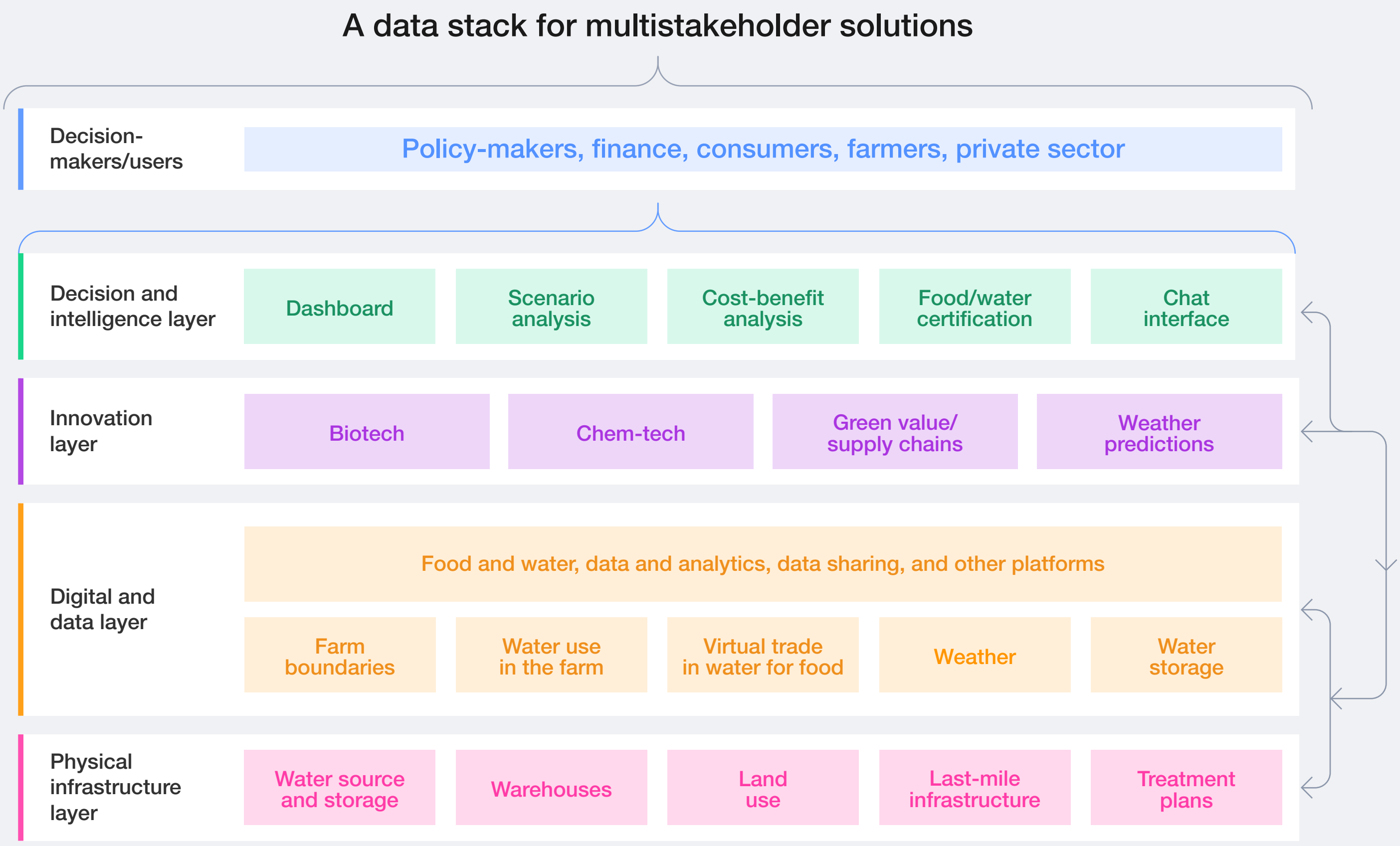
Users can simulate various scenarios, such as the effects of climate change or policy shifts, to better anticipate outcomes and prepare effective responses. The stack delivers insights and collective analysis offering customized recommendations based on specific roles within the system.

BOX 2

What is a data-stack-based approach?

Globally, there are few reliable, evidence-based frameworks that can inform decision-makers on the interlinked influence of food and water security. A stack-based approach (structured layering and integration of multiple data sources for collective analysis) can enable cooperation among a diverse set of stakeholders while spurring innovation. The stack allows decision-makers from different parts of the food-water value chain to visualize and synthesize diverse layers of information and analysis. Data and analysis can be conducted and used by many sectors, including but not limited to farming and production, investment and finance, the private sector, and policy-makers. Ultimately, the stack can hold a full body of information and – depending on the need – specific elements can be activated. In addition, as technology evolves, these stacks can enable data privacy protocols, including predictive analysis and other reasoning tools. The stack also allows for innovation and flexibility within the different layers (i.e. refinement and addition of data in the data layer, inclusion of new technology in the innovation layer, or application of a new tool in the decision and intelligence layer, as seen in Figure 1).

FIGURE 1 | **Framework for data integration and decision-making using the stack**



Note: Figure 1 illustrates an example of the types of data, frameworks and decisions that can be made using the stack. The "physical infrastructure" and "digital and data" layers provide the basis for data collection and the capabilities of the system under assessment. Through the implementation of options in the "innovation layer" and analysis from the "decision and intelligence" layer, decision-makers or users of the stack can make informed choices. List of sources and technologies is not exhaustive.

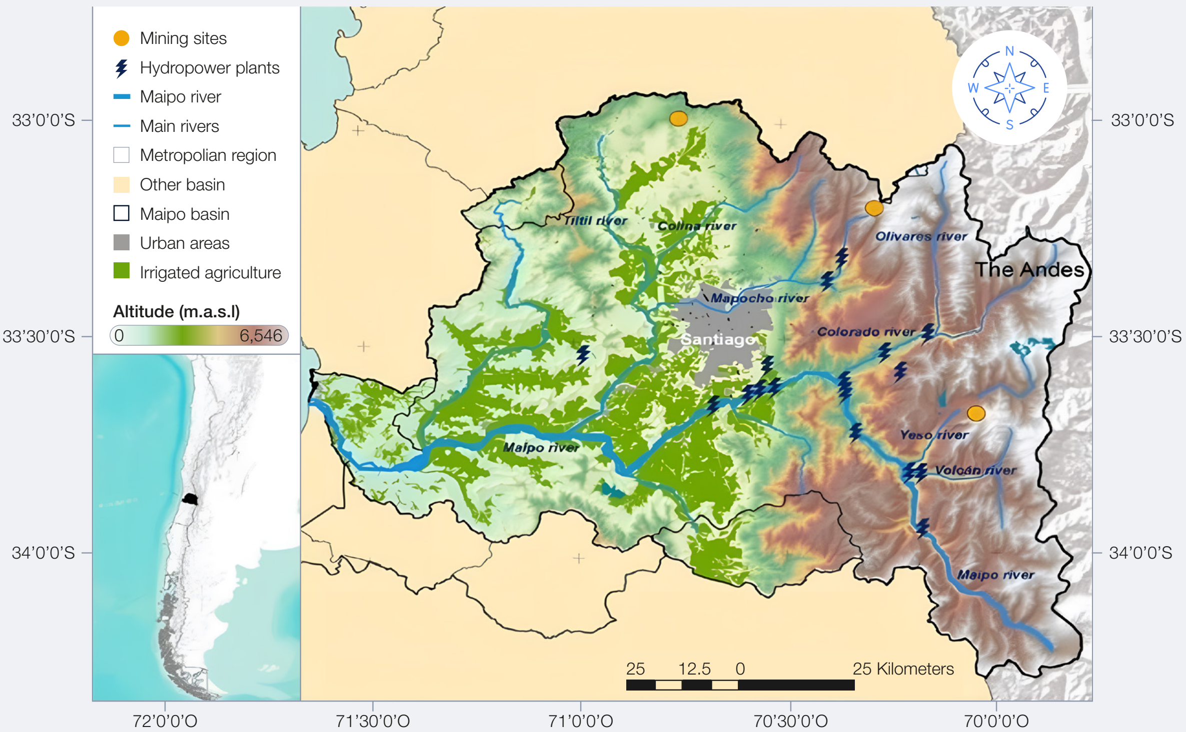
By collating specialized expertise, data stacking can not only promote effective collaboration but also ensure clear roles and responsibilities, reducing ambiguity and building trust. By providing open access, facilitating tailored analyses and enabling real-time, forward-looking decisions, the approach can drive progress in the food and water sectors and ensure equity in access to information and innovation. Additionally, it could support advanced data collection and aggregation platforms that empower stakeholders to make well-informed decisions and thereby realize fit-for-purpose innovation.

The Maipo River Basin is home to 40% of Chile's population and is highly vulnerable to water shortages and drought. Overall, 80% of water is extracted for agriculture, domestic and industrial use annually. A stack could be applied in this scenario to ensure that water is being appropriately allocated to meet the needs of both industry and agriculture, while remaining resilient to the effects of climate change.

Data generated at each layer of the stack must be used to determine water allocation methods, the costs and benefits of a public-private partnership structure for treatment plants, and the kind of infrastructure to be used to convey water for agricultural use.

Decision-makers and stakeholders are found in a multitude of sectors, including agriculture, the private sector, farming, technology, investment, and water and finance ministries. Data stacks can help to establish consensus among these distinct sectors by synthesizing data that would otherwise remain disaggregated. For example, a team made up of ministers of agriculture, water and finance would need project documents, maps, historical data and cost-benefit analyses to assess a project and decide on key steps. In this scenario, the data stack would provide a scenario analysis of which set of decisions works best.

Chile's Maipo Basin



Source: Vicuna, S., Gil, M., Melo, O., Donoso, G. & Merino, P. (2018). Water option contracts for climate change adaptation in Santiago, Chile. *Water International*, vol. 43, issue 2, pp. 237-256.

Stack for decision-making on wastewater treatment plant

Decision/intelligence layer
Cost/benefit of public private partnerships, benefit/income to farmer, dashboard for policy-makers

Innovation layer
Treatment technology, non-NIMBY (not-in-my-backyard) applications, infrastructure footprint, modular source and conveyance infrastructure

Digital and data layer
Water quality, agricultural use (type of crop, cropping patterns, weather), integrating data from agriculture, water and finance ministries, satellite imagery, cubic metres of water needed

Physical infrastructure layer
Capacity of treatment plant, land allocation, right of way/licences, wastewater source and related infra, conveyance infra, dams

2 Applications and use cases of the food-water stack

Countries are using digital tools to enhance sustainable agriculture and water management, supporting resilient food systems.

Three cases illustrate how the stack framework can bring together stakeholders for more sustainable management of water resources.

2.1 Country-based use cases for the food-water stack

India

India's initiative promoting the use of digital technologies in agriculture aims to boost productivity, sustainability and resource-use efficiency while delivering actionable insights on value chains for farmers, markets and governments. It seeks to combine various data sets, including soil health and weather patterns, with advanced technologies like AI and the internet of things (IoT). A few examples include:

- The Agricultural Development Trust in Baramati, Maharashtra, in partnership with Microsoft, Oxford University and Click2Cloud, sought to enhance crop productivity and sustainability by integrating real-time crop, weather and market information through IoT- and cloud-hosted data points. Initial use of this technology in farming has led to 20% increases in production and 8% reductions in water uses.[7]

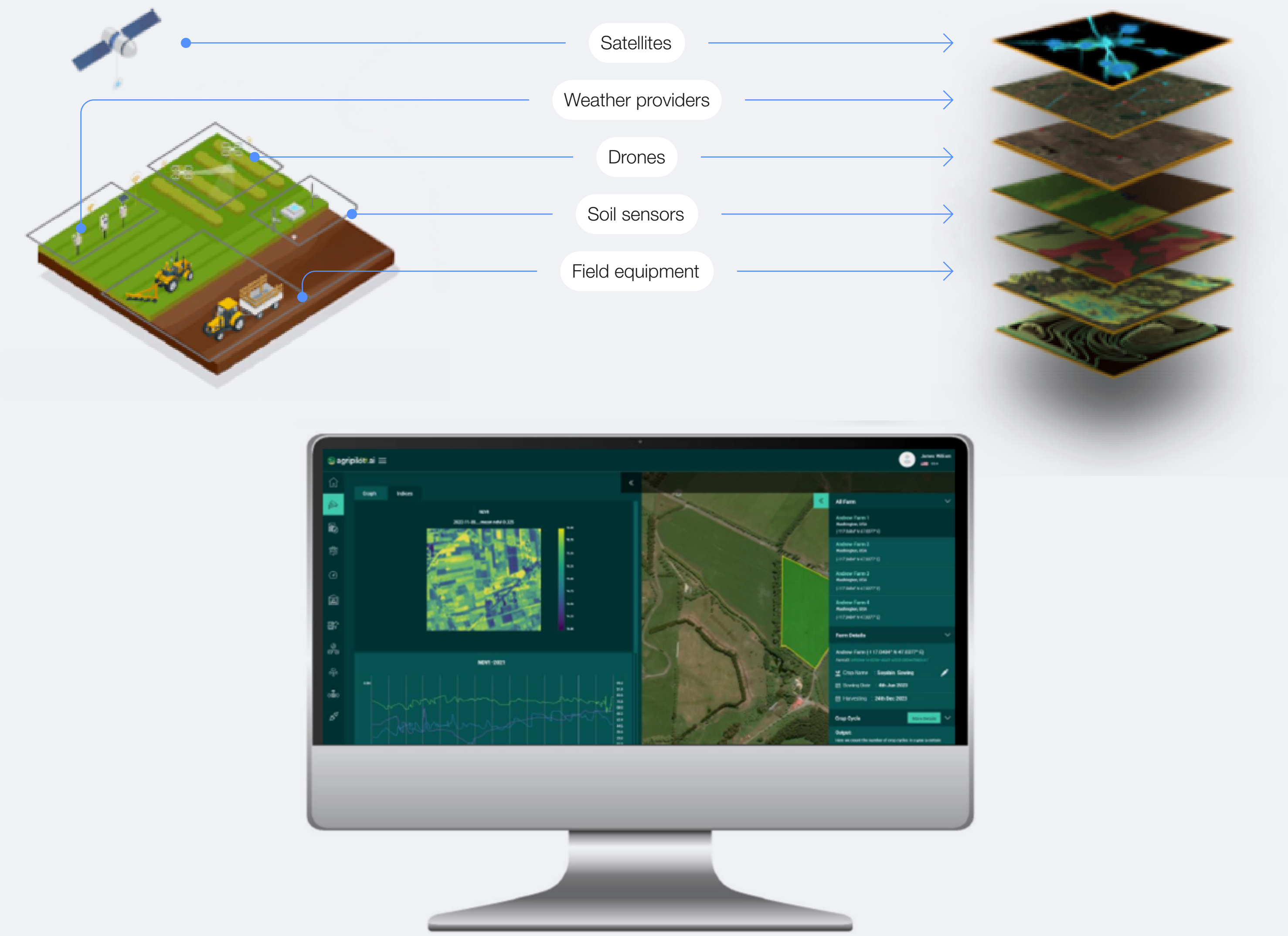
- The 2030 Water Resources Group (2030 WRG), the World Bank and the Government of Uttar Pradesh (UP) worked with Microsoft to pilot a holistic solution for data-driven sustainable agriculture. The advisory support, powered by AI, aims to markedly lower carbon and water footprints and production costs while boosting the stagnant yields of rice and sugarcane crops. Once validated, this AI-assisted model is anticipated to aid the Department of Agriculture in refining policies and enhancing the efficiency of resource planning and management.

Significant enablers influence the deployment and scale of these programmes. Macro-level pro-innovation policies have driven the rapid adoption, mainstreaming and acceptance of AI-based solutions to public policy issues. The establishment and scale-up of pilot projects rely on a strong, responsive multistakeholder partnership.

Partnerships at the grassroots level in Maharashtra and Uttar Pradesh have highlighted how crucial institutions are in providing resources and data-driven support to train and validate models. The UP-Accelerator platform by 2030 WRG has facilitated a private-sector-driven ecosystem designed for public/private partners (e.g. the government and Microsoft). There is a significant need to enhance AI literacy among stakeholders, including the government, to effectively conceive, create, enable and deploy solutions in agriculture and water management.

These examples illustrate how data and a stack framework can effectively help a diverse set of stakeholders, including different government agencies, farmers and the private sector, make data-driven decisions to improve food and water outcomes while supporting development and livelihoods.

FIGURE 2 | AgriPilot.ai is transforming agriculture in India using AI and machine learning



Note: AgriPilot.ai uses generative AI, IoT, satellite imagery and machine learning to support farmers in adapting their practices for a more sustainable global food system. In Baramati, India, AgriPilot.ai has been used to increase crop yields by 20%, reduced water consumption by 8% and improved soil quality by 18% on farms where applied. The platform uses the stack format that would combine the following data into the layers described in chapter 1.

Source: AgriPilot.ai

FIGURE 3 | Stack used to support farmers in improving productivity in a drought region, while saving costs

Decision/intelligence layer

Chat interface for farmers, web dashboard for private sector and policy-makers

Innovation layer

Multi-modal AI across over 20 satellite indices, microclimate prediction, smart crop suggestions, optimized crop placement, precision irrigation and fertilizer insights, sensor placement

Digital and data layer

Weather forecasts, satellite imagery, soil samples, farm boundary, crops' and seeds' availability

Physical infrastructure layer

Canals, crop storage, logistics, subsidies

Limpopo River Basin

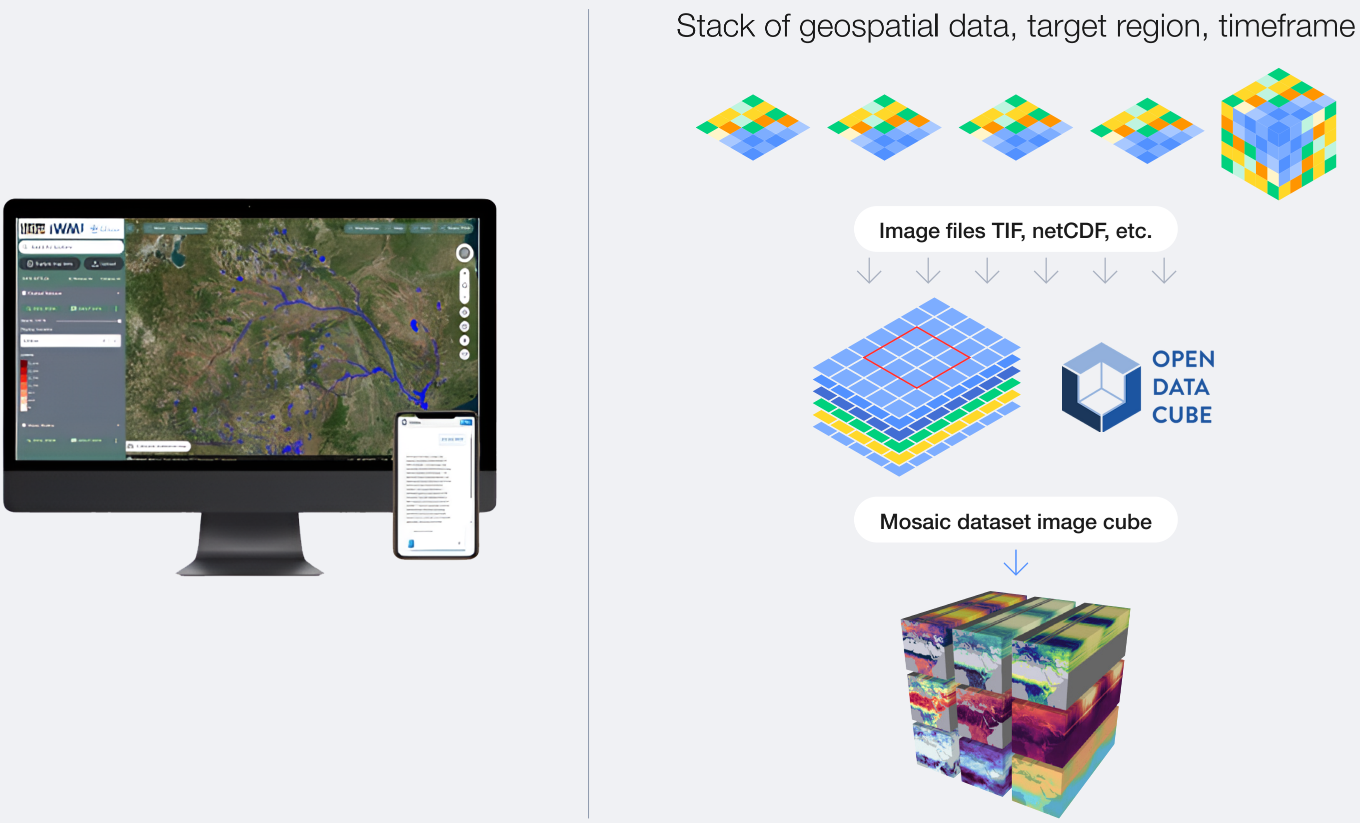
The Limpopo River Basin (LRB), one of the largest in the Southern African Development Community (SADC) region, spans 408,250 kilometres squared (km²) across Botswana, Mozambique, South Africa, and Zimbabwe, supporting 18 million people who depend on its water resources. However, climate variability and overuse have led to severe challenges. Some sections of the river now run dry for 70% of the year, while ongoing droughts strain farmers' ability to sustain crops and livestock. On the other hand, recurrent floods during the rainy season – or those triggered by tropical cyclones – pose additional challenges for agricultural sustainability and other uses, particularly in Mozambique. Effective, climate-smart water management has become essential to address urban demands, over-extraction and deteriorating water quality, all of which threaten the resilience of small-scale farmers and rural communities.

To tackle these challenges, the International Water Management Institute (IWMI), in collaboration with CGIAR Digital Innovation and the Limpopo Watercourse Commission (LIMCOM), has developed a prototype digital twin for the LRB.[8] This platform, aligned with the stack framework, integrates 3D models, Earth observation, IoT sensors and field data, providing a holistic view of water dynamics. It includes an AI virtual assistant tool to interrogate and visualize key actionable data and forecasts, offering a holistic view of water dynamics in the basin.

Built on FAIR data principles (findability, accessibility, interoperability, and reuse of digital assets) and Open Data Cube practices, the digital twin provides near real-time insights on water availability, ecosystem health and more. It will support evidence-based discussions among the four countries, addressing their diverse priorities while encouraging collaboration. Managing the needs and priorities of four different countries is complex. However, this platform is an important starting point for evidence-based discussions.

At the core of this innovative system is an AI-based virtual assistant as part of the decision layer, co-designed with Microsoft Research and LIMCOM and tailored for water managers, researchers and citizens to provide guidance on efficient water practices in the basin. This virtual assistant, powered by GPT-4, allows users to interact with complex datasets through a natural language chat interface.

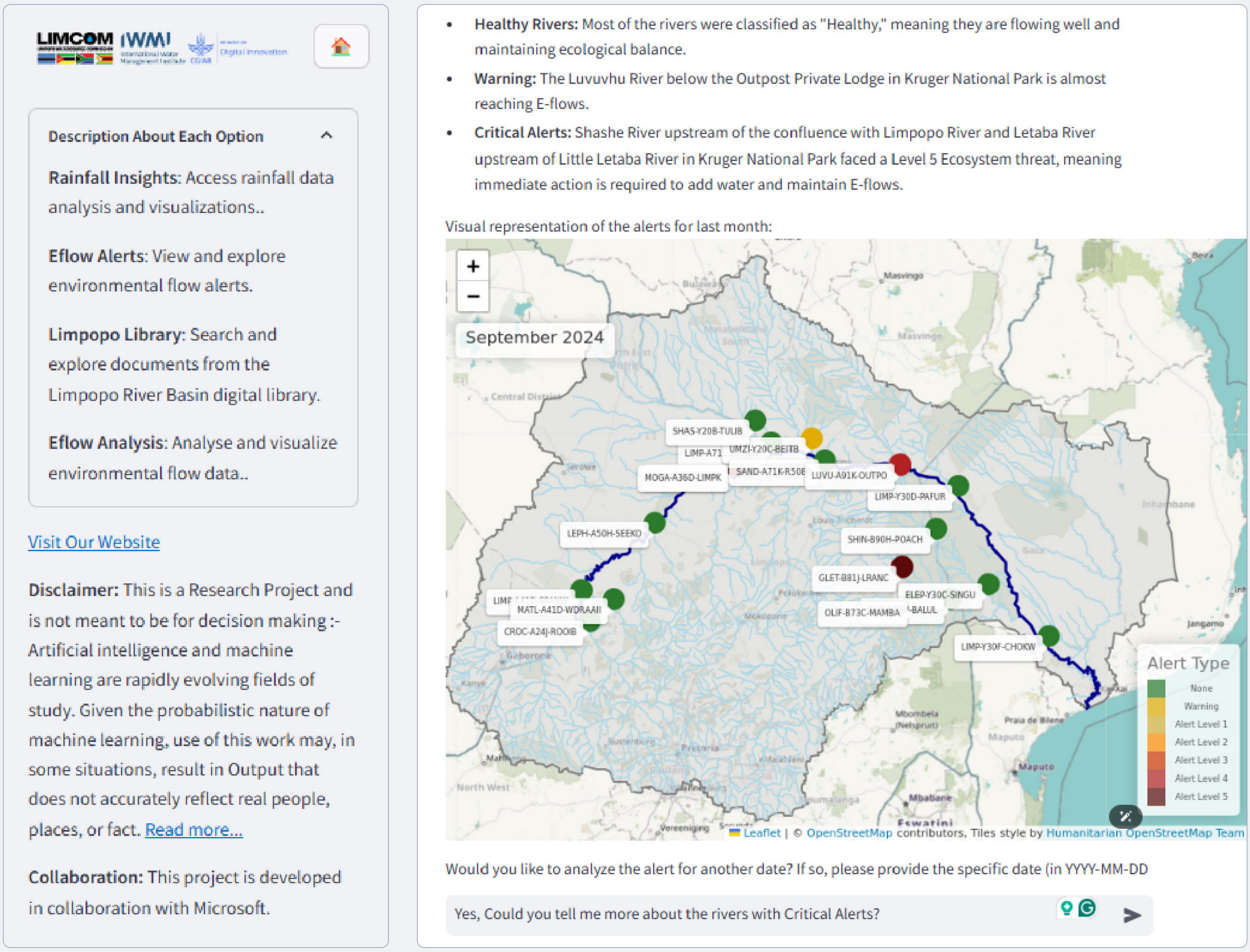
FIGURE 4 **Digital twin prototype and water manager virtual assistant for the Limpopo River Basin**



Note: This system uses a stack of geospatial data within the Digital Earth Africa Open Data Cube framework. It enables targeted analysis by region and timeframe, with FAIR data practices ensuring accessible and interoperable data management;

Source: Mahecha, M. et al. (2020). Earth system data cubes unravel global multivariate dynamics. *Earth System Dynamics*, vol. 11, pp. 201–234. https://doi.org/10.5194/esd-11-201-2020__;!!Im8kQaqBCw!tBw69sOJXmSkTtEp-Vb0vDptVy5zpR9SHB2BVBrCfAhJi0r3KhtvyB62HIlgpiERHrBog62SmJ_62h3ug0M05_hWPUD6cjJl$"https://doi.org/10.5194/esd-11-201-2020.

FIGURE 5 | **AI virtual assistant displaying a visual map of environmental flow and water availability in the Limpopo River Basin**



Note: This map highlights areas requiring immediate action as of October 2024. The summary includes healthy rivers, warning zones and critical ecosystem threat levels, aiding in timely decision-making and resource management.

By facilitating natural language queries, the assistant enhances accessibility and usability, transforming raw data into actionable information. It can help users draft reports, plot maps and explore various scenarios, making it a crucial tool for anticipating risks and strategizing in developing climate-resilient water management solutions that will improve the sustainable use of natural resources in the basin.

This initiative is based on a multistakeholder approach. By collaborating with local agencies and making use of country-specific resources, the platform remains adaptable, scalable and aligned with regional needs. Partnerships with tech experts such as Microsoft and Amazon Web Services (AWS) have created a robust, flexible infrastructure that promotes shared ownership and maximizes impact across the region.

Moving forward, IWMI is working with the UNICEF-YOMA platform to integrate citizen science data into the LRB digital twin, empowering local communities to report basin challenges. This inclusion enriches the data ecosystem with insights for the voices that were never heard before while building capacity within the communities, allowing for more responsive, localized decision-making.

The digital twin prototype offers a transformative solution for the Limpopo River Basin, with scalability to other basins through its adaptable infrastructure. By enabling seamless integration within a water-food system, it supports resilience and sustainability. Through advanced data integration, real-time monitoring and AI-driven insights, the digital twin aligns with the food-water stack's vision for a secure and sustainable future in global food and water systems.

Costa Rica

In Costa Rica, bananas are one of the largest and most important agricultural exports. Banana exports in 2022 accounted for $1.22 billion, and approximately 28,000 people work on banana farms nationwide.[9] Costa Rican bananas also play a crucial role in global banana supply, as Costa Rica is the world's third-largest exporter.[10] Limón, a province located on the Caribbean coast, encompasses 80% of Costa Rican banana plantations.[11] This region is the poorest province in Costa Rica, and 76% of the workforce is employed in the banana industry. Thus, the local economy heavily relies on banana production.[12] Climate change, however, poses an existential threat to banana farming in Costa Rica, which would have damaging economic implications in the province.

Limón's climate is humid and tropical. The province has historically experienced significant rainfall throughout the year, which facilitates the cultivation of bananas and has made irrigation systems historically unnecessary.[13] In recent years, however, Limón has received less rainfall and irregular weather patterns due to climate change, which negatively impacts banana farming and harvesting. As the climate shifts, Limón will continue to receive less rainfall, further hurting banana production.[14] Banana plantations need better data to develop improved resilience to the effects of climate change and, in particular, greater rainfall variability.

This use case provides farmers with detailed data to support informed decision-making about climate-smart strategies and investments for their farms, particularly regarding irrigation. Irrigation is costly, and farmers need to understand a variety of factors to determine the most appropriate and cost-effective solutions. This stack will bring multiple data sets together. These sets – featuring data about climate and weather, soil health and productivity, prevalence of diseases and pests, market and financial factors, and new and emerging technologies – will provide farmers with a more complete, integrated picture that enables them to make the best decisions for their farms in a rapidly changing environment. Bananas are a key crop for global food security, involving millions of farmers in nations across the Global South. This gives this use case relevance and replication potential far beyond Costa Rica.

BOX 4

Developing a water stack for farmers

A key benefit of the stack would be the democratization of data use and of (typically expensive) emerging technologies like AI. This would benefit the more than 500 million farmers in the value chain, guiding them towards better decision-making on water in food production and consumption.

Key recommendations to develop a minimum viable product:

– The stack should account for the diversity of farmers and their goals, assuming a shared interest in profitability, land preservation and the mitigation of crop yield losses related to water stress. Transparency and user-friendly technology are crucial.

– Market mechanisms influence investment decisions on what crops are being planted, with water as one factor that must be considered. Farmers need data on the volume of water available, weather forecasts and the consistency with which water will be provided. Farmers can also use this data to determine the type of crop to grow or practices to use during the growing process to make their fields more resilient to local conditions or potential water stress.

– Local policy and influence are critical in decision-making. Peer-to-peer exchange and community-based development can influence the uptake of the stack.

– Currently, only about 25% of smallholder farmers produce a surplus exclusively for the market. Determining how the data stack can be customized for subsistence farmers is a key consideration. Furthermore, land tenure influences decision-making and investment. Farmers who do not own land may focus less on its health and prioritize high yields.

– The outcomes of the stack should be available in many languages, be applicable to a range of smart and other phones, and feature accessible, easily navigable user interface (including through channels like WhatsApp, voice-based and radio services).

– Finally, the use of the stack application will have to be economically feasible and enable profitable business decisions. It should provide insight on key insurance, subsidies and financial packages, water use permits, technologies and other data that can enable the adoption of water-efficient practices. For instance, providing information to markets on the water use effectiveness of different crops or food from different origins has the potential to generate financial value for farmers.

Initial data required:

– **Macro data**: For example, water availability, water quality, water use effectiveness, weather forecasts, salinity, current land use, sea level, soil mapping

– **Technical packages**: Sowing and farm management practices that will enable water efficiency and resiliency

– **Technologies**: Digital and non-digital, emerging equipment and machinery that can support farmers (e.g. precision agriculture, drip irrigation, etc.)

– **Policies and market mechanisms**: guaranteed offtake, subsidies and other policy packages (e.g. carbon credit markets)

– **Financial mechanisms**: Financial packages that can de-risk water-resilient practices

– **Historical data**: Focused on agricultural practices and outcomes

– **Organizational data**: Size of the organization, number of producers and their profiles, average and total size of farms, profitability over time, etc.

2.2 Design components to strengthen data-readiness

The stack-based approach can provide insights into the food-water nexus (including some of the non-apparent interlinkages) and be a go-to tool for decision-making. It should be flexible and customizable to various scenarios, use cases and multistakeholder engagements.

It is crucial to address constant variables like political dynamics, citizen engagement and historical policies. The stack should be inclusive, catering to both low-tech and high-tech solutions, with a focus on new incentivization and collaboration models.

Data fragmentation remains a significant obstacle to building efficient intelligence infrastructure for food-water systems. While AI tools can help address several challenges, it is still critical to recognize the importance of authoritative data sources. The efficacy of the stack will depend on the quality of data. To ensure data readiness, the following design components need to be considered:

Data collection and aggregation

Data can be difficult to consolidate, as different sources provide it in various formats. In remote areas, the infrastructure needed for data collection is usually either insufficient or absent.[15] Furthermore, guaranteeing data quality from a multitude of sources is also a challenge due to inaccurate equipment, gaps in coverage or human error. The stack will need to integrate the following:

– **A unified data integration layer:** A set of connectors and technologies (e.g. IoT devices, satellite imagery, manual input) can help unify disparate data sources, improve infrastructure access, and ensure data quality. This layer enables different data formats (structured and unstructured) to coexist on one platform.

– **Aggregation tools:** These include IoT gateways and edge computing devices that can collect and process data locally in environments with limited or intermittent connectivity.[16] These devices can store and aggregate data locally and then synchronize with the cloud or central system when connectivity is restored. Another option is the use of satellite connectivity in areas where terrestrial internet infrastructure is insufficient to transmit data.[17]

– **Data quality:** Machine learning models can detect and flag outliers or erroneous data in real time, helping to clean and validate the data. Tools like Apache NiFi[18] or Talend[19] can be used to perform real-time cleansing and transformation as data is integrated. These can be implemented in the stack with protocols for regular calibration. Maintaining sensors to ensure they provide accurate data or incorporating self-diagnosing sensors (IoT devices that can flag performance issues) is also critical for consistent data quality.

– **Community engagement:** Engaging local farmers, researchers, extension workers, governments, water managers and others through mobile apps to provide data, manual data validation, or feedback is critical for data efficacy. The data accuracy and density requirements will vary based on the specific use case (e.g. higher aggregation for policy-makers versus higher granularity for pre-season and in-season decisions by farmers).

As the stack will collect various sources of data under a unified platform, data privacy and data sharing protocols will become necessary, where data can be anonymized when needed and strict standards of access will need to be developed to protect the most vulnerable. The stack-based approach might risk monetization by a few and consequentially increase the data gaps, thereby limiting the application.

Data standardizing and operability

Once data is integrated into the stack, it needs to be standardized into a consistent format that can be processed by AI algorithms. This includes cleaning the data, resolving inconsistencies, ensuring platform compatibility, and applying consistent metrics.

A set of automated ETL (extract, transform, load) pipelines can synthesize data from various sources into a unified format (i.e. clean/normalize it) and load it into a central database for analysis.[20] A cloud-based data lake – e.g. AWS,[21] Azure[22] or Google Cloud[23] – can act as a scalable storage solution for all collected data, making it easier to aggregate and access. Here, open data standards – e.g. JavaScript Notation (JSON), comma-separated values (CSV), extensible markup language (XML), representation state transfer (REST) application programming interfaces (APIs) – are implemented to ensure that data from different systems can be easily integrated and exchanged across platforms.[24]

Data interpretation, analysis and forecasting

Once data is available in a standardized form, the next layer of the stack applies AI and machine learning models to interpret the data, uncover patterns and forecast trends (e.g. crop yields, drought predictions, soil fertility decline and/or water use). AI models require large amounts of high-quality, diverse data to generate accurate insights. However, in many cases, particularly in underdeveloped or remote regions, this data may be incomplete or low quality.[25] To solve this, the layer can use the following techniques:

- Synthetic data generation uses simulated datasets (e.g. from climate models or remote sensing) to fill gaps in real-world data, thus improving model accuracy.[26]

- The layer can use models that are pre-trained on similar problems (such as crop yield prediction or weather forecasting) and have been adapted to specific local conditions, reducing the need for large volumes of local data.

- The stack should also incorporate crowdsourced data from farmers and local communities via mobile applications to supplement sensor and satellite data, increasing both the quantity and diversity of available data.[27] This also acknowledges the unique role of agronomists and advisers in checking for the accuracy of such output as part of data quality assessment.

- It is necessary to conduct regular bias audits of the AI models, using fairness metrics to test whether the predictions are disproportionately skewed towards or against certain populations (e.g. smallholder farmers in low-income regions). It is similarly important to engage with local stakeholders to source input for the model development process.[28] The ethics of the AI should be continuously monitored to ensure that the food-water stack remains a public good.

BOX 5

AI as a companion

To assess the complex interactions in food and water systems, AI models that integrate data from various sources (e.g. climate data, market data, soil sensors, socioeconomic data) should be considered to generate more holistic predictions. Furthermore, it is also essential to implement agent-based models in conjunction with AI to simulate interactions between different agents (e.g. farmers, markets, policy-makers, water systems) and environmental factors.[29] Finally, it is crucial to use AI to generate scenario-based forecasts rather than singular predictions and incorporate feedback loops into the AI model so that the system continually learns from real-time data and adjusts its predictions accordingly.[30] This can help the model keep up with the ever-changing nature of food and water systems. Ultimately, AI models are meant to complement, not replace, existing and future human intelligence.

Communication of findings

The final layer turns AI-driven insights into practical information that can be distributed to farmers, water managers, policy-makers, the private sector and other stakeholders. This could be done through mobile apps, dashboards, reports or decision-support systems. To solve key challenges around accessibility, the digital divide and trust, careful design and intervention are necessary.

- Information needs to be communicated in a way that is understandable and accessible to end users (e.g. smallholder farmers, businesses and local communities).[31]

- The technology needs to consider language, education and literacy levels, and culture to provide relevant messaging to inform robust decisions. Many stakeholders may lack the necessary digital tools (e.g. smartphones and the internet) to receive these insights. Third-party dissemination through government extension, research non-governmental organizations (NGOs), communities, farmer-producer organizations or the private sector should be harnessed to deliver their products or services.

- Lastly, AI-generated insights can be erroneous, explaining why stakeholders may be reluctant to adjust traditional practices based on new data.[32] While acknowledging the useful impact of these tools as helpful in decision-making, human judgement and experience cannot be discounted.

3 The food-water stack as a public good: a roadmap to action

The stack can empower decision-makers to invest in water by illustrating the right incentives on the local, country and global scales.

Ownership by the public sector can unlock development funding, as the stack can be used to make the investment case for long-term and integrated action on food and water.

The stack's ability to use standardized, multidimensional real-time data to create forecasts and scenario analyses will help policy-makers craft more effective and responsive policies. For instance, governments can harness predictive models to foresee droughts or food shortages, allowing for timely adjustments in water allocation or farming subsidies. Furthermore, the tool will assist financial institutions and governments in prioritizing investments in infrastructure and sustainability, identifying high-impact areas (like regions needing irrigation), supporting risk management and unlocking funding and repurposing subsidies through data-backed insights. In addition, it can spur collaboration across regions and countries, especially around transboundary water management, boosting integration. Finally, it can help farmers protect and adapt their livelihoods to the changing climate, providing insights into the right crops, practices and financing options available to match their climatic conditions, water availability and technological capacity.

The experts from the GFC recommend the development of a food-water stack as a public good. As such, the development and decision-making needs are contextual and need to be localized. To begin with, context-specific country-led approaches are suggested where implementation of the stack framework is led by the public sector, which convenes key stakeholders to develop a common good. Subsequently, the GFC also recommends factoring in the energy nexus to ensure resource optimization and understanding the trade-offs better. Key country recommendations:

- **Develop efficient and collective data infrastructures**. In the first phase, existing data sources across ministries and stakeholders can provide the foundational layer. However, as the tool progresses, common data-sharing protocols, as well as contours around privacy, access and monetization, need to be developed. A key focus of the stack is to address data interoperability issues, with research and development partners tasked with designing a robust AI-driven architecture. For governments providing initial policy support, their existing data, funding and infrastructure can provide multiple benefits. Data must be continually evaluated to ensure relevancy, and the stack will require continuous maintenance to be fit for purpose.

- **Intentional co-creation is critical, especially with end users (e.g. farmers, policy-makers and consumers)**, to ensure that the stack applies to different contexts and includes necessary data for sufficiently tailored, scenario-specific applications. This also allows the stack to use the data sources centrally available, add more contextual and scattered data (multinational, regional, national, farm, etc.) and work towards the unified goal of improving decision-making.

- **Design to ensure localization and adoption.** While some high-level characteristics of food and water systems are similar across the world, they often possess specific features unique to the country and region. Localization guarantees ownership and commitment to improving implementation over the long term. At the same time, regional and global cooperation and coordination are encouraged, especially among countries that share a water basin. Ensuring a multistakeholder approach to stack development and use is critical, especially for situations in rain-fed agricultural areas and other stakeholders, including the private sector and community organizations.

- **Ensuring open access**: As the stack would assist with decision-making that impacts public and common goods, it should be managed and governed by a neutral, trustworthy platform or initiative. Guided by a framework established by the individual country, this approach offers guardrails against misuse and interference by external actors. It also allows for a more collaborative platform that brings net benefits

> The transformation of smallholder farming requires significant support in terms of access to knowledge, finance and markets.

to users and whole countries. Thus, private companies and entities can share their data as they get benefits from it. The neutral initiative or manager of the stack would also help to incentivize and anonymize proprietary data where needed and allow for greater security of contributions of sensitive information that is nevertheless critical to consider for informed decision-making. The stack manager can promote tangible benefits and incentives to encourage data sharing from different sources. This demonstration of value can also serve as a mechanism to highlight the validity and importance of the stack framework.

- **Leveraging nature markets and innovative financing for multiplying benefits**. As such, alongside technology, establishment and communication costs, key financing needs will include an investment in skills, monitoring and maintenance of the stack infrastructure as well as digital infrastructure needs. Various sources of financing, including multilateral systems (e.g. the World Bank) and the development of philanthropic-public-private partnerships, can catalyse the establishment after the stack facilitates digital monitoring, reporting, and verification (MRV), which unlocks results-based financing. In the long run, water outcomes can be used as a measurable statistic combined with the collective analysis from the stack, which can link water and food to climate and nature finance, thereby using carbon, water, biodiversity and other credits to incentivize adoption.

- **Convene a multi-ministerial and multistakeholder coordinating mechanism** to coordinate the development of the stack, including key issue areas to focus on. To begin with, ministries of agriculture, food processing, water, environment and information, communication and technology will be critical stakeholders alongside multilateral institutions, the private sector, farmer organizations, civil society and others. This approach will also allow for further understanding and integration of related ministries or agencies while allowing national or sub-national governments to adapt the stack to their needs and local contexts. Additionally, ownership by the public sector can unlock development funding, as the stack can be used to make the investment case for long-term and integrated action on food and water.

- **Integrate food and water outcomes into national action plans**, including climate and social development targets, the national food systems pathways developed from the United Nations (UN) Food Systems Summit, national biodiversity strategies and action plans (NBSAP), water roadmaps and more. It is also critical to adapt the stack development to the national digitization and AI plans. Through a significant evidence base and the aggregation of information from different sectors, the stack will guide the required mindset changes across different parts of the economy with specific output metrics (e.g. water productivity or water use effectiveness) that directly affect food and water outcomes. This alternative framing will produce greater social inclusion for youth, women and disadvantaged groups.

- **Precompetitive industry collaboration is critical to driving implementation**. It is key to work with private sector actors and private users in the food and water systems. These actors are likely to drive rapid adoption as they see the value of applying technology and AI across the value chain. Industry collaboration is essential to driving the solution safely in real-world scenarios while maintaining user trust and system integrity. In addition, mutual benefits and incentives need to be developed based on the stakeholder type.

- **Future-proof for improved resilience and decision-making on new innovation**. As the stack develops, building on the capabilities, accounting for future required decision-making in food and water – for example, water use in future food innovation or the water footprint of AI – will be key. AI is an important tool in translating data into actionable steps, but as it scales, its own water footprint should be considered.

As demonstrated by the use cases in Chapter 2, the stack should be implemented first in a few pilot circumstances, working with farmers to optimize their water consumption. This could be a collaboration between national and sub-national governments, neutral parties, and farmer and community organizations in an area to continue to build on the framework and recommendations in this paper. The Global Future Council will work with the World Bank and other key stakeholders to create such pilots in a few relevant countries or sub-national regions that have the data and enabling environment in place.

The use of data stacks such as those proposed here – together with other cutting-edge technologies – should be an essential cornerstone in the creation of a new generation of young leaders who can help to build a secure water-food future. The transformation of smallholder farming requires significant support in terms of access to knowledge, finance and markets. This, in turn, requires a cadre of leaders on the ground who can support small farmers and farmer-producer organizations in the transition towards strategies that benefit their families, communities and the planet. This group of leaders must be prepared effectively through agricultural higher education and technical and vocational education and training institutions so that, over the next couple of decades, farmers around the world (especially small farmers) receive the support they need to transform their farms and provide a dignified livelihood for their families.

Conclusion

More holistic and integrated data for food and water systems is critical for advancing sustainable interventions and enhancing decision-making. The challenges posed by climate change, resource scarcity and rising global food demands necessitate a unified approach to data management. The insights provided in this paper underscore the importance of a comprehensive food-water stack framework, which can drive meaningful improvements in both food and water security.

This paper emphasizes the importance of collaborative efforts among stakeholders, including governments, the private sector and local communities, to develop tailored solutions that address the unique challenges within different contexts. The proposed food-water stack framework serves as a roadmap for advancing interoperability and data aggregation, enabling real-time insights that are essential for the proactive management of water resources in agriculture.

Moving forward, stakeholders are encouraged to take specific steps to implement this framework. These include integrating food and water outcomes into national action plans, ensuring open access to data while maintaining robust privacy protections and promoting the development of sustainable financing mechanisms that support water-resilient practices. Additionally, encouraging youth and community leadership is vital for building a generation of leaders capable of driving positive change in food and water systems.

By prioritizing data integration and investing in innovative solutions, stakeholders can navigate the complexities of food and water security while promoting resilience against future challenges. This proactive approach not only safeguards resources but also ensures that agricultural practices remain sustainable, equitable and capable of supporting communities for generations to come.

Contributors

World Economic Forum

Morgan Booher
Specialist, Food and Water

Noopur Desai
Food Initiatives and Partnerships Manager

Levi Orero
Hoffman Fellow, Data and Digital Solutions

Tania Strauss
Head, Food and Water

Global Future Council on Food and Water Security

Co-Chairs

Usha Rao-Monari
Commissioner, Global Commission on the Economics of Water

Ranveer Chandra
Chief Technology Officer, Agri-Food, Microsoft

Members

Chris Armitage
Chief Executive Officer, Global EverGreening Alliance

Marcel Beukeboom
Permanent Representative, United Nations Food and Agriculture Organizations (UN FAO)

Rhett Butler
Founder, Chief Executive Officer and Executive Editor, Mongabay

Cao Duc Phat
Chair, Board of Trustees, International Rice Research Institute (IRRI)

David Chen
Co-Founder and President, Equilibrium Capital Group

Kevin Z. Chen
Qiushi Chair Professor, Zhejiang University

Arturo Condo
President, EARTH University

Gina Domanig
Managing Partner, Emerald Technology Ventures

Joyeeta Gupta
Professor of Environment and Development in the Global South, University of Amsterdam

Arif Husain
Chief Economist and Director, Research, United Nations World Food Programme (WFP)

Santhosh Jayaram
Senior Vice-President and Global Head in Sustainability, HCL

Saroj Kumar Jha
Global Senior Director, World Bank

Manual Otero
Director-General, Inter-American Institute for Cooperation on Agriculture (IICA)

Rejane Souza
Senior Vice-President, Global Innovation, Yara International

Sandhya Sriram
Group Chief Executive Officer and Co-Founder, Shiok Meats

Ishmael Sunga
Chief Executive Officer, Southern African Confederation of Agricultural Unions (SACAU)

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Amal Al Ahmadi
Senior Project Manager, Ministry of Climate Change and Environment, United Arab Emirates

Fuzan Alkhalidi
Director, Healthcare Strategy and Policy, Office of the Prime Minister of the United Arab Emirates

Chris Dickens
Principal Researcher, Sustainable Water infrastructure & Ecosystems (SWIE), International Water Management Institute

Mariangel Garcia
Research Group Leader, Water Futures Data and Analytics, International Water Management Institute

Valentin Golovtchenko
Lead, Climate Technologies, Centre for the Fourth Industrial Revolution Physical Technologies, World Economic Forum

Mohsin Hafeez
Director, Water-Food and Ecosystems, International Water Management Institute

Emily Fintel Kaiser
Strategic Advisor to the President, EARTH University

Ruth McLachlin
Lead, Climate Technologies, Centre for the Fourth Industrial Revolution Physical Technologies, World Economic Forum

Rachael McDonnell
Deputy Director-General, Research for Development, International Water Management Institute

Braulio Eduardo Morera
Head, Strategy and Resilience Solutions, World Economic Forum

Ajith Radhakrishnan
Senior Specialist, World Bank

Federico Ronca
Lead, Data and Digital Solutions, Food and Water, World Economic Forum

Jaskiran Warrik
Lead, Regenerative and Climate Adaptive Projects, Food and Water, World Economic Forum

Michael John Webster
Programme Manager, 2030 Water Resources Group, World Bank

Jorge Werthein
Senior Advisor, Inter-American Institute for Cooperation on Agriculture (IICA)

Production

Louis Chaplin
Editor, Studio Miko

Laurence Denmark
Creative Director, Studio Miko

Xander Harper
Designer, Studio Miko

Endnotes

1. UNESCO. (2024). *Food security, a key driver of peace and prosperity.* https://www.unesco.org/reports/wwdr/en/2024/agriculture.
2. World Economic Forum. (2024). *Quantifying the Impact of Climate Change on Human Health*. https://www.weforum.org/publications/quantifying-the-impact-of-climate-change-on-human-health/.
3. Wang, X. (2022). Managing land carrying capacity: Key to achieving sustainable production systems for food security. *Land*, vol. 11, no. 4, pp.484. https://www.mdpi.com/2073-445X/11/4/484/.
4. Global Commission on the Economics of Water. (2024). *The Economics of Water: Valuing the Hydrological Cycle as a Global Common Good.* https://economicsofwater.watercommission.org/.
5. World Economic Forum. (2023). *Building a resilient future: The power of data and AI for food and water security.* https://www.weforum.org/agenda/2023/10/building-a-resilient-future-the-power-of-data-and-ai-in-food-and-water-security/.
6. Ibid.
7. Microsoft AI First Movers. (n.d.). Data-driven farming. https://www.microsoft.com/en-in/aifirstmovers/adt.
8. CGIAR. (2024). *Digital Twin of the Limpopo Basin advances with new prototype.* https://www.cgiar.org/news-events/news/digital-twin-of-the-limpopo-basin-advances-with-new-prototype/.
9. Fox, M. (2024). Everything Isn't Pura Vida in Costa Rica. Sierra. https://www.sierraclub.org/sierra/everything-isn-t-pura-vida-costa-rica.
10. Ibid.
11. ResearchGate. (n.d.). *Number of banana farms and planted hectares by province in Costa Rica, 2014.* https://www.researchgate.net/figure/Number-of-banana-farms-and-planted-hectares-by-province-in-Costa-Rica-2014_tbl1_335150152.
12. Corbana. (n.d.). *Banano de Costa Rica.* https://www.corbana.co.cr/banano-de-costa-rica-2/.
13. Climate Change Knowledge Portal. (n.d.). Costa Rica. https://climateknowledgeportal.worldbank.org/country/costa-rica/trends-variability-historical.
14. Ibid.
15. Carnahan, E. et al. (2024). Root causes of COVID-19 data backlogs: a mixed methods analysis in four African countries. *Oxford Open Digital Health*, vol. 2, issue 1, pp. i16-i28. https://academic.oup.com/oodh/article/2/Supplement_1/i16/7663968.
16. Oliveira, F., Costa, D.G., Assis, F. & Silva, I. (2024). Internet of Intelligent Things: A convergence of embedded systems, edge computing and machine learning. *Internet of Things*, vol. 26, pp.101153. https://www.sciencedirect.com/science/article/pii/S2542660524000945.
17. Baganzi, S. & Romel, M. (2024). Towards Ubiquitous Broadband Access: Policy Imperatives for Developing Next-Generation Non-Terrestrial Networks. *Econstor*. https://www.econstor.eu/bitstream/10419/302531/1/ITS-Seoul-2024-paper-139.pdf.
18. Wnęk, K. and Boryło, P. (2023). A data processing and distribution system based on apache NiFi. *Photonics*, Vol. 10, No. 2, pp. 210. https://www.mdpi.com/2304-6732/10/2/210.
19. Cheruku, S.R., Goel, O. & Jain, S. (2024). A Comparative Study of ETL Tools: DataStage vs. Talend. *Journal of Quantum Science and Technology*, vol.1, no. 1, pp. 80-90. https://www.researchgate.net/publication/383536496_A_Comparative_Study_of_ETL_Tools_DataStage_vs_Talend.
20. Foidl, H., Golendukhina, V., Ramler, R. & Felderer, M. (2024). Data pipeline quality: Influencing factors, root causes of data-related issues, and processing problem areas for developers. *Journal of Systems and Software*, vol. 207, pp. 111855. https://www.sciencedirect.com/science/article/pii/S0164121223002509.
21. Wittig, A. and Wittig, M. (2023). *Amazon Web Services in Action: An in-depth guide to AWS*. Simon and Schuster.
22. Microsoft AI Skills Challenge. (n.d.). *How does Azure work?.* https://learn.microsoft.com/en-us/azure/cloud-adoption-framework/get-started/what-is-azure.
23. Google Cloud. (n.d.). *Google Cloud overview*. https://cloud.google.com/docs/overview.
24. Villarreal, V. et al. (2024). A methodological approach for data standardization and management of Open Data portals for scientific research groups: a case study on mobile and ubiquitous ecosystems. *Frontiers in Computer Science*, vol. 6, pp. 1420709. https://www.frontiersin.org/journals/computer-science/articles/10.3389/fcomp.2024.1420709/full.
25. Aldoseri, A. Al-Khalifa, K.N. & Hamouda, A.M. (2023). Re-thinking data strategy and integration for artificial intelligence: concepts, opportunities, and challenges. *Applied Sciences*, *13*(12), pp.7082. https://www.mdpi.com/2076-3417/13/12/7082.
26. Ferrara, E. (2023). Fairness and bias in artificial intelligence: A brief survey of sources, impacts, and mitigation strategies. *Sci*, vol. 6, no. 1, pp.3. https://www.mdpi.com/2413-4155/6/1/3.

27. Karagiannopoulou, A., Tsertou, A., Tsimiklis, G. & Amditis, A. (2022). Data fusion in earth observation and the role of citizen as a sensor: A scoping review of applications, methods and future trends. *Remote Sensing*, vol. 14, no. 5, pp. 1263. https://www.mdpi.com/2072-4292/14/5/1263.

28. Bird, S. et al. (2020). *Fairlearn: A toolkit for assessing and improving fairness in AI*. Microsoft. https://www.microsoft.com/en-us/research/uploads/prod/2020/05/Fairlearn_WhitePaper-2020-09-22.pdf.

29. Lavin, A. et al. (2021). Simulation intelligence: Towards a new generation of scientific methods. *arXiv*. https://arxiv.org/abs/2112.03235.

30. Jallbjørn, S. (2022). *Multi-population mortality models and scenario-based projections*. Department of Mathematical Sciences, University of Copenhagen. https://noter.math.ku.dk/phd23sj.pdf.

31. Mapiye, O. et al. (2023). Information and communication technologies (ICTs): The potential for enhancing the dissemination of agricultural information and services to smallholder farmers in sub-Saharan Africa. *Information Development*, vol. 39, issue 3, pp. 638-658. https://journals.sagepub.com/doi/abs/10.1177/02666669211064847.

32. Glikson, E. & Woolley, A.W. (2020). Human trust in artificial intelligence: Review of empirical research. *Academy of Management Annals*, vol. 14, issue 2, pp. 627-660. https://journals.aom.org/doi/10.5465/annals.2018.0057.

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World Economic Forum
91–93 route de la Capite
CH-1223 Cologny/Geneva
Switzerland

Tel.: +41 (0) 22 869 1212
Fax: +41 (0) 22 786 2744
contact@weforum.org
www.weforum.org