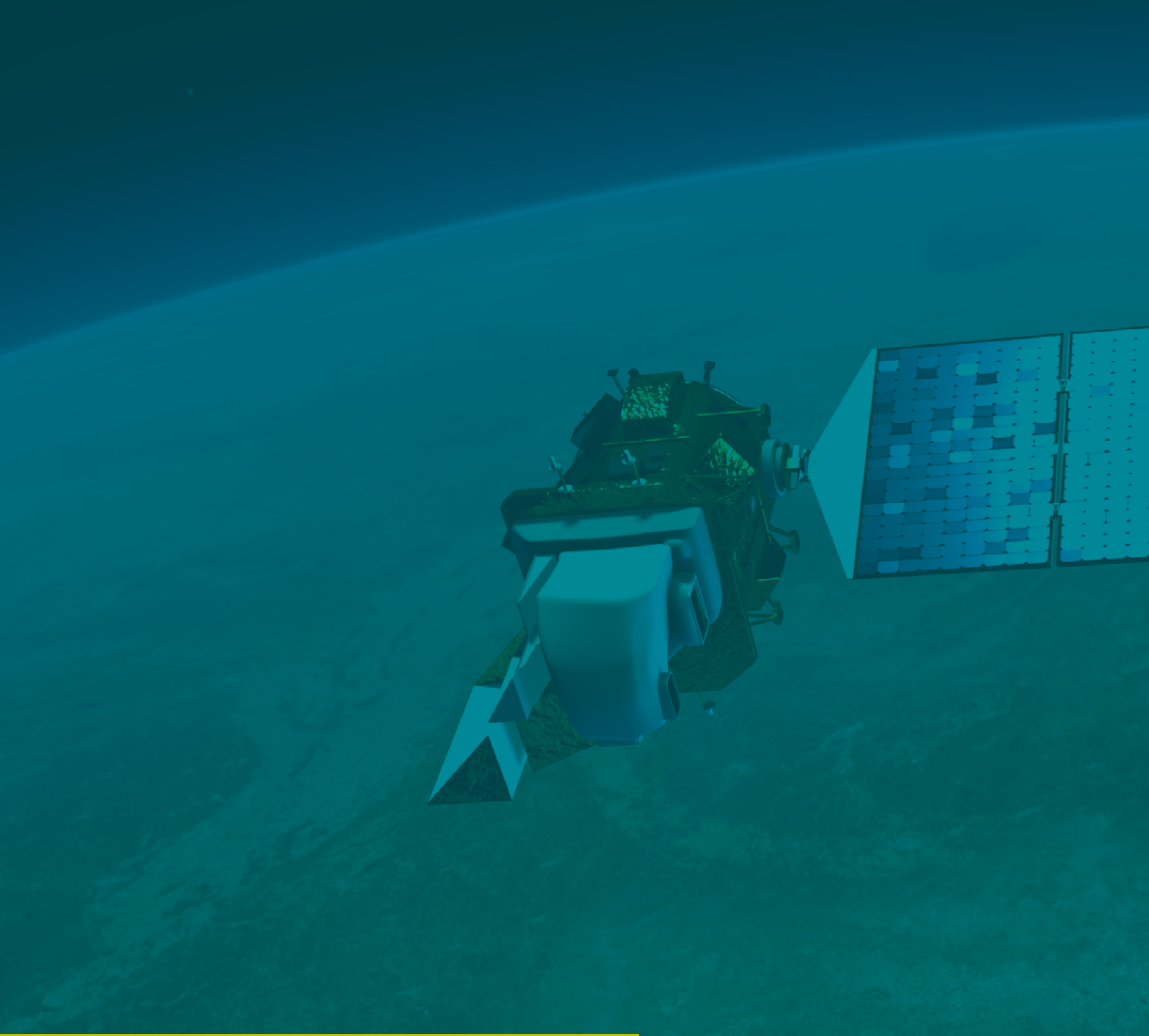
Food and Agriculture Organization of the United Nations

UNITED NATIONS
OFFICE FOR OUTER SPACE AFFAIRS

LEVERAGING SPACE TECHNOLOGY FOR AGRICULTURAL DEVELOPMENT AND FOOD SECURITY

UNITED NATIONS



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LEVERAGING SPACE TECHNOLOGY

for Agricultural Development and Food Security

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FOREWORD

Through the work of the United Nations inter-agency coordination mechanism on space activities (UN-Space), and on the tenth anniversary of a previous joint publication on space for agriculture and food security, it is a pleasure for the Land and Water Division (NSL) at the Food and Agriculture Organization of the United Nations (FAO) and the United Nations Office for Outer Space Affairs (UNOOSA) to jointly present a report on the intersection of space technology and agriculture. Its aim is to inform space industry professionals, Governments and policymakers, researchers and academics, and international experts involved in these domains about ways to drive transformative change that can significantly advance the global food security agenda.

In 2022, the population of the Earth passed the eight billion mark and forecasts predict that it will continue to grow, with global food security remaining a pressing global challenge. The disparity in food availability across regions underscores the urgency to find innovative solutions, and the international community seeks ways to turbocharge the implementation of the 2030 Agenda for Sustainable Development, including Sustainable Development Goals 2 on zero hunger. In this context, space technology has emerged as a game-changer. Satellite imagery, global navigation satellite systems data and their integrated applications are now critical tools for agriculture, enabling stakeholders, ranging from local farmers to international policymakers, to monitor crop health, manage water resources, detect and control pests, and plan for weather uncertainties, among various other applications.

Geospatial technologies are already being applied to food security. One example is the FAO Hand-in-Hand Geospatial Platform, part of the broader Hand-in-Hand Initiative. This platform employs a collaborative and data-driven approach to agricultural development and food security, leveraging the power of advanced geospatial analytics and satellite data. By integrating over two million layers of open-access geospatial and agricultural statistics data from global public data providers, this platform offers a comprehensive visualization and analysis tool for the stakeholders concerned.

Another example can be found in Togo, where a multi-stakeholder collaboration led by NASA Harvest, Planet Labs and the University of Maryland demonstrated the power of space technology in a real-world crisis. When the COVID-19 pandemic disrupted food supply chains in Togo, food insecurity in the country was exacerbated. By utilizing satellite imagery and advanced analytics, the collaboration provided crucial insights into the agricultural landscape, enabling the Government of Togo to quickly respond through relief programmes in the midst of a pandemic.

Multi-stakeholder partnerships are needed to harness the full potential of space technology for agriculture. We hope that this publication will be thought-provoking and support the mission of the United Nations in building bridges to ensure that space technologies are deployed for the benefit of all. UNOOSA and FAO, including through the framework of UN-Space, are committed to continue fostering international collaborations, investing in capacity-building and promoting innovative policies to transform agricultural practices globally, ensuring food security, sustainability and resilience.

Together, let us commit to this vision and work to create a future where technology and agriculture unite to nourish our fast-evolving world.

Ms. Aarti Holla-Maini
Director, United Nations Office
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CONTENTS

EXECUTIVE SUMMARY

As the global population is expected to approach the 9.7 billion mark by 2050, food security is becoming an increasingly critical issue. Agriculture, essential for sustaining life and economies, faces numerous challenges including climate change, extreme weather, limited resources, evolving dietary needs and population growth. To address these challenges, innovative solutions are necessary, among which space technology plays a vital role.

Space technologies such as satellite imagery and global navigation satellite systems (GNSS) are integral to modern agriculture. They provide high-resolution data essential for precision agriculture, effective water management, crop monitoring and accurate weather forecasting, thereby supporting informed decision-making and promoting sustainable agricultural practices. However, the rapid expansion of space activities poses risks, particularly in terms of space debris, which can threaten the operational safety of satellites and hinder future missions.

Engaging experts from the space sector, including within the United Nations, is crucial for the effective integration of space technology in agriculture. Cooperation between the United Nations Office for Outer Space Affairs (UNOOSA) and the Food and Agriculture Organization of the United Nations (FAO), in the framework of the inter-agency meeting on outer space activities (UN-Space), aims to strengthen the link between GNSS, remote-sensing technologies and the overall space sector with applications in the agrifood sector, which is essential for the advancement of updated and effective technologies to ensure food security.

This publication was developed by UNOOSA and FAO to emphasize the current applications of space technology in agriculture. This publication aims to support sustainable development and the 2030 Agenda by integrating GNSS and remote-sensing technologies with agricultural practices. It is structured into three key segments.

The upstream segment focuses on the development of space infrastructure, including satellites and data acquisition systems. Notable Earth observation missions such as Landsat and Copernicus provide valuable data for agriculture, while GNSS systems offer critical positioning information for precision farming. The integration of Earth observation and GNSS data enhances agricultural applications. To ensure the long-term viability of these technologies, it is essential to develop space infrastructure more efficiently and sustainably, addressing the challenges posed by space debris and minimizing the environmental impact of space activities.

The midstream segment addresses data processing, storage and management. It highlights the importance of spatial data infrastructure (SDI) and standards in geospatial information-sharing and use. Emerging technologies and frameworks, such as the Global SDI Association and the United Nations Integrated Geospatial Information Framework (UN-IGIF), are crucial for improving data accessibility and quality as well as strengthening capacity development programmes in geospatial applications. The integration of satellite and ground-based data is essential for agriculture monitoring and management. Enhancing the efficiency of data management systems can further reduce operational costs and support the effective use of space technology.

The downstream segment applies satellite data to practical agricultural uses, including monitoring crop and land conditions through essential agricultural variables and utilizing platforms such as the FAO Hand-in-Hand Geospatial Platform, for global to local information and for diverse applications with variable levels of interoperability.

The publication also outlines challenges and provides recommendations for enhancing the use of space technology in agriculture. These include tailoring technologies to specific needs, improving Earth observation missions, addressing data gaps and implementing measures to promote sustainable space development.

In conclusion, space technology has transformative potential for agriculture, offering solutions to improve food security and sustainability. Integrating advanced technologies while addressing the risks associated with space debris and ensuring efficient and sustainable space development is crucial. Collaborative efforts among stakeholders are essential for addressing global agricultural challenges and ensuring a sustainable future for agriculture.

INTRODUCTION

With the world's population expected to reach 9.7 billion by 2050, food security is a critical global concern. Agriculture is the backbone of food security, from local communities to the global population, providing the essential goods that sustain human life and drive economies worldwide. Ensuring the sustainable development of agriculture is not just a necessity – it is a critical mission for the future of our planet and societies. However, agriculture faces numerous challenges such as climate change, extreme weather events, resource limitations, economic growth with associated changes in dietary patterns, and population growth. Overcoming these challenges requires innovative solutions for sustainable agricultural development, including benefiting from space technology and enhancing geospatial programmes.

Leveraging space technology, specifically satellite imagery and global navigation satellite systems (GNSS), provides valuable tools for addressing agricultural challenges. It offers navigation systems and satellite imagery with varying spatial and spectral resolutions, time-series data and an array of spectral bands. Such resources enable the monitoring, analysing and managing of agricultural activities, land use and environmental conditions for various applications. These applications of space technology in agriculture include precision agriculture, water management, crop monitoring, weather forecasting, soil fertility management, pest and disease control, and sustainable land-use planning among others. These applications facilitate informed decision-making for different actors, including farmers, Governments and international organizations.

With the aim of providing a comprehensive overview of the current use of space technology, particularly remote sensing and GNSS, in the agricultural sector, and to support sustainable space and agricultural development, as well as the 2030 Agenda for Sustainable Development, the United Nations Office for Outer Space Affairs (UNOOSA) and the Food and Agriculture Organization of the United Nations (FAO), in the framework of the inter-agency meeting and coordination mechanism on outer space activities (UN-Space), jointly developed this publication by engaging experts from the space and agricultural sectors, including within the United Nations. This publication also aims to strengthen the link between GNSS, remote-sensing technologies and the overall space sector with applications in the agrifood sector, which is essential to the advancement of updated and effective technologies for ensuring food security.

Therefore, this publication highlights the essential role played by agriculture in ensuring global food security, as the primary source of food for billions of people worldwide. It recognizes the increasing challenges faced by agriculture arising from climate change, resource constraints, population growth and other developments, as well as the need for innovative solutions to monitor, manage and optimize resources. It underscores the role of space technology as vital in transforming agricultural practices and helping to address these challenges. It discusses the application of space data in agriculture, which enables more informed decision-making, allowing farmers and policymakers to develop strategies that boost agricultural productivity and resilience while minimizing environmental impact. It culminates in recommendations on leveraging the transformative potential of space technology in shaping the future of agriculture, providing valuable insights for policymakers.

By leveraging their respective experiences in addressing global agricultural challenges and advancing space technology, FAO and UNOOSA jointly developed this document to enhance space-related capacity-building and to promote awareness among policy and decision makers in various countries. It aligns with the ongoing endeavour to strengthen space-related capabilities and offers practical test cases contributing to technological advancement through remote sensing.

This publication zooms in on three key segments of the space sector: upstream, midstream and downstream. It examines the current state of each segment, highlights existing limitations and identifies areas for improvement.

In the upstream segment, which involves the manufacturing and production of space infrastructure – including the development of satellites and the acquisition of agricultural data – the publication provides an overview of Earth observation and GNSS missions. It also discusses challenges and opportunities in development capacities and mission planning.

For the midstream segment, which covers the processing, storage, access and integration of space-derived data, the focus is on spatial data infrastructure, geospatial standards, and data access and management.

Finally, in the downstream segment, which deals with the analysis and application of space-derived data for agriculture, the publication provides an overview of essential agricultural variables, user-specific requirements and existing monitoring platforms. It also assesses data gaps and highlights opportunities to bridge these gaps.

This approach allows for a comprehensive examination, with inputs from the Committee on Earth Observation (CEOS), of gaps within the space domain. It makes the publication particularly valuable for technical stakeholders, and policy and decision makers, as it offers an overview of the status of the upstream, midstream and downstream segments as well as recommendations for various aspects of utilizing space-based technologies, primarily remote sensing and GNSS, to enhance agricultural practices, including, but not limited to:

- Considering local, national and regional contexts and needs when developing global remote-sensing and GNSS technologies, such as considerations related to land representation, definition, zoning and boundaries
- Providing recommendations for future Earth observation missions, with scientific requirements, desired data format, observation frequency, spatial coverage, etc.
- Avoiding gaps, in terms of time and spatial coverage, in remote-sensing data
- Establishing standards for methods, data, information and procedures
- Increasing availability of analysis-ready data by removing obstacles related to data pre-processing
- Improving access to field and remote-sensing data, documentation and metadata through existing platforms
- Providing established, accessible and standardized processing chains for the analysis of remote-sensing and agricultural data

THE IMPORTANCE OF AGRICULTURE IN GLOBAL FOOD SECURITY

In 2015, the adoption of Sustainable Development Goal 2 (SDG-2),[1] as part of the 2030 Agenda for Sustainable Development,[2] set the goal to end hunger, achieve food security, improve nutrition and promote sustainable agriculture worldwide by 2030. However, with only five years remaining, world hunger is still projected to reach 670 million by the year 2030,[3] the same number as when the Goals were first set.

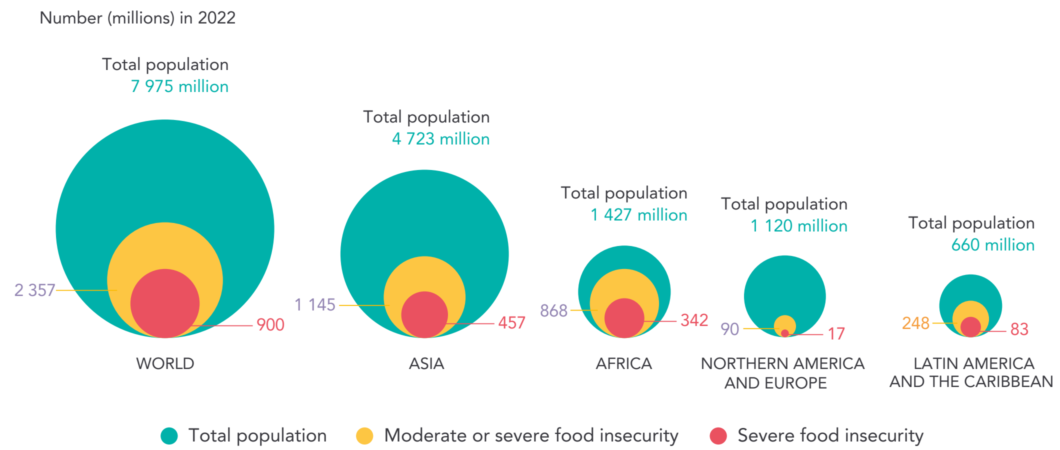
Food security indicators such as the prevalence of undernourishment and the prevalence of moderate or severe food insecurity either have yet to improve or have worsened over the past few years. Global food insecurity drivers such as climate change and economic and sociopolitical factors remain key issues that adversely impact agricultural production chains. As illustrated in figure 1, in 2022, food insecurity impacted 900 million people globally, with the most severe impacts observed in Asia and Africa. While efforts are being made to address these issues, more work is needed to tackle each of the stages of the food system value chain.

[1] www.un.org/sustainabledevelopment/hunger/.

[2] https://sdgs.un.org/goals.

[3] FAO, IFAD, UNICEF, WFP and WHO. 2023. *The State of Food Security and Nutrition in the World 2023. Urbanization, agrifood systems transformation and healthy diets across the rural–urban continuum*. Rome, FAO. https://doi.org/10.4060/cc3017en.

Figure 1. Global food insecurity concentration and distribution categorized by severity



Source: FAO, IFAD, UNICEF, WFP and WHO. 2023. *The State of Food Security and Nutrition in the World 2023. Urbanization, agrifood systems transformation and healthy diets across the rural–urban continuum*. Rome, FAO. https://doi.org/10.4060/cc3017en.

GLOBAL FOOD INSECURITY DRIVERS

Climate change

The consequences of climate change include extreme weather events, rising sea levels, habitat loss, food and water scarcity, biodiversity decline, and threats to human health and livelihoods.[4] Low-lying agricultural areas, for instance, are at particular risk. Additionally, water supply may become saline due to rising sea levels and unsuitable for irrigation. Residential areas located in the affected regions can lead to the displacement of communities that may increase the conversion of agricultural land into urban areas for rebuilding displaced communities.[5] Meanwhile, extreme weather events such as drought, frost and hail, intensity and variability in precipitation, and increasing temperature accelerate a drop in crop productivity. As these phenomena are likely to increase in the future, their impact on food security on a local to global scale will worsen, and communities which are currently suffering high levels of food insecurity will become even more vulnerable.[6] Many countries, specifically in sub-Saharan Africa, are at risk and experience extreme weather changes.

[4] IPCC. 2022. Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, H.-O. Pörtner, D.C. Roberts, and others, https://www.ipcc.ch/report/ar6/wg2/.

[5] Mârza, B., Angelescu, C. and Tindeche, C. 2015. "Agricultural Insurance and Food Security. The New Climate Change Challenges." *Procedia Economics and Finance*, 27: 594–599. https://doi.org/10.1016/S2212-5671(15)01038-2.

[6] Wheeler, T. and Von Braun, J. 2013. "Climate Change Impacts on Global Food Security." *Science*, 341(6145): 508–513. https://doi.org/10.1126/science.1239402.

Areas that are already facing water scarcity are projected to face even worse conditions in the future while regions that are currently not susceptible to drought are expected to experience it in the years to come. Climate change in the sub-Saharan Africa region does not only affect food security, but it is also closely linked to food accessibility and utilization issues.[7] Ethiopia, a highly populous sub-Saharan country, faced the highest percentage of food insecurity in 2023. Rapid population growth has increased the demand for food, but the combined impacts of climate change have rendered the food supply insufficient. Additionally, land degradation and unsustainable agricultural practices have significantly contributed to food insecurity.[8]

Economic factors

Several economic factors can greatly influence the availability, accessibility and stability of food supplies which in turn can directly affect global food security. Poverty and income inequalities, for example, can limit purchasing power and heighten vulnerability to price shocks. Communities living in poverty often lack the resources to purchase healthy and adequate food which often leads to malnutrition and chronic hunger. Above all, their high vulnerability to price inflation very often prevents them from accessing food and meeting their basic dietary and nutritional needs.

Sociopolitical factors

Sociopolitical factors contribute to vulnerability in food security. As an example, the conflict in Ukraine has shown to have affected not just regional but also global food systems, with wheat, corn and barley being among the country's major export products.[9] The disruption in the food system has not only been caused by the reduction of their agricultural production due to impacts of armed conflict, but is also influenced by import and export supply restrictions.

In the face of these challenges, sustainable agriculture emerges to play a critical role in ensuring global food security by serving as primary source of food for the global population. Initiatives such as the Alliance for a Green Revolution in Africa (AGRA),[10] for instance, have demonstrated the potential of sustainable agriculture to address food security challenges. AGRA has impacted agricultural transformation in Africa to improve food production by establishing efforts to modernize agriculture through sustainable farming, as well as providing financial access and support to farming communities. The provision of climate-resilient

[7] Connolly-Boutin, L. and Smit, B. 2016. "Climate change, food security, and livelihoods in sub-Saharan Africa." *Regional Environmental Change*, 16(2): 385–399. https://doi.org/10.1007/s10113-015-0761-x.

[8] Bezu, D.C. 2018. "A Review of Factors Affecting Food Security Situation of Ethiopia: From the Perspectives of FAD, Economic and Political Economy Theories." *International Journal of Agriculture Innovations and Research*, 6(6).

[9] Chepeliev, M., Maliszewska, M. and Pereira, M.F.S.E. 2023. "The War in Ukraine, Food Security and the Role for Europe." *EuroChoices*, 22(1): 4–13. https://doi.org/10.1111/1746-692X.12389.

[10] AGRA. 2024. AGRA - Sustainably Growing Africa's Food Systems, cited 16 August 2024, https://agra.org/.

and high-yielding seeds and fertilizers to smallholder farmers has significantly improved agricultural productivity leading to increased availability of food in African countries, thereby improving national food security in the region.

In view of the various new and recurring drivers of food insecurity, sustainable agriculture is key to increasing agricultural production in order to meet the demands of the growing population equally and ensure that undisruptive agrifood systems achieve global food security. In this context, space technology is undoubtedly part of the solution.

THE ROLE OF SPACE TECHNOLOGY IN AGRICULTURE

Historically, agricultural land monitoring and management relied on manual methods, which were labour-intensive, time-consuming and resource-demanding. These approaches posed significant challenges, particularly when covering large areas with high spatial variability or handling an increasing number of data indicators.

To address these limitations, new methods and technologies have emerged that capture real-time data and reduce human bias, even in remote or inaccessible areas. Navigation systems, remote sensing, geospatial applications, services and digital technologies have been increasingly developed and utilized to collect vast amounts of data from both airborne (such as unmanned aerial vehicles, helicopters or planes) and spaceborne platforms, revolutionizing agricultural land monitoring and management. These innovations allow for more efficient, accurate and near real-time data collection, enabling farmers to make informed decisions based on localized and spatial data.

Satellite-based data, when integrated with geospatial tools and ground truth information, offer powerful capabilities for agricultural monitoring. This technology allows farmers to identify problematic areas, such as zones with low productivity or moisture stress, and take corrective action. Additionally, space technology has the advantage of covering large tracts of agricultural land quickly, reducing the need for manual labour, saving time and resources.

Recent advancements in satellite technology, particularly in Earth observation satellites, have expanded the availability and diversity of data sets. These satellites, equipped with sensors offering various spatial, temporal and spectral resolutions, can address specific agricultural needs and challenges. Accurate positioning data from navigation satellites also support operations such as precision agriculture, further enhancing productivity and efficiency.

Satellite remote sensing offers numerous useful applications for agriculture. To name a few, optical Earth observation satellites are widely used for crop damage assessment due to their high availability and ease of use. Synthetic aperture radar (SAR) data from Earth observation satellites can penetrate cloud cover and can be most useful to monitor pre- or post-disaster situations such as agricultural flooding.[11] Additionally, SAR data can also be combined with optical imagery to enhance the mapping of different crop types.[12] Earth observation satellites with higher spatial resolution, known as very high resolution (VHR) satellites, have significantly enhanced the detailed and accurate mapping of agricultural areas through fine-scale crop type mapping, advancing from moderate resolution imagery (10 to 30 metres spatial resolution) to less than one metre.[13] Recent developments in space-borne hyperspectral sensors have proven to be significant, especially in precision agriculture where high resolution of spectral information is crucial for vegetation characterization and resource management in farmlands.[14]

Accurate location information obtained from GNSS satellites can also play a key role in supporting agricultural operations. Precise positioning data can be used to enhance farming techniques, including the use of automated machinery such as ground platforms and autonomous tractors. This technology helps farmers increase yields while reducing operating costs.[15]

The integration of Earth observation and GNSS data plays a pivotal role in precision agriculture management systems (PAMS). Several countries have already adopted the concept of PAMS, where integration of Earth observation data, GNSS data and other geospatial information is used.[16] Moreover, satellite, aerial and ground data integration in agricultural applications are demonstrated to be beneficial to specifically address food insecurity, particularly in most vulnerable nations. Such a satellite, aerial and ground integration (SAGI) framework would utilize the integration of diverse data sets from multiple platforms and scales to tackle food security issues at the national level.[17]

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[11] Boryan, C.G., Yang, Z., Sandborn, A., Willis, P. and Haack, B. 2018. Operational Agricultural Flood Monitoring with Sentinel-1 Synthetic Aperture Radar. In: IGARSS 2018 - 2018 IEEE International Geoscience and Remote-sensing Symposium. IGARSS 2018 - 2018 IEEE International Geoscience and Remote-sensing Symposium, Valencia, IEEE, July 2018. https://doi.org/10.1109/IGARSS.2018.8519458.

[12] Fontanelli, G., Crema, A., Azar, R., Stroppiana, D., Villa, P. and Boschetti, M. 2014. Agricultural crop mapping using optical and SAR multi-temporal seasonal data: A case study in Lombardy region, Italy. In: 2014 IEEE Geoscience and Remote-sensing Symposium. IGARSS 2014 - 2014 IEEE International Geoscience and Remote-sensing Symposium, Quebec City, QC, IEEE, July 2014. https://doi.org/10.1109/IGARSS.2014.6946719.

[13] Cai, Z., Wei, H., Hu, Q., Zhou, W., Zhang, X., Jin, W., Wang, L. et al. 2023. "Learning spectral-spatial representations from VHR images for fine-scale crop type mapping: A case study of rice-crayfish field extraction in South China." *ISPRS Journal of Photogrammetry and Remote-sensing*, 199: 28–39. https://doi.org/10.1016/j.isprsjprs.2023.03.019.

[14] Teke, M., Deveci, H.S., Haliloğlu, O., Gürbüz, S.Z. and Sakarya, U. 2013. A short survey of hyperspectral remote-sensing applications in agriculture. In: 2013 6th International Conference on Recent Advances in Space Technologies (RAST). 2013 6th International Conference on Recent Advances in Space Technologies (RAST), June 2013. https://doi.org/10.1109/RAST.2013.6581194.

[15] Bhanumathi, V. and Kalaivanan, K. 2019. "The Role of Geospatial Technology with IoT for Precision Agriculture." In *Cloud Computing for Geospatial Big Data Analytics*, Springer Nature Switzerland. https://doi.org/https://doi.org/10.1007/978-3-030-03359-0_11.

[16] Kahveci, M. 2017. Contribution of GNSS in precision agriculture. In: 2017 8th International Conference on Recent Advances in Space Technologies (RAST). 2017 8th International Conference on Recent Advances in Space Technologies (RAST), Istanbul, Turkey, IEEE, June 2017. https://doi.org/10.1109/RAST.2017.8002939.

[17] Shi, Y., Ji, S., Shao, X., Tang, H., Wu, W., Yang, P., Zhang, Y. and Ryosuke, S. 2014. "Framework of SAGI Agriculture Remote Sensing and its Perspectives in Supporting National Food Security." *Journal of Integrative Agriculture*, 13(7): 1443–1450. https://doi.org/10.1016/S2095-3119(14)60818-2.

The potential of space-based technologies for agriculture and sustainable development is recognized as one of the four objectives of the "Space2030" Agenda,[18] a forward-looking strategy for reaffirming and strengthening the contribution of space activities and space tools and the achievement of global agendas. It addresses the long-term sustainable development concerns of humankind, which called for the maximization of the role of the space sector as a significant driver in sustainable development, including for agriculture and food security, by enhancing the contributions of space technology and applications, as well as the integration of satellite, aerial and ground data, especially in vulnerable regions.

In recent years, several international programmes have also been launched to support agricultural monitoring using space-based technologies, including remote-sensing data. For example, in 2011 the Group on Earth Observations Global Agricultural Monitoring (GEOGLAM) was established to enhance global food security by leveraging satellite data with the purpose of improving crop monitoring, yield forecasts and early warning systems, and facilitating better agricultural decision-making and responses to food crises worldwide. In 2014, the Sentinel-2 for Agriculture (S2-Agri) Project was launched to provide global Earth observation products specifically for crop monitoring. These products include global vegetation status maps, crop type maps for major crops by region, dynamic cropland masks and monthly cloud-free composite imagery.[19] Additionally, various national programmes were launched such as in 2008, when the United States Department of Agriculture (USDA) developed its own country-level Cropland Data Layer (CDL) where land cover map and crop data were provided based on various satellite and ground truth data.[20]

These initiatives demonstrate the growing importance of space technology in global, regional and national agricultural monitoring, improving decision-making and helping to combat food crises.

APPLICATIONS OF SPACE DATA IN AGRICULTURE

In the past few decades, space technology has seen a significant surge in its use across various fields. With increased demand for geospatial data, different types of spaceborne platforms, particularly Earth observation and positioning satellites, have been continuously developed and launched. As a result, research institutions, government agencies and

[18] United Nations. 2021. The "Space2030" Agenda: space as a driver of sustainable development.

[19] Bontemps, S., Arias, M., Cara, C., Dedieu, G., Guzzonato, E., Hagolle, O., Inglada, J. et al. 2015. "Sentinel-2 for agriculture": Supporting global agriculture monitoring. In: 2015 IEEE International Geoscience and Remote Sensing Symposium (IGARSS). IGARSS 2015 - 2015 IEEE International Geoscience and Remote Sensing Symposium, Milan, Italy, IEEE, July 2015. https://doi.org/10.1109/IGARSS.2015.7326748.

[20] USDA. 2015. CropScape - Cropland Data Layer. U.S. Department of Agriculture, cited 17 January 2024. https://agdatacommons.nal.usda.gov/articles/dataset/CropScape_-_Cropland_Data_Layer/24660315/1.

international organizations, as well as the private sector, are increasingly using these technologies to obtain timely information that supports more informed decision-making. This has gradually increased the accessibility and utilization of remote-sensing data for finding solutions to addressing complex challenges, particularly in agriculture. However, the vast amounts of raw data generated by remote sensing and GNSS often require specialized analytical tools, such as statistical analysis, to extract meaningful information.[21]

This publication focuses on two types of space data critical for agriculture: Earth observation data and positioning and navigation data from navigation satellite systems.

EARTH OBSERVATION DATA

Earth observation is the gathering of information about the Earth's surface, water and atmosphere via ground-based, airborne and satellite remote-sensing platforms. Information from satellite imagery, unmanned aerial vehicles (UAVs) and ground-based sensors provides a wealth of insights that can be harnessed for optimizing farming practices, ensuring resource efficiency and promoting sustainable agricultural development.

Remote-sensing technologies have become indispensable tools for collecting vast amounts of data across agricultural landscapes. Satellites equipped with high-resolution sensors capture detailed imagery, enabling the monitoring of crop health, soil conditions and environmental factors. UAVs equipped with specialized sensors offer a more granular perspective, capturing real-time data at a localized level. Ground-based sensors provide valuable information on microclimates, soil moisture levels and nutrient content. The fusion of data from these diverse sources creates a holistic understanding of the agricultural ecosystem, forming the basis for data-driven decision-making.

Space-derived Earth observation data are collected using various sensors that measure parameters useful for agricultural purposes. These sensors can be broadly classified into two categories:

- *Active sensors*: These sensors emit electromagnetic waves to the Earth and then measure parameters (e.g., amplitude, delay, phase shift, polarization) of the reflected waves. As they carry their own source of electromagnetic waves, it is possible to tune them to see through clouds and operate in all weather conditions, independent of the solar illumination (day and night operations). The two primary types of active sensors used in agriculture are:
    - Synthetic aperture radar (SAR): SAR can be useful to monitor the crop canopy and soil moisture. It is extremely valuable for assessing damage during disasters, especially floods, as it can see through clouds and easily detect surface water.

[21] Global Strategy to improve Agricultural and Rural Statistics (GSARS). 2017. Handbook on Remote Sensing for Agricultural Statistics. GSARS Handbook: Rome.

  - Light detection and ranging (LiDAR): LiDAR can be used in precision farming, particularly for irrigation planning and optimizing field layouts. It also aids in identifying risks related to soil erosion.
- *Passive sensors*: These sensors rely on electromagnetic waves that are reflected or emitted by the Earth but are not sent by the sensor itself. There is a wide variety of sensors, but it is worth mentioning two types as they are widely used in agriculture:
  - Multispectral sensors: These sensors capture imagery across a few wavelength bands (e.g., red, green, blue, near-infrared) and are commonly used for analysing surface features and vegetation.
  - Hyperspectral sensors: These sensors capture images across many contiguous bands, providing detailed information that can be used to detect and identify crop conditions, such as disease or pest infestation, nutrient deficiencies or water stress.

While sensor type is important for determining the use of an application, other factors such as revisit time and spectral, temporal and radiometric resolution are also critical in matching a sensor to a specific agricultural need.

GLOBAL NAVIGATION SATELLITE SYSTEMS

In agricultural applications, GNSS provides essential location information for various operations. Two key aspects must be considered when using GNSS:

- Coverage:
  - Global coverage: provides continuous coverage worldwide
  - Regional coverage: provides coverage over specific regions
  - Local coverage: delivers high-precision positioning in localized areas
- Receiver type:
  - Single frequency: these receivers use signals from one frequency band
  - Dual-frequency: these receivers use signals from two frequency bands; they are more accurate and less prone to errors, making them the preferred choice for high-precision applications such as surveying and mapping

CASES OF SPACE TECHNOLOGY USE FOR AGRICULTURE

In the realm of agricultural development and food security, the integration of space technology and multi-stakeholder collaboration has proven transformative. This section highlights two notable case studies that exemplify the impact of leveraging satellite data and global partnerships in addressing complex agricultural challenges. The first case study focuses on assessing the impacts of the COVID-19 pandemic on food security in Togo by utilizing satellite imagery and advanced data analytics. The second case study explores an agro-informatics platform, which integrates information from diverse sources to enhance agricultural development and food security. Together, these case studies illustrate how the innovative use of space technology and collaborative frameworks can address urgent global challenges in agriculture, demonstrating the profound impact of combining technological advancements with international cooperation.

CASE STUDY

Multi-stakeholder collaboration with the United States National Aeronautics and Space Administration (NASA) Harvest, Planet Labs and the University of Maryland[a]

Involvement

NASA (public sector), Planet Labs (private sector), University of Maryland (research and academia), Government of Togo (public sector)

Solution

NASA Harvest, through its global agricultural monitoring initiative, aimed to understand and address the impacts of the COVID-19 pandemic on food security in Togo. By utilizing satellite imagery and data analytics, NASA Harvest, in collaboration with Planet Labs and the University of Maryland, has provided critical insights on the agricultural situation in Togo. By applying machine learning to ESA Sentinel-2 data and the NASA Landsat satellite United States Geological Survey (USGS), in combination with the Skysat imagery of Planet Labs, a new method to rapidly generate crop maps of Togo was developed without the need for in situ data.

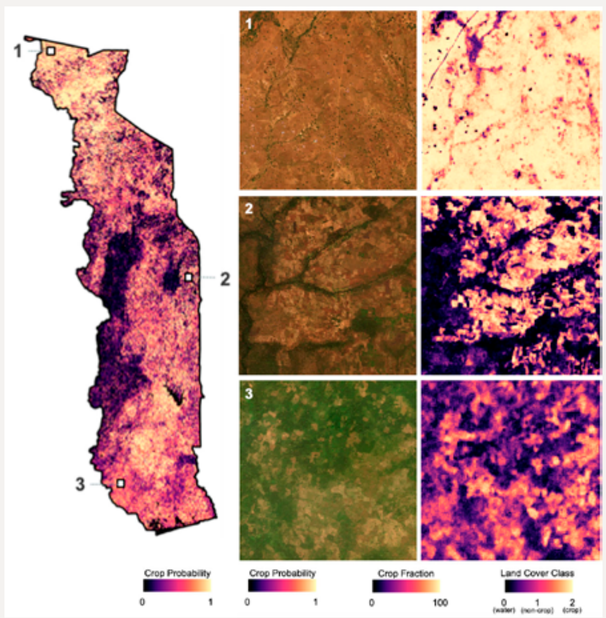
Impact

This enabled the Government of Togo to quickly respond through relief programmes in the midst of a pandemic.

This initiative demonstrates the importance of international and multi-stakeholder collaboration and the use of space technology in addressing complex global challenges where urgent decision-making is needed.

Multi-stakeholder collaboration with the United States National Aeronautics and Space Administration (NASA) Harvest, Planet Labs and the University of Maryland[a] *(continued)*

Figure 2. NASA Harvest's output result 10-m Togo crop map



[a]NASA Harvest. 2020. Rapid Response to Ripple Effects Of COVID-19: Food Security in Togo. In: NASA Harvest, https://www.nasaharvest.org/news/a-hrefhttpsnasaharvestorgnewsrapid-response-ripple-effects-covid-19-food-security-togorapid-response-to-ripple-effects-of-covid-19-food-security-in-togoa?rq=rapid%20response%20ripple.

CASE STUDY

FAO Agro-Informatics Platform

Involvement

FAO, as well as multiple stakeholders from the private and public sectors, including academia, research centres and civil society.

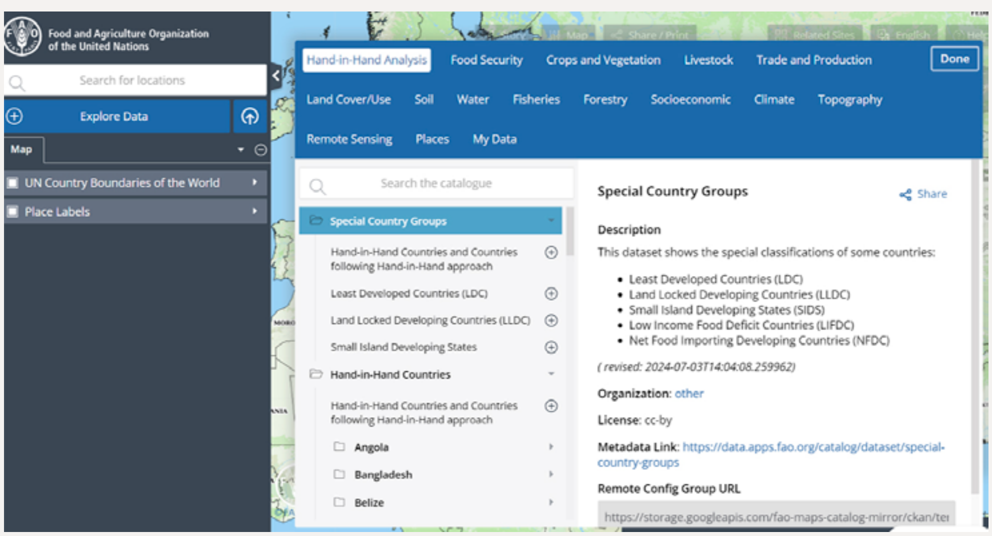
Solution

The FAO Agro-Informatics Platform, the geospatial component supporting the Hand-in-Hand (HiH) Initiative, is a collaborative effort led by FAO to drive agricultural development and food security through leveraging the use of data and technology, including Earth observation and GNSS, as well as global partnerships. It implements a geospatial catalogue with more than 2 million layers of open access data ranging from satellite-derived products to agricultural statistics. These data sets are sourced from the FAO thematic divisions as well as from different public data providers including the private sector, national space agencies, research and academic sector, non-governmental organizations and other United Nations entities.

Impact

The platform has had a profound impact in enhancing critical decision-making and supporting the Sustainable Development Goals. It supports data-driven agricultural decision-making through providing access to a wide range of geospatial and agricultural data which supports public and private sectors from the local to the national level across the globe. As of 2024, there are over 70 member countries supported by the HiH Initiative. It also promotes capacity-building and knowledge-sharing by serving as a centralized hub for capacity development for member countries, which helps strengthens the capacity of local institutions and stakeholders to use geospatial data for agriculture and food security.

Figure 3. The FAO Hand-in-Hand Geospatial Platform Dashboard



A scientist pointing at a section of the satellite imagery of forested areas. © FAO

A drone flies as farmers work on a crop field at a farm at Tengeru, near the city of Arusha, United Republic of Tanzania. © FAO

I.

THE SPACE TECHNOLOGY VALUE CHAIN FOR AGRICULTURE AND FOOD SECURITY

INTRODUCTION TO THE SPACE TECHNOLOGY AGRICULTURAL VALUE CHAIN

Space technology has become integral to enhancing agricultural practices and ensuring global food security. Earth observation satellites and GNSS each offer unique capabilities that, when combined, significantly boost the potential for agriculture monitoring, including precision applications. Earth observation satellites provide a range of sensing technologies, including optical, hyperspectral and SAR sensing, while GNSS satellites deliver critical positioning information. The integration of these data sources, alongside ground-based sensors, enhances the development of solutions and products that are crucial for improving agricultural productivity and achieving global food security. Moreover, the incorporation of automation and artificial intelligence (AI) with information technologies further amplifies these capabilities, enabling faster, more accurate decision-making processes, while reducing the need for manual intervention and ensuring more efficient use of resources.

To promote the effective use of space technology for agriculture, this publication aims to closely examine the current landscape and identify gaps across key segments of the space value chain within the context of agriculture. This section will introduce the concept of the space value chain, providing insights into the broader space ecosystem and highlighting its significance for all stakeholders involved.

The space value chain encompasses the various segments – upstream, midstream and downstream – and the activities related to the design, development, production and utilization of space-related products and services, data processing, access to data, data analytics and space applications. It is a complex and interconnected system involving diverse actors such as policymakers, space agencies, commercial space companies, agricultural businesses, research institutions and end users.

The value chain of space technology for agricultural applications, as depicted in figure 4, illustrates the progression from conceptualizing and developing Earth observation or GNSS satellites to the operationalization of the information retrieval process.[22] This encompasses mission planning aligned with stakeholders' requirements, data acquisition, pre-processing, analysis, and ultimately, the transformation of acquired data into actionable information for end users in agriculture. Typically, space activities, products and services are categorized in three main segments, i.e. the upstream or space segment, the midstream segment and the downstream or user segment. The definition of these three segments is shown in figure 4.

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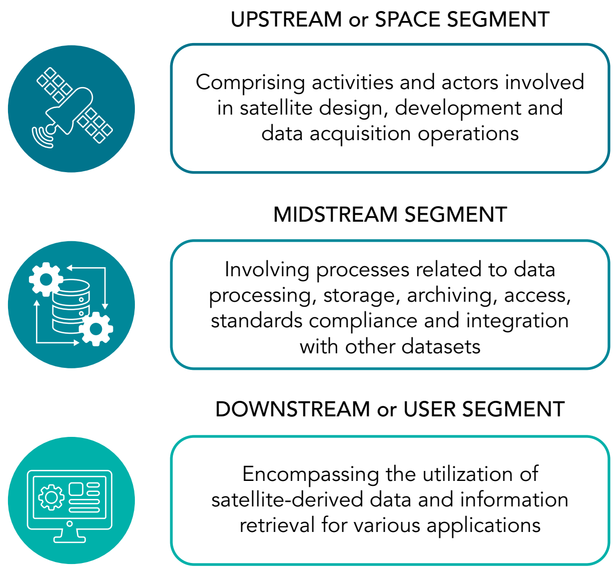
[22] European Union Agency for the Space Programme. 2022. *EUSPA EO and GNSS Market Report.2022/Issue 1*. LU, Publications Office. https://data.europa.eu/doi/10.2878/94903.

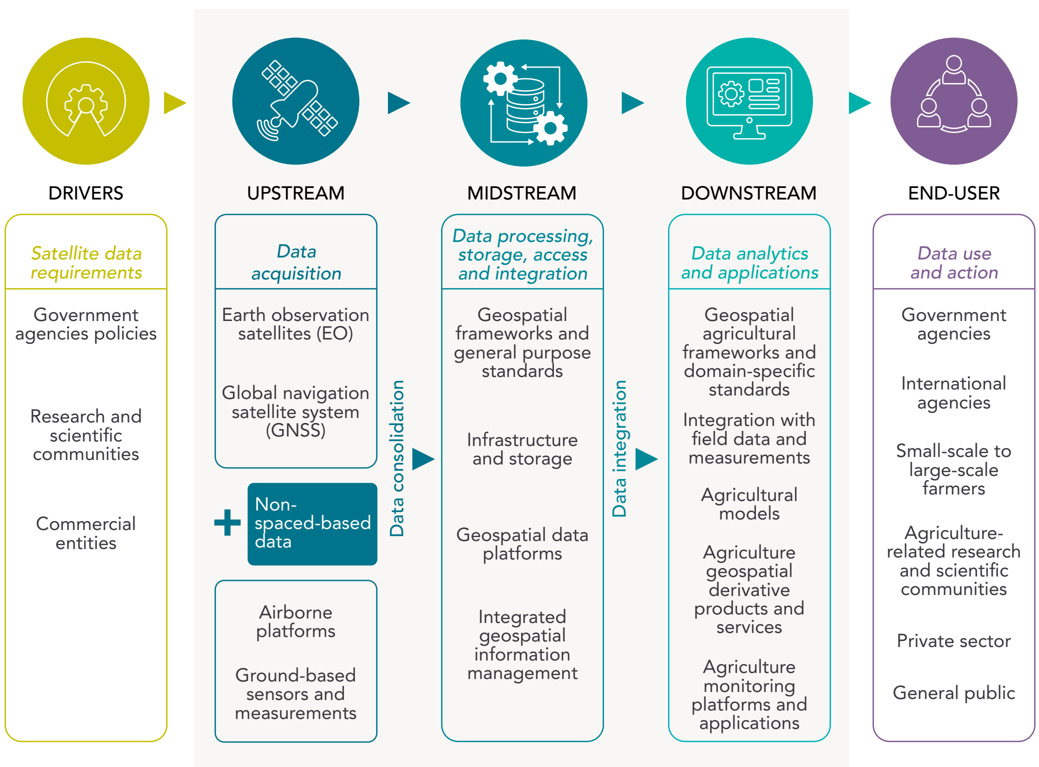
Figure 4. Overview of the upstream, midstream and downstream segments in the space sector value chain



The end-to-end perspective provided by the three-segment conceptualization is crucial for understanding the interdependencies within the value chain. Each segment – upstream, midstream and downstream – affects and relies on the others, creating a complex system where coordination is key. This is further highlighted in figure 5 where the space value chain is reported with its interactions with driver entities, end users and non-space data. Hence, the upstream segment considers Earth observation and GNSS data, which are complemented for application in agriculture with non-space data coming (for instance) from airborne platforms or ground measurements. The midstream is focused on data consolidation by means of processing, storage and applying standardized pre-processing. Then, working on data integration, the downstream segment transforms the stored data into available information for the users. Ensuring alignment among these segments and establishing a feedback loop from downstream to upstream are essential for optimizing the entire value chain. It is therefore expected that an overview of each segment of the space value chain would provide insights to stakeholders from one segment on gaps, opportunities or needs for collaboration in other segments, and, potentially, may lead to the coordination of investments.

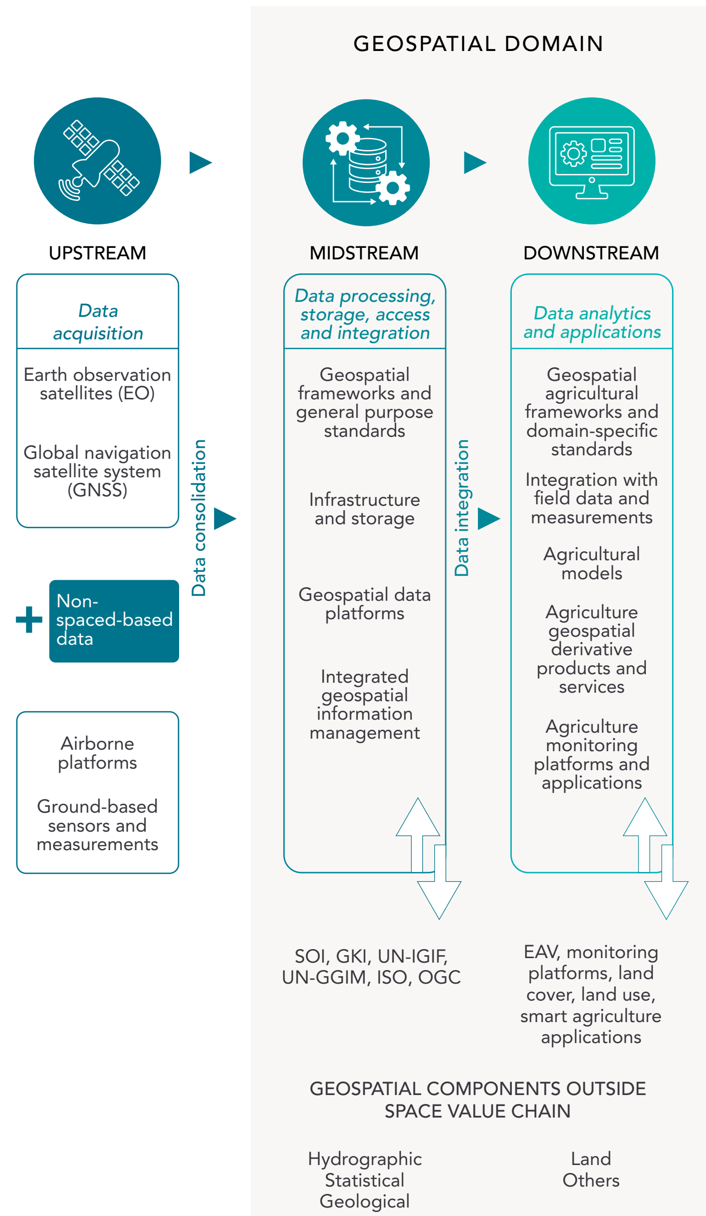
It is noteworthy that the space value chain contributes to the geospatial domain, providing part of the data and infrastructure, as depicted in figure 6, where the interaction and overlap between the space value chain and the geospatial domain is reported. The diagram emphasizes geospatial components outside the space value chain, such as hydrographic, statistical and geological information, which contribute to the broader geospatial domain and provide additional context for space-derived data. In this interplay, the geospatial domain both complements and extends the space value chain, ensuring that spatial data are fully utilized across various sectors, with standards from organizations such as the International Standards Organization (ISO), the Open Geospatial Consortium (OGC), and the United Nations Committee of Experts on Global Geospatial Information Management (UN-GGIM) helping to maintain consistency across different platforms and data sets. This integration results in more comprehensive geospatial applications, and improves accuracy and decision-making across sectors such as agriculture, urban planning and environmental monitoring.

Figure 5. Earth observation and global navigation satellite systems value chain for agricultural applications



Source: FAO/UNOOSA

Figure 6. Interaction and overlapping between the space value chain and the geospatial domain



UPSTREAM SEGMENT: OVERVIEW OF EARTH OBSERVATION AND GLOBAL NAVIGATION SATELLITE SYSTEMS MISSIONS

The upstream segment plays a foundational role in the space value chain, encompassing the design, development and launch of satellites and sensors that collect critical data, which are essential for monitoring and analysing agricultural conditions, enabling innovations in farming, land-use monitoring and food security. This section explores the key Earth observation and GNSS missions, their evolution and their applications in agriculture, highlighting the technological advancements that drive improvements in data acquisition and analysis.

OVERVIEW OF EARTH OBSERVATION MISSIONS

Introduction to Earth observation missions for agriculture

In 1972, the first Earth observation mission for agricultural applications was developed and launched from a collaboration between NASA and the United States National Academy of Sciences. Landsat-1, also known as the Earth Resources Technology Satellite, was equipped with optical sensors using visible and near-infrared bands, enabling the monitoring of the Earth's surface.[23] Since then, the Landsat programme has continued to evolve, releasing additional Earth observation satellites that build on mission continuity and design improvements, with Landsat-9 being the latest satellite to be launched in 2021 and Landsat Next planned for release in late 2030.[24] A complementary mission to the Landsat programme is the Copernicus programme, launched in 2014, managed and coordinated by the European Commission, which relies on different operative satellite platforms (Sentinel-1, Sentinel-2, Sentinel-3, Sentinel-5P, Sentinel-6), comprising optical remote-sensing satellites (Sentinel-2A and Sentinel-2B). It is crucial to acknowledge that this section only skims the surface and does not present a comprehensive list of optical remote-sensing programmes.[25]

In parallel, the advent of spaceborne SAR technology for Earth observation started with the launch of the Quill satellite in 1964 under a highly classified experimental programme of the United States National Reconnaissance Office.[26] The use of SAR has proven to be

[23] NASA. 2021. Landsat 1 | Landsat Science, cited 21 January 2024, https://landsat.gsfc.nasa.gov/satellites/landsat-1/.

[24] NASA. 2023. Landsat Next | Landsat Science, cited 21 January 2024, https://landsat.gsfc.nasa.gov/satellites/landsat-next/.

[25] Wong, M.S., Zhu, X., Abbas, S., Kwok, C.Y.T., Wang, M. 2021. "Optical Remote Sensing." In: Shi, W., Goodchild, M.F., Batty, M., Kwan, M.P., Zhang, A. (eds.) *Urban Informatics. The Urban Book Series.* Springer, Singapore. https://doi.org/10.1007/978-981-15-8983-6_20.

[26] NRO. undated. > About NRO > history > history-quill, cited 21 January 2024, www.nro.gov/About-NRO/history/history-quill/.

beneficial for consistent agricultural monitoring since it can capture data regardless of cloud cover – a limitation faced by optical satellites. The Sentinel-1A and 1B constellations, launched by ESA as part of the Copernicus Programme in 2014 and 2016, respectively, are tasked with monitoring the land surface of the Earth, including forests, water bodies, soil and agriculture. Although the development of SAR satellites started with the public sector, the commercial space sector has been contributing greatly to the increasing development of SAR satellites with varying monitoring capabilities[27] and constellations of up to 34 units.[28] Other commercial SAR satellites currently in orbit include those from Maxar Technologies, Umbra Space and Capella Space in the United States, as well as Synspective and iQPS in Japan. Additionally, Singapore has recently launched NeuSAR.[29]

More advanced sensors, such as hyperspectral and LiDAR technologies, are also emerging on the Earth observation scene, representing the next generation of satellite technology. Hyperspectral satellites have a greater number of bands – up to several hundreds – and a narrower wavelength range compared to typical optical multispectral Earth observation satellites. The higher spectral resolution of hyperspectral sensors permits the detection of a higher level of detail compared to multispectral sensors. Only the spatial resolution will usually be lower than multispectral images. The first hyperspectral satellite, Hyperion, was sent to orbit by NASA in 2000 aboard the Earth Observing-1 (EO-1) spacecraft and had a ground sampling distance of 30 metres. The Hyperion Imaging Spectrometer was developed to assess the capability of a space-based hyperspectral sensor for Earth observation applications.[30] This was then proven to be useful in agriculture applications such as crop disease monitoring,[31] land-use classification and vegetation properties estimation,[32, 33] thanks to the estimation of a continuous spectral signature for soil, trees and crop type. Since then, technology has rapidly improved, with different hyperspectral missions being launched or planned to be launched soon by national and international space agencies. One example is PRISMA or the Hyperspectral Precursor of the Application Mission satellite, a mid-resolution hyperspectral satellite, owned by the Italian Space Agency (ASI) with an expected five-year mission lifespan, which focuses on global monitoring of natural resources, particularly land cover and crops.[34]

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[27] ESA. 2021. ICEYE, the World's First SAR New Space Constellation - Earth Online, cited 21 January 2024. https://earth.esa.int/eogateway/news/iceye-the-world-s-first-sar-new-space-constellation.

[28] ICEYE. 2024. Satellites | ICEYE, cited 16 August 2024, www.iceye.com/satellites.

[29] ESA. 2023. NeuSAR – eoPortal, cited 21 January 2024, www.eoportal.org/satellite-missions/neusar#missionstatus.

[30] Folkman, M.A., Pearlman, J., Liao, L.B. and Jarecke, P.J. 2001. "EO-1/Hyperion hyperspectral imager design, development, characterization, and calibration.". Second International Asia-Pacific Symposium on Remote Sensing of the Atmosphere, Environment, and Space, Sendai, Japan, 8 February 2001. https://doi.org/10.1117/12.417022.

[31] Apan, A., Held, A., Phinn, S. and Markley, J. 2004. "Detecting sugarcane 'orange rust' disease using EO-1 Hyperion hyperspectral imagery." *International Journal of Remote Sensing*, 25(2): 489–498. https://doi.org/10.1080/01431160310001618031.

[32] Eckert, S. and Kneubühler, M. 2004. Application of HYPERION data to agricultural land classification and vegetation properties estimation in Switzerland. https://doi.org/10.5167/UZH-98420.

[33] Aneece, I. and Thenkabail, P. 2018. "Accuracies Achieved in Classifying Five Leading World Crop Types and their Growth Stages Using Optimal Earth Observing-1 Hyperion Hyperspectral Narrow bands on Google Earth Engine." *Remote Sensing*, 10(12): 2027. https://doi.org/10.3390/rs10122027.

[34] EO Portal. 2024. PRISMA (Hyperspectral) – eoPortal, cited 14 August 2024, www.eoportal.org/satellite-missions/prisma-hyperspectral#eop-quick-facts-section.

All the aforementioned missions operate in low Earth orbits (LEOs), with an altitude of approximately between 500 to 800 kilometres, which guarantees spatial resolutions in the order of metres and submetres, and revisit times in the order of days at the Equator. Other remote-sensing satellites, mostly used for meteorological services, are placed in geostationary orbits (GEO), at an altitude of about 36,000 km, where the satellite appears to remain fixed over a single point on the Earth's surface. In this case, while the spatial coverage is larger than for LEO satellites, the spatial resolution is lower, typically in the range of kilometres. However, the advantage of geostationary satellites is their ability to provide near-continuous data, with temporal resolutions of minutes, which is essential for monitoring weather patterns and dynamic phenomena.

Increasing access to space-based data

As technology advances, sensors are becoming more advanced and satellite development and launches are becoming less costly. This trend has significantly impacted the space sector, leading to an increase in the number of satellites launched globally, particularly after 2010 when many countries began encouraging private-sector participation in space missions.

Since the beginning of the space age in 1957, over 17,000 satellites have been successfully launched.[35] Notably, in 2023, there were 212 successful launches[36] and deployments from the International Space Station, resulting in the placement of approximately 2,900 new satellites in Earth orbit or beyond.[37]

In recent years, more countries have invested in their own Earth observation constellations as part of their broader national space strategies. This trend has been observed across several regions, reflecting the growing importance of satellite technology in advancing capabilities in remote sensing and other applications.

While more countries are achieving satellite development and launch capabilities, more effort is needed to ensure that other nations are not left behind. Leveraging international cooperation and ensuring that more countries benefit from satellite development and launch capabilities, would promote a more equitable distribution of technological capacities worldwide and enhance responsiveness to land and agriculture issues.

Initiatives such as the Virtual Constellations (VC) initiative under the Committee on Earth Observation Satellites (CEOS), a mechanism that promotes international coordination of civil space-based Earth observation programmes, aim at advancing and optimizing space-based

[35] European Space Agency (ESA), Space safety, "Space debris by the numbers", 6 December 2023.
[36] Available at www.space-track.org/.
[37] Database and Information System Characterising Objects in Space website (DISCOS). Available at https://discosweb.esoc.esa.int/.

and ground-based efforts, as well as data delivery systems among its member agencies.[38] The VC initiative harmonizes data acquisition and processing across these agencies, supports standardized data products such as CEOS Analysis Ready Data (ARD), and addresses data gaps to meet global user needs. At present it consists of Atmospheric Composition VC (AC-VC) for collecting and delivering data for monitoring air quality and climate-related changes; Coastal Observations Applications Services and Tools (COAST-VC) for coastal applications such as hazards and risks in coastal zones; Land Surface Imaging (LSI-VC) for harmonizing data and coordination of efforts to fill archive data gaps; Ocean Color Radiometry (OCR-VC) for producing calibrated and validated ocean colour products from satellite and in situ measurements; Ocean Surface Topography (OST-VC) for data sets to monitor surface topography of oceans globally; Ocean Surface Vector Wind (OSVW-VC) for collection of high-quality ocean surface vector wind data; Precipitation (P-VC) for calibration and validation; as well as the harmonization of global precipitation measurements which are crucial for the prediction of weather events; and sea surface temperature (SST-VC). All the above offer precious resources that can collect and gather data to observe and monitor a specific Earth system parameter.

Continuing and expanding collaboration is crucial in maximizing the impact and value of data derived from satellites. By sharing resources and information, this synergistic approach enables a more effective response to address challenges in agriculture and food security. By coordinating efforts, the international community can better harness satellite technology to tackle pressing environmental and agricultural issues.

OVERVIEW OF NAVIGATION SATELLITE SYSTEMS

The International Committee on Global Navigation Satellite Systems (ICG), to which UNOOSA serves as executive secretariat, promotes the development and use of GNSS, focusing on enhancing their interoperability and compatibility.[39] ICG works to ensure that the benefits of GNSS are maximized for the global community by improving navigation, positioning and timing services. It fosters cooperation among GNSS providers and users, helping to support a wide range of applications, from transportation to emergency response.

[38] CEOS. 2024. Committee on Earth Observation Satellites (CEOS) Land Surface Imaging Virtual Constellation (LSI-VC) Terms of Reference, cited 16 August 2024.

[39] UNOOSA. 2024. International Committee on Global Navigation Satellite Systems (ICG), cited 16 August 2024, www.unoosa.org/oosa/en/ourwork/icg/icg.html.

Global navigation satellite systems

There are currently four global operating systems and one in development. The BeiDou system (BDS) of China, Galileo of the European Union, the Global Navigation Satellite System (GLONASS) in the Russian Federation and the Global Positioning System (GPS) in the United States currently offer services worldwide, with the Korean Position System from the Republic of Korea currently in development. In the 2024 report of the Scientific and Technical Subcommittee of the Committee on the Peaceful Uses of Outer Space, the different system owners provided status updates: BDS improved with two new launches in 2023 and has been introducing innovations that seamlessly integrate the position, navigation and timing functions of the system. The European Satellite Navigation System (Galileo) offers metre-scale accuracy and a new high-accuracy service. GPS celebrated its fiftieth anniversary in 2023 with upgrades through GPS Block III and new capabilities for GPS Block IIIF satellites. In the Russian Federation, GLONASS operated on open access navigation signals in the L1 and L2 bands, marked by the 2023 launch of the first satellite of the fourth generation of GLONASS, the GLONASS-K2 satellite. Finally, the Korean Positioning System of the Republic of Korea was initiated, aiming for completion by 2035.[40] GNSS satellites primarily operate in medium Earth orbit (MEO), typically at altitudes between 19,000 and 24,000 kilometres, ensuring global coverage and high accuracy for position, navigation and timing services.

Regional navigation satellite systems

These provide regional coverage and can often provide augmented and enhanced services with additional satellites. There are several ongoing national and regional navigation satellite systems: BDS introduced innovations, including building major services such as the satellite-based augmentation system service. The European Union EGNOS continues operations. India is pursuing two satellite navigation programmes: the GPS-aided Geostationary Augmented Navigation system, a satellite-based augmentation system, and the Indian Regional Navigation Satellite System, also known as "Navigation with Indian Constellation", which was strengthened in 2023 through the launch of the NVS-01 satellite. The Quasi-Zenith Satellite System of Japan, also known as "Michibiki," provides three types of services: a service complementing GPS with ranging signals, a high-accuracy service that augmented GNSS by providing error corrections, and a messaging service for disaster risk reduction. The Republic of Korea is developing a satellite-based augmentation system and began providing safety-of-life services in 2023 with the first geostationary satellite launched in 2022. The Pakistan Space-Based Augmentation System (Pak-SBAS) had been implemented with support from the Pakistan Civil Aviation Authority and would utilize GPS and BDS

[40] Report of the Scientific and Technical Subcommittee on its sixty-first session, held in Vienna from 29 January to 9 February 2024. https://undocs.org/A/AC.105/1307.

signals, scheduled to enter into service in 2024.[41] Regional navigation satellite systems primarily operate in a combination of geosynchronous orbits and geostationary orbits (GEO), providing enhanced accuracy and specialized services over specific regions through satellite-based augmentation systems (SBAS) and additional geostationary satellites.

SATELLITE INTEGRATION

The use of both Earth observation and GNSS satellite data has become increasingly vital across Governments and the public sector, industrial and private actors, non-governmental organizations and the scientific community. However, it is possible to further enhance the capabilities and performance of satellite missions by leveraging an important concept in satellite upstream integration: the space service volume (SSV).

Global navigation satellite systems were designed to provide services to users on land, sea and in the air. Now, they are also being used in space, in higher orbits, in what is known as SSV. This refers to the region surrounding Earth where GNSS provides useful navigation signals for space-based users (e.g., satellites and spacecraft). Unlike the terrestrial service volume, which is intended for users on or near the Earth's surface, SSV is critical for users operating at higher altitudes, such as those in low Earth orbit or even geostationary orbits.

This integration brings benefits for certain satellite configurations such as providing improved relative positioning between spacecraft, enabling formation flying (the flight of multiple objects in coordination), which could impact how satellite constellations operate. In addition, the use of a multi-GNSS SSV results in greater availability of enhanced precision information in space, which can improve the on-board processing power of satellites, resulting in enhanced observations and new and enhanced applications, including for agriculture. The integration of information obtained from both space-based satellite types can further drive the development of applications used in agriculture and help to ensure global food security.

[41] Report of the Scientific and Technical Subcommittee on its sixty-first session, held in Vienna from 29 January to 9 February 2024. https://undocs.org/A/AC.105/1307.

MIDSTREAM SEGMENT: SATELLITE-BASED DATA MANAGEMENT AND ACCESS

The midstream segment of the space value chain centres on managing and processing data collected by satellites, which includes data storage, archiving and integration with other data sets in support of valorizing space data and information through, for example, geospatial, navigation, telecommunication and connectivity applications.

As we delve deeper into the landscape of the midstream segment, this section provides an overview of spatial data infrastructure (SDI), initiatives such as the United Nations Integrated Geospatial Information Framework (UN-IGIF) that provides strategic guidance for Governments to establish an integrated geospatial information framework, geospatial knowledge infrastructure (GKI) and standards. With a combination of SDI as the foundational layer, national capacity development through UN-IGIF, and the advancement of GKI, the transformation of geospatial data into actionable knowledge, as emphasized by UN-GGIM, the potential of geospatial science and technology can be realized on a global scale.

OVERVIEW OF SPATIAL DATA INFRASTRUCTURE AND GEOSPATIAL READINESS

Spatial data infrastructure

With the increase in availability of spatial data across various sources and platforms, both Governments and the private sector have realized the need for a better system to manage this increasing volume of information effectively. The use of common standards across data and services within a specific infrastructure has proven to be essential. Defined as a "framework of policies, institutional arrangements, technologies, data and people that enable the effective sharing and use of geographic information", SDI creates a framework to enable an efficient way of managing, accessing and sharing geospatial information across different stakeholders and decision makers.[42] SDI serves as the foundation for organizing, cataloguing and providing access to geospatial data ensuring their accessibility and interoperability, creating a solid basis for efficient data management and enabling the development of services and applications across sectors. The importance of SDI was internationally recognized by various entities including the Global Spatial Data Infrastructure (GSDI) association. To ensure the usefulness of data and information for agriculture and other sectors, enhancing

[42] Bernard, L.; Craglia, M.; Gould, M.; Kuhn, W. 2005. Towards an SDI research agenda. In Proceedings of the eleventh EC GIS and GIS Workshop-ESDI: Setting the Framework-Abstracts Handbook, Alghero, Sardinia, Italy, 29 June–1 July 2005; pp. 147–151.

capacities in the use of space data in SDI is critical at different levels including for specific thematic areas.

Thematic space data infrastructure

There is a growing trend towards developing thematic SDIs to cater to specific environmental use cases. These SDIs are designed to provide comprehensive and detailed information pertaining to environmental issues such as disaster management,[43] arctic region monitoring,[44] sustainable land management[45] and precision agriculture.[46]

Several SDI frameworks focused on agricultural solutions and system development have recently been proposed. A recent study[47] demonstrated the use of open international standards provided by OGC to create a precision agriculture tool to increase accessibility and integration with multiple data and services, and to drive the digitalization of agriculture. It considered multi-sensor and platform data collection and acquisition utilizing OGC Sensor Web Enablement, data management (storage and handling) as well as analysis using OGC data standards to visualization using the OGC Web Mapping Service (WMS) and Web Feature Service.

To address land degradation and the implementation of soil protection measures in Europe, an SDI for land planning and applications was developed and implemented in the Sicilian region of Italy by the Council for Agricultural Research and Economics.[47] Sicily, the largest island in the Mediterranean, is highly vulnerable to land degradation, facing significant risk of desertification due to soil erosion, salinization and aridity. Although several studies have already demonstrated these threats, a framework to monitor their impact is missing. This research established SOILPRO, a reference monitoring system considering localized conditions with the aim of scaling it up to other regions through collaboration with local authorities and farmers.

An assessment report on developing a specific SDI for agriculture[48] emphasizes the need for a well-coordinated system focused on the agri-environmental sector. This necessity arises from the increasing demand for collaborative efforts in data coverage, interoperability and access. Agro-environmental indicators, which can be quantified and derived from geospatial

[43] Mansourian, A., Rajabifard, A., Valadan Zoej, M.J. and Williamson, I. 2006. "Using SDI and web-based system to facilitate disaster management." *Computers & Geosciences*, 32(3): 303–315. https://doi.org/10.1016/j.cageo.2005.06.017.

[44] Li, W., Yang, C., Nebert, D., Raskin, R., Houser, P., Wu, H. and Li, Z. 2011. "Semantic-based web service discovery and chaining for building an Arctic spatial data infrastructure." *Computers & Geosciences*, 37(11): 1752–1762. https://doi.org/10.1016/j.cageo.2011.06.024.

[45] Groot, R. 1997. "Spatial data infrastructure (SDI) for sustainable land management." *ITC Journal*, 3(4).

[46] Jackenkroll, M. 2020. *Development of a Spatial Data Infrastructure for Precision Agriculture Applications.* Stuttgart, Germany.

[47] Costantini, E.A.C., Branquinho, C., Nunes, A., Schwilch, G., Stavi, I., Valdecantos, A.and Zucca, C. 2016. "Soil indicators to assess the effectiveness of restoration strategies in dryland ecosystems." *Solid Earth*, 7(2): 397–414. https://doi.org/10.5194/se-7-397-2016.

[48] Orshoven, J.V. 2004. Do we need a spatial data infrastructure for agri-environmental applications?

data sets, drive this need. Although there are existing local to national initiatives for general applications, further development of agriculture-focused solutions requires a globally coordinated effort across different sectors. This is evidenced by the successful implementation of an agricultural SDI in Germany,[49] involving the Chamber of Agriculture and local farmers. The German SDI demonstrated its effectiveness in optimizing agriculture-related operations management and its potential for developing user-driven agricultural solutions.

At the national level, an SDI has the potential to support the integration of spatial data and information within a country and efficiently support national plans and strategies for agriculture and other sectors.

National space data infrastructure

There are multiple SDIs implemented at country-level known as national spatial data infrastructure (NSDI). The development of SDIs on a national level in several countries is driven by the increasing need to manage and centralize geographical information and services obtained from various sources, including different ministries and sectors.

One of the earliest adopters of NSDI is the United States, which established the Federal Geographic Data Committee (FGDC) during the 1990s to lead the implementation of the framework.[50] FGDC is composed of member representatives from different government agencies working to develop practices and standards for geospatial data use. Similarly, the Canadian Geospatial Data Infrastructure was started in 1992 with the objective of making geographical information and technology more accessible and interoperable by utilizing publicly open standards and specifications.[51] Countries such as Malaysia and Nigeria have also initiated the establishment of SDI frameworks (in 2002 and 2003, respectively). Likewise, the National Basic Geographic Information System in China provides an excellent foundation for building various applications including for land-use planning, disaster management and agriculture.

As more countries began adopting the SDI framework, a hierarchical structure model of SDI, highlighting how relationships across levels can be conceptualized.[52] For instance, national SDI can serve as a building block for the development and implementation of regional and global-level SDI frameworks. Simultaneously, national SDI provides additional support at the local and corporate levels by contributing to country-level policies which can further

[49] Nolle, O. 2004. *SDIs: potentials for agriculture*. 15th International Workshop on Database and Expert Systems Applications, IEEE, September 2004.

[50] Bishop, Bradley Wade. Organizing geographic information: The creation of the National Spatial Data Infrastructure. Advances in Classification Research Online, 2007.

[51] Kian Fadaie, Julie Binder Maitra, Valerie E. Hume, Harold Moellering, Henri J.G.L. Aalders, "North American Metadata Standards Developments in Canada and the United States of America.", Editor(s): Harold Moellering, Henri J.G.L. Aalders, Aaron Crane, In International Cartographic Association, *World Spatial Metadata Standards*, Elsevier Science, 2005, Pages 63-82, ISBN 9780080439495, https://doi.org/10.1016/B978-008043949-5/50006-1.

[52] Rajabifard, A., and Williamson, I. P. (2001, April). Spatial data infrastructures: concept, SDI hierarchy and future directions. In Proceedings of GEOMATICS'80 Conference (Vol. 10).

enhance spatial information access and sharing. Countries within a region often share socioeconomic and biophysical characteristics, which may help explain why regional SDIs have the potential to benefit them.

Regional spatial data infrastructure

The objective of regional SDI is to set up platforms that act as a dependable and secure infrastructure for users in need of regional coverage, where regional similarities, from socio-economic or biophysical aspects, may be considered. This will allow them to access and retrieve comprehensive and consistent data sets in a simpler way. Multiple stakeholders across a region with common environmental or socioeconomic challenges can utilize a regional SDI to share and optimize resources and technology. Examples include regional mapping or responses to disaster through emergency management, environmental monitoring or agriculture and forestry management.[53]

Several existing regional SDIs are recognized within the Asia-Pacific region. In 1995, the Permanent Committee on GIS Infrastructure for Asia and the Pacific was established by the United Nations Regional Cartographic Conference for Asia and the Pacific (UNRCC-AP). This aims to implement an Asia-Pacific SDI to facilitate efficient development, access and integration of geospatial data across the region and to foster collaboration in the region on the use of geospatial information.

Meanwhile, in 2007, the European Union passed a directive named Infrastructure for SPatial InfoRmation in Europe, also known as INSPIRE. This directive provides a framework for SDI built from existing national SDI focusing on environmental policies. It aims to improve the access and sharing of geospatial data in Europe across all levels from local to global.[54] INSPIRE is based on existing and established national SDI across member States in the European Union. This is also aligned with the European Union legal framework and two other important directives – the Public Access to Environmental Information Directive and the Open Data Directive.

SDIs, including national SDIs and regional SDIs, play a crucial role in supporting global programmes and frameworks, such as the 2030 Agenda for Sustainable Development. By providing a standardized and accessible platform for geospatial data, SDIs facilitate data-sharing and integration, which are essential for monitoring and achieving the Sustainable Development Goals (SDGs). Specifically, SDIs enable the tracking of progress on global issues such as climate change, poverty reduction, sustainable cities and ecosystem management by

[53] Abbas Rajabifard, Mary-Ellen F. Feeney, Ian P. Williamson, "Future directions for SDI development." *InternationalJournal of Applied Earth Observation and Geoinformation*, Volume 4, Issue 1, 2002, Pages 11-22, ISSN 1569-8432, https://doi.org/10.1016/S0303-2434(02)00002-8.

[54] European Commission, Executive summary of the evaluation of directive 2007/2/EC establishing an Infrastructure for Spatial Information in the European Community. Link: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52016SC0243 (accessed on 24/09/2024).

providing timely and reliable geospatial data to support decision-making at both national and regional levels. These infrastructures promote data interoperability and collaboration, allowing countries and regions to align with global sustainability efforts.[55]

Global spatial data infrastructure

With the increasing need to better address social, economic and environmental issues, including sustainable development, the GSDI association was formed in 2004. Its goal is to advocate for the adoption of spatial data infrastructure, specifically for socioeconomic and environmental applications which can be integrated at all scales. It aims to improve access to geospatial data, services and metadata, and promote the adoption of common standards through collaboration among the public and private sectors, academia and non-governmental organizations around the world.[56] Composed of representatives from different institutions and organizations, it promotes international collaboration and partnerships for local, regional and global SDI. More specifically, its mission is to be the global point of contact in implementing and developing SDI and to promote SDI awareness through capacity-building. This is realized by supporting different countries in developing their own NSDI at a country level.

This initiative has also led to the publication of a reference handbook on how to develop and implement SDI, usually referred to as the "SDI Cookbook".[57] Implementing SDI at the regional level, through improved collaboration and partnership, can contribute to improving the efficiency and cost-effectiveness of geospatial applications and obtaining enhanced benefits from space data and information.

The development and adoption of SDIs at the national, regional and global levels have established an evolving and solid foundation for organizing, managing and sharing geospatial information. SDIs, by enabling data interoperability, accessibility and collaboration, have become essential tools for addressing critical challenges such as environmental monitoring, disaster management and sustainable development. As SDIs mature, their potential to support global initiatives such as the 2030 Agenda for Sustainable Development has become increasingly apparent. However, as the demand for comprehensive and integrated geospatial data grows, there is a need for a more coordinated and holistic approach to geospatial information management.

[55] UN-GGIM. 2020. The role of geospatial data in achieving the 2030 Agenda. United Nations Committee of Experts on Global Geospatial Information Management (UN-GGIM).

[56] Stevens, A. R., Onsrud, H. J., and Rao, M. 2005. Global spatial data infrastructure (GSDI): Encouraging SDI development internationally. In ISPRS Workshop on Service and Application of Spatial Data Infrastructure, XXXVI (4/W6), Oct (pp. 14-16).

[57] D. Nebert. 2004. Developing Spatial Data Infrastructures: The SDI Cookbook. Technical report, Global Spatial Data Infrastructure.

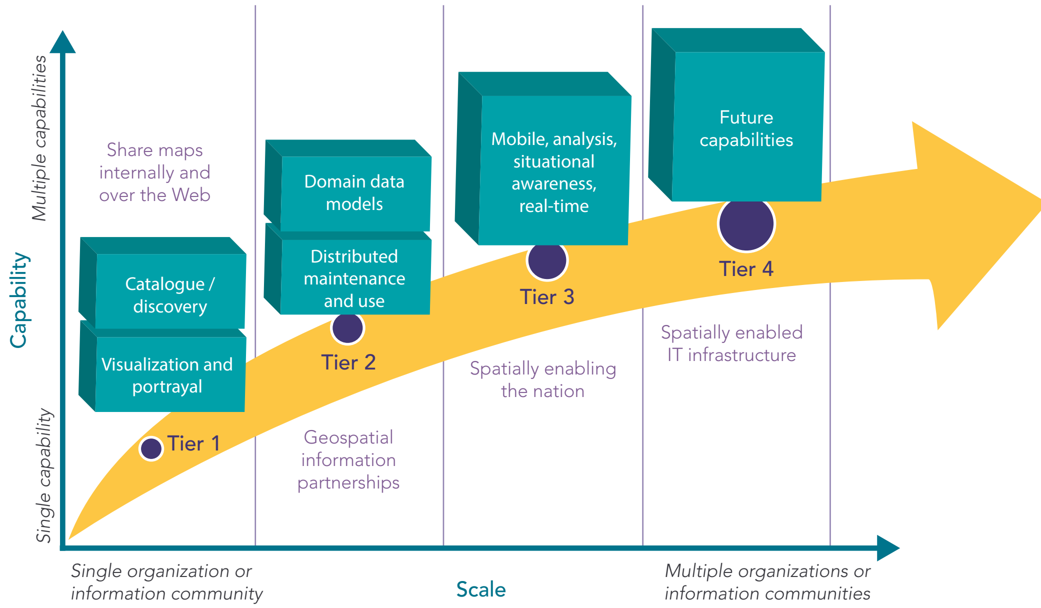
In response to this growing need, the United Nations Integrated Geospatial Information Framework (UN-IGIF) was introduced to provide countries with a strategic guide for improving their geospatial infrastructure and capabilities. Unlike SDIs, which focus on the technical and operational aspects of managing spatial data, the UN-IGIF offers a governance and policy framework designed to help countries strengthen their institutional, legal and technological systems. By complementing and enhancing the implementation of national and regional SDIs, UN-IGIF enables countries to better leverage geospatial data for informed decision-making, especially in the context of global development goals. Through collaboration with international organizations such as ISO and OGC, UN-IGIF promotes standardized approaches to geospatial data management, ensuring that countries can align their efforts with global best practices and initiatives.

THE UNITED NATIONS FRAMEWORK FOR INTEGRATED GEOSPATIAL INFORMATION MANAGEMENT

In 2018, the United Nations adopted a comprehensive framework called the United Nations Integrated Geospatial Information Framework (UN-IGIF),[58] developed by the United Nations Committee of Experts on Global Geospatial Information Management (UN-GGIM). This framework is designed to provide guidance to countries in developing, managing and improving their national geospatial information resources.[59] When it was initially established, in collaboration with the World Bank, it aimed to support lower and middle-income countries in implementing and enhancing their geospatial information management capabilities and strengthening their infrastructure to enable their Governments to improve policy and decision-making by leveraging geospatial information. Although it is not an infrastructure in itself, it complements and augments the implementation of SDIs and NSDIs.

[58] UN-GGIM. 2018. UNSD — UN-GGIM, cited 30 December 2023, https://ggim.un.org/UN-IGIF/.
[59] UN-GGIM. 2018. Part 1: Overarching strategic framework. Integrated geospatial information framework.

Figure 7. Standardization adaptation guide per tier level with corresponding capabilities for each stage



Source: UN-GGIM. 2022. A Guide to the Role of Standards in Geospatial Information Management. https://standards.unggim.ogc.org/unggim_guide.pdf

UN-GGIM has been collaborating with ISO/TC 211 and OGC, as well as other international organizations such as the International Hydrographic Organization (IHO), to develop an implementation guide to the role of standards in geospatial information management[60] for countries seeking to implement and support the UN-IGIF initiative. More specifically, it aims to support four main target stakeholders: decision makers, developers of interoperable solutions, standard users and public and private sector practitioners. Each of those identified target stakeholders have roles to play in each step of recommended actions from direction setting to achieving outcomes in standardizing geospatial information. More importantly, the UN-GGIM guide also presents comprehensive information on proper standard adaptation, divided into tiers dependent on the scale of implementation (from single entities to multiple organizations or communities) and capability (whether it is single or multiple capability). It also includes the defined technology involved for each tier and the recommended international standards framework which can be used based on ISO and OGC standards as summarized below. Building upon the foundational work of SDIs and UN-IGIF, UN-GGIM works to establish international standards and best practices, ensuring that geospatial data

[60] UN-GGIM. 2022. A Guide to the Role of Standards in Geospatial Information Management. https://standards.unggim.ogc.org/unggim_guide.pdf.

can be effectively used to support policymaking and development efforts. The Geospatial Knowledge Infrastructure (GKI) represents the next evolution in geospatial data management. While SDIs and frameworks such as UN-IGIF focus on infrastructure and data standards, GKI expands the scope by integrating geospatial data with digital societies, economies and public services.

GEOSPATIAL KNOWLEDGE INFRASTRUCTURE

Introduction to geospatial knowledge infrastructure

The concept of GKI is built on existing geospatial frameworks, such as SDIs. Led by the United Nations Statistics Division (UNSD) and Geospatial World, this initiative seeks to combine these fundamental geospatial approaches and technologies with digital societies, economies and citizens to provide location-based knowledge and services. A framework called the GKI Readiness Index has been created to evaluate how prepared countries and regions are to effectively use and benefit from geospatial information and technologies. This assessment is typically based on several key criteria: integrated policy framework, geospatial data, partnerships and collaborations, public engagement and awareness, technical capacity and leadership, and infrastructure for applications, analytics and modelling:[61]

- *Integrated policy framework*: The institutional framework examines the strength of policies, regulations and institutions governing geospatial information, which supports effective data management and usage.
- *Geospatial data*: The measure of data availability and quality evaluates the comprehensiveness, accuracy and accessibility of geospatial data within a region. High readiness indicates strong data-collection systems and the availability of up-to-date information.
- *Partnerships and collaboration*: Collaborative efforts across stakeholders highlight the importance of strong partnerships in creating and maintaining an effective geospatial infrastructure. Solid partnerships not only enhance data-sharing, resource optimization and capacity-building but also drive innovation and improved policy development from local to national and global perspectives.
- *Public engagement and awareness*: This indicator measures the extent to which the public and decision makers are aware of and utilize geospatial information in their activities and decision-making processes.
- *Technical capacity*: Technical capacity criteria evaluate the level of expertise and training available to work with geospatial technologies and data. This includes education programmes, professional training and the presence of skilled professionals.

[61] Geospatial World and UNSD. 2022. Geospatial Knowledge Infrastructure: Readiness Index and Value Proposition in World Economy, Society, and Environment.

- *Technical infrastructure*: The infrastructure used for applications, analytics and modelling assesses the presence of technology and platforms required for managing and analysing geospatial data. This includes GIS software, data storage solutions and analytical tools.

Insights from geospatial knowledge infrastructure assessments

Disparities between nations

States able to access more advanced technical infrastructure, higher technical capacity, more access to high quality data, and stronger policy frameworks have higher GKI readiness scores. Other nations encounter challenges in these same areas, including lack of technical infrastructure and technical capacity, limited access to high quality data, and more room for improvement in terms of development and implementation of institutional frameworks involving geospatial data. However, even countries with high readiness can also face regional variations where urban areas can have higher readiness owing to more accessible infrastructure and resources, compared to their rural regions.

Efforts at geospatial knowledge infrastructure readiness improvement

Several countries are improving their GKI readiness by increasing investments in technology infrastructure and capacity-building, developing frameworks to enhance data collection and quality, and the creation and implementation of institutional frameworks. The recognition of the importance of the use of geospatial data and information to address social and environmental challenges in these countries, whether they are obtained from ground or space, further advances these improvement initiatives more effectively. To address the regional disparities and support advancements in geospatial technology, international cooperation focusing on capacity-building initiatives, data and knowledge-sharing and infrastructure investments is crucial. One of the critical elements to facilitate and support regional and international collaborations is the adoption of standards and the SDI Framework.

As countries aspire to enhance their GKI, the importance of standardized practices in geospatial information becomes increasingly evident. The successful implementation of GKI relies not only on robust policies, technical capacity and effective partnerships but also on the adoption of clear and consistent geospatial standards. These standards serve as the backbone for interoperability, ensuring that diverse data sources can be integrated and utilized effectively. As countries assess their readiness to leverage geospatial technologies through frameworks such as the GKI Readiness Index, the necessity for established standards becomes a critical focus for enhancing data-sharing and collaborative efforts. This brings us to the overarching framework of geospatial standards, which play a pivotal role in facilitating the effective exchange and utilization of geospatial information across various applications.

Overview of geospatial standards and SDI framework for agriculture applications

Overview of standards for geospatial information

ISO defines standards as documents, established by a consensus of subject matter experts and approved by a recognized body, that provide guidance on the design, use or performance of materials, products, processes, services, systems or persons.[62] These are developed to provide a set of guidelines and specifications that ensure consistency and interoperability between different systems, applications and platforms, where they serve as a common language that enables diverse stakeholders to communicate effectively and efficiently, and to achieve their objectives with minimal confusion or ambiguity.

In the context of geospatial applications, the need for standardization comes with the urgency of handling and managing huge volumes of geospatial information obtained from various sources and translating them into shareable solutions and applications. As shown in figure 8, there are three known general classifications of geospatial standards according to levels of use: general-purpose standards for basic information technology, general purpose standards for geospatial information, and domain-specific standards.[63] In the framework of this document, general-purpose standards are mainly related to the midstream segment, where high-level standards related to data transmission and formats are defined. On the contrary, domain-specific standards better fit the downstream segment, where standards related to information from geospatial data are defined.

International standards development organizations (SDO) for geospatial information such as OGC and the International Organization for Standardization Technical Committee 211 (ISO/TC 211) provide frameworks to promote geospatial data interoperability through general-purpose and domain-specific standardization of metadata and formats. OGC, a non-profit organization working on international consensus standards, was established in 1994, with the aim of promoting and facilitating the use and implementation of open standards for geospatial data processing and sharing, and ensuring that solutions derived from these are interoperable and accessible.[64] It is currently composed of over 500 stakeholders from the public and private sectors, academia and research organizations. The mandate of ISO/TC 211, comparatively, is to create, produce and implement standards related to digital

[62] ISO. undated. Consumer Standards, cited 3 January 2024, www.iso.org/sites/ConsumersStandards/1_standards.html.

[63] UN-GGIM. 2022. A Guide to the Role of Standards in Geospatial Information Management. https://standards.unggim.ogc.org/unggim_guide.pdf.

[64] Reichardt, M. 2017. "Open Geospatial Consortium standards." In: D. Richardson, N. Castree, M.F. Goodchild, A. Kobayashi, W. Liu and R.A. Marston, eds. *International Encyclopedia of Geography*. First edition, pp. 1–8. Wiley. https://doi.org/10.1002/9781118786352.wbieg0348.

geographic information under the ISO.[65] While OGC and ISO/TC 211 are separate entities, the two organizations closely coordinate, including in their work with the United Nations.

When it comes to the combined use of these standards from different standards development organizations,, one study demonstrated the interoperability of different geospatial information-related standards including FDCG, OGC and ISO/TC 211 to ensure consistency by harmonizing related geospatial standards.[66] While implementing this interoperability requires considerable effort, the ease of use and interoperability for geospatial data, as well as its application for platform users, are positive improvements, as evidenced by an implementation report for an industrial use case.[67] National initiatives for standardization have also emerged globally, one of which is the United States Federal Geographic Data Committee (FGDC) to develop and promote the use of standards in geospatial data. In line with the distinction between midstream and downstream information used in this document, general-purpose standards will be introduced and examined here, while domain-specific standards will be covered in the following section, which focuses on downstream applications.

[65] Ostensen, O.M. and Smits, P.C. 2002. ISO/TC211: Standardisation of geographic information and geo-informatics. In: IEEE International Geoscience and Remote Sensing Symposium. IEEE International Geoscience and Remote Sensing Symposium. IGARSS 2002, Toronto, Ont., Canada, IEEE, 2002. https://doi.org/10.1109/IGARSS.2002.1025006.

[66] Liping Di. 2003. The development of remote-sensing related standards at FGDC, OGC, and ISO TC 211. In: IGARSS 2003. 2003 IEEE International Geoscience and Remote Sensing Symposium. Proceedings (IEEE Cat. No.03CH37477). IGARSS 2003. 2003 IEEE International Geoscience and Remote Sensing Symposium. Proceedings, Toulouse, France, IEEE, 2003. https://doi.org/10.1109/IGARSS.2003.1293868.

[67] Beshaha, B.T., Martineza, M. and Stojica, M. 2008. "ISO/OGC Standards Impact on Next Generation Enterprise Spatial Platform." In: *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*. 2008.

Figure 8. General classification of geospatial standards according to level of use

General-purpose

IT, Internet and information

Organizations: W3C, OASIS, IETF, IEEE, ISO/IEC JTC 1, OMG, etc.

Example of standards:

HTML:	Hypertext markup language standard
XRI:	Extensible resource identifier protocol
Ipv6:	Internet protocol version 6
IEEE 802:	Standards for local, personal and metropolitan area networks
JPEG:	Joint Photographic Experts Group standard

Geospatial information and technology

Organizations: ISO/TC 211, OGC, IHO, etc.

Example of standards:

ISO 6709:	Standard representation of geographic point location by coordinates
ISO 19103:	Geographic information — Conceptual schema language
ISO 19115-1:	Geographic information — Metadata
WMS:	OGC Web Map Service standard protocol
WFS:	OGC Web Feature Service Interface Standard

Domain-specific

Geospatial information and technology

Organizations: ISO/TC 211, ISO 19144, OGC, IHO, DGIWG, WMO, ICAO, etc.

Example of standards:

ISO 19160-1:	Conceptual model for address information
ISO 19144:	Classification systems and land cover meta language standard
WaterML:	Hydrology and water resource management standards
DGIF:	Defence Geospatial Information Framework standard
S-100:	Hydrographic, maritime and GIS standards

Source: Modified from UN-GGIM. 2022. A Guide to the Role of Standards in Geospatial Information Management https://standards.unggim.ogc.org/unggim_guide.pdf

General-purpose standards

General-purpose geospatial standards serve as the essential building blocks for a wide range of applications by ensuring uniformity in data representation, including specifications, metadata and coordinate reference systems. Although these standards often operate behind the scenes, they play a pivotal role in maintaining accuracy and consistency across various geospatial technologies.[68] For example, aligning national coordinate systems with global geodetic references allows for a standardized representation of locations on Earth, enabling seamless data-sharing and analysis across different regions and platforms. Additionally, the calibration of remote-sensing devices is crucial for ensuring data quality, facilitating reliable insights into environmental changes and resource management.

These standards encompass a range of organizations and protocols, such as those from ISO/TC 211 and OGC, which develop specifications such as ISO 6709 for geographic point location and WMS (Web Map Service) for accessing geospatial data. In the IT and Internet domains, standards established by organizations such as W3C and IEEE further enhance the interoperability of geospatial applications with broader technological frameworks. For instance, the use of HTML for web-based mapping applications or the incorporation of Internet Protocol version 6 (IPv6) ensures efficient data transmission and accessibility.

As geospatial technologies increasingly integrate into mainstream business environments, these standards are continuously evolving. Recent efforts, such as accommodating JSON encoding, illustrate the drive towards enhancing flexibility and compatibility within diverse data spaces. This evolution reflects the growing demand for geospatial data interoperability, as organizations seek to leverage geospatial insights alongside other data sets for more informed decision-making. Ultimately, the ongoing development and adoption of general-purpose geospatial standards are critical for fostering collaboration, enhancing data quality and promoting innovative applications in a rapidly advancing technological landscape.

Access to satellite-based data

Access to Earth observation data

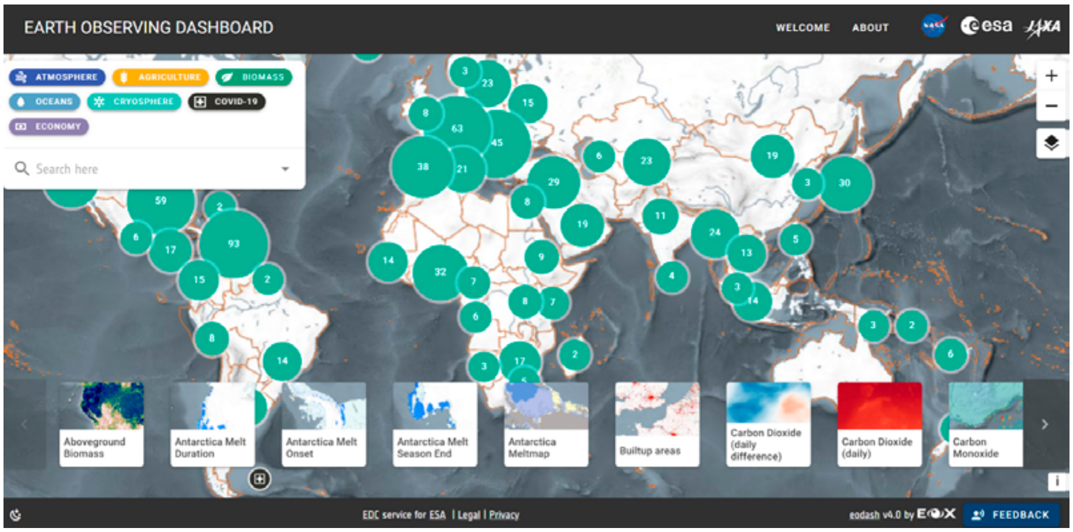
The access to Earth observation satellite imagery can be obtained through government agencies, international organizations and commercial providers. The NASA Landsat programme, for example, provides open and free access to its archive through different platforms such as EarthExplorer, LandsatLook, GloVis and even through Amazon Web Services (AWS). These Landsat data collections are processed and distributed by the USGS Earth Resources Observation and Science.[69] Meanwhile, Sentinel satellites data which are managed and delivered by ESA can also be primarily accessed in multiple platforms such as SCI Hub, Copernicus Space Component Data Access Planetary Data Access (CSCDA PANDA) and the Copernicus Data Space Ecosystem.[70]

[68] United Nations. 2024. Implementation and adoption of standards for the global geospatial information community (E/C.20/2024/17/Add.1). Economic and Social Council, Committee of Experts on Global Geospatial Information Management. https://ggim.un.org/meetings/GGIM-committee/14th-Session/documents/E_C20_2024_17_Add_1_Implementation_and_adoption_of_standards_5July2024.pdf.

[69] NASA. 2023. Data Access | Landsat Science, cited 10 March 2024, https://landsat.gsfc.nasa.gov/data/data-access/.

[70] European Commission. 2022. Conventional Data Access Hubs | Copernicus, cited 10 March 2024, www.copernicus.eu/en/access-data/conventional-data-access-hubs.

Figure 9. View of the Earth Observing Dashboard developed by NASA, ESA and JAXA



Computing and analysis platforms such as Google Earth Engine, Microsoft Azure, Amazon Web Services and Esri also provide a way not only to access and download, but also to analyse both Landsat and Sentinel data sets for free – specifically as noncommercial use cases for Google Earth Engine and to existing subscribers of Esri with access to the Internet. Meanwhile, ESA, JAXA and NASA have recently collaborated to create a tri-agency dashboard,[71] born of the need for coordinated data-sharing during the COVID-19 global pandemic. Currently it houses various kinds of geospatial data sets on a global scale, which can be applied to seven thematic areas: atmosphere, agriculture, biomass, oceans, cryosphere, COVID-19 and the economy.

Currently there are multiple platforms being developed to enable access to, and the search of, different kinds of Earth observation data. These include platforms developed by private companies who also have satellite development capability to deliver their data. There are also commercial marketplaces which combine commercial and public data sets into a single platform. International initiatives to promote improved accessibility to Earth observation data through open access have also been emerging. To address accessibility challenges encountered in big data handling, these platforms provide a more efficient way of managing, storing and visualizing large volumes of Earth observation data.

[71] ESA. 2020. A Tri-Agency Dashboard by NASA, ESA, JAXA. In: *Earth Observing Dashboard*, cited 10 March 2024, https://eodashboard.org/.

CEOS launched an initiative called Open Data Cube[72] to support the implementation of the CEOS open data cube, an open-source geospatial data management and analysis software project, focused on utilizing its global partnerships to deploy data cubes in different countries globally by engaging stakeholders and demonstrating how country-level ODC can be beneficial for their use. These are utilized primarily for forestry and environmental use.

Table 1. Open Data Cube status implementation as of June 2024.

Data cube	Scope	Home page/public mention
WFP	Global	https://innovation.wfp.org/project/prism
Africa	Regional	https://www.digitalearthafrica.org https://www.digitalearthafrica.org/african-regional-data-cube Code: https://github.com/digitalearthafrica/deafrica-sandbox
Pacific	Regional	https://digitalearthpacific.org/?c=177.2314%2C-8.7114&z=4.00&v=2#/
Australia	National	https://www.dea.ga.gov.au/about/open-data-cube Code : https://github.com/GeoscienceAustralia/dea-sandbox
Austria	National	https://acube.eodc.eu/
Brazil	National	https://www.brazildatacube.org/ Code: https://github.com/brazil-data-cube
Chile	National	https://datacubechile.cl/
Colombia	National	No publicly available operational deployment https://appliedsciences.nasa.gov/what-we-do/projects/validating_the_effectiveness_of_the_nasa_open_data_cube_on_augmenting_deforestation_analysis_in_colombia
Ghana	National	No publicly available operational deployment https://www.youtube.com/watch?v=DnKURdWsagg
Ireland	National	In development
Kenya	National	In development
Mexico	National	No publicly available operational deployment https://ggim.un.org/meetings/2018-International-Seminar-Kenya/documents/01_OJJC_06_DEC_2018_1600_hrs_Internac_Seminar_ODC.pdf
Sweden	National	https://www.ri.se/en/what-we-do/projects/digital-earth-sweden
Switzerland	National	https://www.swissdatacube.org/ Code: https://github.com/unep-grid/SwissDataCube

[72] CEOS. 2017. CEOS. In: Open Data Cube, cited 15 December 2023, www.opendatacube.org/ceos.

Data cube	Scope	Home page/public mention
United Republic of Tanzania	National	No publicly available operational deployment https://www.youtube.com/watch?v=EIxjIaekrw0
Viet Nam	National	No publicly available operational deployment https://publications.csiro.au/publications/publication/PIcsiro:EP186600
Virginia	Local	No publicly available operational deployment https://www.youtube.com/watch?v=T8XTrMeJoX4 https://datacube.vmasc.org/

Source: CEOS team as of 14 May 2024

One of the distinguishing features of ODC among other platforms is its ability to leverage analysis ready data (ARD) in the form of multidimensional data cubes. CEOS established an initiative to further advance the use of ARD in Earth observation monitoring applications. This is referred to as the CEOS ARD, currently being led by the CEOS Land Surface Information Virtual Constellation (LSIVC). LSIVC is in charge of the creation of a framework to define requirements and its implementation for Earth observation ARD.[73]

ESA also proposed a draft of ARD standards under the Earthnet Data Assessment Pilot project. This is built from the work of CEOS ARD, with considerations from the perspective of commercial applications.[74] Although the work towards standardization of the definition of ARD in the context of Earth observation data and applications is still under development, several national space agencies have already been implementing it with their own defined specifications and have found it useful for improving their Earth observation applications workflow.

Access to global navigation satellite systems data

GNSS technology began with the recognition of satellite-based positioning possibilities following the launch of Sputnik in 1957. Over time, several nations developed their own systems, and today, GNSS is a global technology underpinning critical applications across industries, from aviation and shipping to smartphones and autonomous vehicles.

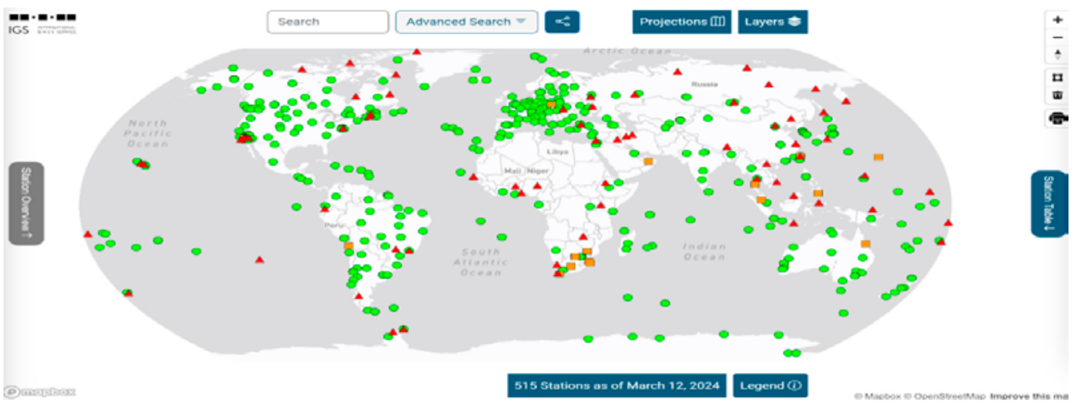
Established in 1992 and formally launched in 1994, the international GNSS service or IGS is a voluntary global organization which “provides, on an openly available basis, the highest-quality GNSS data, products and services in support of the terrestrial reference frame, Earth

[73] Siqueira, A., Tadono, T., Rosenqvist, A., Lacey, J., Lewis, A., Thankappan, M., Szantoi, Z. et al. 2019. CEOS Analysis Ready Data for Land – An Overview on the Current and Future Work. In: IGARSS 2019 - 2019 IEEE International Geoscience and Remote Sensing Symposium. IGARSS 2019 - 2019 IEEE International Geoscience and Remote Sensing Symposium, Yokohama, Japan, IEEE, July 2019. https://doi.org/10.1109/IGARSS.2019.8899846.

[74] Hunt, S., Fox, N. and Albinet, C. 2021. Review of Analysis Ready Data Specification.

observation and research; positioning, navigation and timing; and other applications that benefit science and society".[75] As of 12 March 2024, IGS has 512 stations in 118 countries supported by 350 organizations working together to provide IGS data products. IGS also provides a platform that allows users to search, access and download GNSS data openly.

Figure 10. IGS network global coverage shown in the IGS platform



Source: IGS. 2024. IGS Network. Cited 13 March 2024. https://network.igs.org/

The GNSS Science Support Centre,[76] established in 2017, is an expanded and improved version of the International GNSS Service Global Data Center, supported by ESA. It houses a data repository ranging from space-based receivers to regional GNSS receiver networks and enables users to implement cloud-based GNSS data processing. The operational release of the platform is being conducted in three phases:

- **Stage I - Private beta:** access is restricted to invited GNSS institutions and research groups.
- **Stage II - Public beta:** platform features are added and improved based on feedback from stage I, with access opened to evaluate the implementation scalability of the platform.
- **Stage III - Operations:** the platform aims to be fully accessible, aligning with community requirements while ensuring operational stability.

[75] Teunissen, P.J.G. and Montenbruck, O., eds. 2017. *Springer Handbook of Global Navigation Satellite Systems.* Cham, Springer International Publishing. https://doi.org/10.1007/978-3-319-42928-1.
[76] ESA. 2022. GSSC Now, GNSS Datasets and Datalabs Anywhere | GSSC, cited 31 December 2023, https://gssc.esa.int/news/gssc-now-gnss-datasets-and-datalabs-anywhere/.

Other widely used regional GNSS permanent networks include National Geodetic Survey Continuously Operating Reference Stations (CORS) supported by the National Ocean Service where they provide open access GNSS data products, collected and processed from 1994 to present, through the Comprehensive Large Array Data Stewardship System[77] while the Regional Reference Framework for Europe (EUREF) under International Association of Geodesy has established the European Permanent Network. This consists of more than 370 stations covering the entire European region[78] and can be accessed through the EPOS-GNSS data gateway.

To establish a uniform and consistent basis for positioning data, a standard global reference system is imperative. The UN-GGIM Subcommittee on Geodesy developed the road map for the global geodetic reference frame for sustainable development implementation plan in 2018.[79] Besides aiming to improve accessibility to geodetic data, one other important objective of this road map is to ensure compatibility between standards used in local, national and regional GNSS stations and IGS.

In 2020, UN-GGIM further advanced these efforts by welcoming the establishment of the Global Geodetic Centre of Excellence[80] (UN-GGCE) in Bonn, Germany. Hosted by Germany, the UN-GGCE plays a crucial role in supporting the global geodetic infrastructure, which includes satellite navigation, Earth observation and the monitoring of the Sustainable Development Goals. With its focus on strengthening international geodetic cooperation and coordination, the Centre contributes to ensuring an accurate, accessible and sustainable Global Geodetic Reference Frame (GGRF), essential for scientific, economic and societal applications. Through initiatives such as this, the global community continues to work towards a more integrated geodetic framework that supports sustainable development on a global scale.

Access and integration of satellite-based data with ground-based data

In the context of agrifood and agriculture systems, the access and integration of satellite-based data with ground-based data, and increasingly with training data, plays a pivotal role, particularly in the realm of supervised learning for land cover classification or crop monitoring. Satellite imagery offers a broad-scale perspective, capturing extensive agricultural landscapes, but for meaningful classification, well-defined labels are essential. Ground-based data, collected through field surveys or sensors deployed on-site and training data, collected through satellite or aerial imagery used for training machine learning models on

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[77] United States Department of Commerce, N.O. and A.A. undated. NCN Data and Products - National Geodetic Survey, cited 13 March 2024, https://geodesy.noaa.gov/CORS/data.shtml.

[78] EPN - The EUREF Permanent GNSS Network, 2023. https://epncb.oma.be/_documentation/publications/flyer/epnflyer.pdf.

[79] UN-GGIM Subcommittee on Geodesy. 2018. *Road Map for the Global Geodetic Reference Frame for Sustainable Development Implementation Plan*. https://ggim.un.org/meetings/GGIM-committee/8th-Session/documents/Road-Map-Implementation-Plan.pdf

[80] https://ggim.un.org/UNGGCE.

how to classify or detect specific features, provide the necessary data for supervised learning algorithms. These data provide valuable information with precisely labelled samples, aiding algorithms in distinguishing between different land cover types such as crops, forests or bare soil, and track the different phenological stages for a given crop. It is however of utmost importance that ground and training data and labels are collected according to well-defined and agreed protocols and rules, so as to guarantee proper data quality for the supervised learning procedure that follows.

To effectively leverage satellite-based data in conjunction with ground-based data for comprehensive agricultural insights, the integration of both remote-sensing and GNSS services is imperative. Remote sensing, through satellite imagery, provides valuable visual information about large-scale land cover, land use, crop health and environmental conditions. However, to ensure accurate spatial referencing and ground-truthing of this satellite data, GNSS services play a crucial role. GNSS technologies enable precise geolocation of ground-based data, allowing for accurate alignment and integration with the satellite-derived information.

Supervised learning models, when trained with a combination of satellite and ground-based data, can accurately classify and map land cover at a high resolution. This integration enhances the accuracy and reliability of classification results by accounting for the variability in local conditions and ensuring that the algorithm generalizes well across diverse landscapes. This approach proves especially beneficial in precision agriculture, where farmers and land managers require detailed information about the composition and health of specific areas for optimal decision-making.

By combining the strengths of satellite- and ground-based data, the agrifood sector can harness the power of supervised learning techniques for various agricultural indicators. This integration not only enhances the precision of agricultural monitoring but also contributes to sustainable land management practices and supports data-driven decisions for crop planning, resource allocation and environmental conservation.

This synergy between remote-sensing and GNSS services enhances the reliability and precision of agricultural data analytics. Ground-based data, when georeferenced with GNSS, enables the creation of high-resolution maps and facilitates the calibration of remote-sensing models. This integrated approach ensures that satellite observations are not only visually informative but also accurately linked to specific geographic locations on the ground. The combination of remote-sensing and GNSS services is particularly vital in applications such as precision agriculture, where the spatial accuracy of data is paramount for tasks such as crop monitoring, yield prediction and resource optimization. As a result, this comprehensive integration fosters a more robust foundation for informed decision-making and sustainable agricultural practices.

The integration of remote-sensing and GNSS services is critical for precise and reliable agricultural data analytics, enabling spatial accuracy critical to modern farming practices. Building on this foundation, the rise of big data has further transformed the agricultural sector, where large-scale data sets generated by advanced technologies, including remote sensing, are now key to driving informed decision-making.

Big data handling and management

In recent years, the agricultural sector has witnessed a transformative shift fuelled by the integration of advanced technologies, with big data emerging as a cornerstone for informed decision-making. Big data, particularly from remote-sensing technologies, has revolutionized the way farmers, researchers and policymakers approach agriculture. Big data refers to large and complex data sets that cannot be easily managed, processed or analysed using traditional data-processing tools. It is characterized by three features: volume (large amounts of data), velocity (rapid data generation and processing) and variety (diverse data types). Big data often requires advanced analytics and technologies to extract valuable insights and patterns.[81]

The influx of big data from remote sensing holds immense potential for providing informed decisions for agriculture, however, it also presents challenges in terms of volume, velocity and variety. The sheer volume of data generated necessitates robust storage infrastructure and efficient processing capabilities. The velocity at which data is collected requires real-time or near-real-time processing to enable timely interventions. Additionally, the variety of data sources and formats demands sophisticated integration techniques to derive meaningful insights. Addressing these challenges is essential to unlock the full potential of big data in agriculture.[82]

Effective big data handling involves employing advanced processing and analysis techniques. Machine learning algorithms, including deep learning, play a crucial role in extracting patterns and trends from large data sets. These algorithms can identify crop diseases, assess vegetation health, predict yield outcomes and offer valuable recommendations for precision agriculture. Moreover, spatial analysis tools enable the creation of detailed maps that aid in resource allocation, such as optimizing irrigation patterns or identifying areas prone to pest infestations.

[81] Marr, B. (2015). *Big Data: A Very Short Introduction*. Oxford University Press.

[82] Keith H. Coble, Ashok K. Mishra, Shannon Ferrell, Terry Griffin. "Big Data in Agriculture: A Challenge for the Future." *Applied Economic Perspectives and Policy*, vol.40, issue 1, 2018.

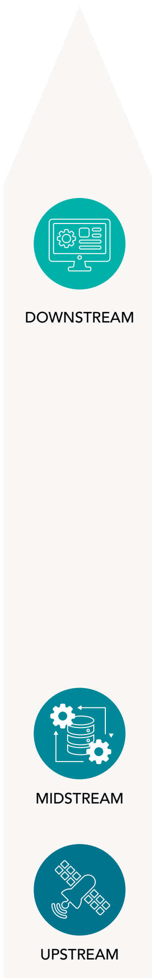
The integration of big data analytics into decision support systems empowers stakeholders at various levels of the agricultural value chain. Farmers can access real-time insights on their crops, enabling initiative-taking management strategies. Researchers benefit from comprehensive data sets for conducting in-depth studies on crop behaviour, climate impact and land-use patterns. Policymakers gain valuable information to formulate evidence-based agricultural policies that promote sustainability, resource efficiency and resilience against climate change.

As technology continues to evolve, the role of big data in agriculture is expected to expand further. Integration with the Internet of Things will enable more precise and dynamic data collection, while blockchain technology may enhance data security and traceability. Collaborative efforts between the agriculture and technology sectors will be crucial to developing standardized data formats and interoperable systems, fostering a more seamless exchange of information.

DOWNSTREAM SEGMENT: AGRICULTURAL SOLUTIONS, PRODUCTS AND SERVICE DEVELOPMENT

The downstream, or user, segment of the space value chain involves utilizing processed satellite data, often combined with field information, for practical end user applications. This includes using satellite-derived information, synthesized in the form of variables or indicators, for agricultural management, monitoring, analytical services, specialized software and platforms, food security monitoring, and early warning systems among others. Often, agricultural information needs are formulated through frameworks such as the 2030 Agenda for Sustainable Development, essential agricultural variables, the Rio conventions, UN-GGIM, among many international, regional and national frameworks. These frameworks help to combine and integrate processed satellite information to contribute to local and national agricultural applications (figure 11).

Figure 11. Example of frameworks supporting the integration of data and information from the mid and upper-stream segments to the downstream segment for agricultural applications



Frameworks	DOWNSTREAM PRODUCTS, APPLICATIONS AND VALUE-ADDED SERVICE				
	Land cover and land use mapping	Crop type mapping	Crop productivity estimation tools	Climate risk indices (drought, floods etc.)	Others
SDG	✓	✓	✓	✓	…
EAV	✓	✓	✓		…
Rio-conventions (UNFCC, CBD, UNCCD)	✓			✓	…
UN-GGIM	✓	✓	✓	✓	…
OTHERS	…	…	…	…	…

Data storage management
Earth observation data platform, GNSS data platform, data cube

Space-based and non-space-based data
Earth observation satellite imagery, GNSS data, UAV data, ground sensor data

Source: Elaborated by the authors.

This section provides an overview of the most relevant downstream products impacting the agricultural sector. It also informs about agricultural variables and indicators such as the essential agricultural variables used in data applications, and reviews the user requirements for Earth observation and GNSS data in agriculture. It also examines monitoring platforms and products that support space-based agricultural solutions.

OVERVIEW OF DOWNSTREAM APPLICATIONS AND PRODUCTS RELATED TO THE AGRICULTURAL SECTOR

A thorough and comprehensive analysis of all the space downstream applications and products related to the agricultural sector is beyond the scope of this document. However, this section provides examples of the most important downstream applications and products where the impact and relevance of remote-sensing and GNSS data is of utmost relevance. Hence, this section encompasses the description of land cover and land-use mapping, as one of the fundamental geospatial data themes as recognized by UN-GGIM, crop type mapping and crop productivity. A list of some of the most relevant indices of high interest for agriculture and retrieved from remote sensing is also reported, and examples of the most relevant GNSS applications in agriculture are discussed.

Land cover and land-use mapping

Land cover is defined as the observed physical cover on the Earth's surface, including vegetation (natural or planted) and human constructions. Land use is characterized by the arrangements, activities and inputs people undertake in a certain land cover type to produce, change or maintain it. Defining land use in this way establishes a direct link between land cover and the actions of people in their environment. [83] Both land cover and land-use data sets play a crucial role in supporting agriculture by providing comprehensive insights into natural, semi-natural and cultivated areas for efficient agricultural monitoring, resource management and decision-making for crop production and sustainability. At the global level, products such as the ESA WorldCover[84] and the Copernicus Land Monitoring Service[85] offer high-resolution data on land cover and biophysical conditions such as vegetation indices and land surface temperature. These data sets help differentiate between irrigated and rainfed croplands, facilitating improved water management, crop health monitoring and yield optimization. Global data sets can be refined to produce more detailed maps at regional, national or provincial scales, especially when integrated with field data from local sources, considering local specific legends and classification systems. This enhances the accuracy of land cover analysis, allowing specific environmental characteristics in targeted areas to be better reflected. Significant efforts by standardization agencies are under way to ensure interoperability between different land cover maps. For instance, ISO, through its Technical Committee-211 (TC211) and Advisory Group-13 (AG13) on Land Cover and Land Use, has

[83] Geospatial information for sustainable food systems, www.fao.org/geospatial/our-work/what-we-do/land-cover-and-land-use/en/ (visited on 9/30/2024), FAO.

[84] Zanaga, D., Van De Kerchove, R., Daems, D., De Keersmaecker, W., Brockmann, C., Kirches, G., ... and Arino, O. (2022). ESA WorldCover 10 m 2021 v200.

[85] Copernicus Land Monitoring Service, https://land.copernicus.eu/en (visited on 9/30/2024).

developed a land cover meta-language,[86] providing a standardized dictionary to describe land cover classes across different spatial and temporal resolutions and extents.

Crop type mapping

Crop type mapping products are essential tools for policymakers, international agencies, Governments and agricultural stakeholders. These products provide information about the types of crops grown in different regions, enabling the monitoring of crop distribution, growth patterns and changes in agricultural systems over time. These products support agriculture, inform food security policies, and guide sustainable land and resource management practices. These products are ideally developed to be consistent with land cover and land-use maps.

Crop type maps are essential for monitoring agricultural patterns, informing food security strategies and supporting sustainable land use by providing detailed insights into the distribution and growth of specific crops. At the global level, the ESA WorldCereal[87] offers global monitoring of cereal crops at 10-metre resolution, helping assess crop health and anticipate yields. Meanwhile, the NASA Crop Data Layer (CDL),[88] although United States-focused, exemplifies crop-specific data's role in monitoring agricultural trends and informing decision-making. These tools support food security policies, disaster preparedness and resource management by providing detailed information on crop types and their distribution.

Global crop information could serve as input for more detailed, higher-resolution, regional, national and provincial crop type data sets. As for land cover and land use, in this case the crop type mapping activity could result from specific local needs, so that the product can be user-specific, considering specific needs such as in terms of crop types, varieties, and temporal and spatial resolution. Very high-resolution images such as those taken from drones or airplanes, provide additional possibilities when combined with information from coarser resolution sensors.

Crop productivity estimation tools

Crop productivity estimation tools that integrate physical models with remote-sensing data are essential for supporting agriculture by providing valuable insights into crop yields, soil conditions, terrain indices and overall productivity. These tools enable policymakers, farmers and agricultural planners to make informed decisions that optimize resource use, enhance

[86] Geospatial information for sustainable food systems, https://www.fao.org/geospatial/events/detail/en/c/1506665/ (visited on 9/30/2024), FAO.

[87] Van Tricht, K., Degerickx, J., Gilliams, S., Zanaga, D., Savinaud, M., Battude, M., ... and Szantoi, Z. (2023). ESA WorldCereal 10 m 2021 v100.

[88] USDA National Agricultural Statistics Service Cropland Data Layer. {YEAR}. Published crop-specific data layer [Online]. Available at https://nassgeodata.gmu.edu/CropScape/ (accessed on 9/30/2024). USDA-NASS, Washington, DC.

food security and promote sustainable agricultural practices. By combining remote-sensing data with physical models, these systems offer reliable and timely estimates of crop productivity, yield forecasts, and indicators of soil and water health.

Crop productivity tools, such as the FAO Global Agro-Ecological Zoning (GAEZ)[89] and Water Productivity Open-access Portal (WaPOR),[90] integrate remote-sensing data with physical models to estimate crop yields, soil conditions and water productivity. GAEZ helps to identify regions with high agricultural potential and to forecast yields based on climate and soil data, supporting food security planning. WaPOR focuses on water use efficiency, crucial for managing agriculture in water-scarce regions. These tools enable better resource allocation, yield prediction and sustainable agricultural practices.

The integration of physical models with remote-sensing data extends to climatic, multispectral and thermal infrared data, as well as to terrain and soil indices, all of which are critical for understanding the environmental factors that influence crop productivity. Climatic data, including temperature, precipitation patterns and humidity levels, provide essential context for assessing the overall viability of crop production in a given area. Multispectral data, captured through satellite imagery, enable the identification of plant health, vegetation cover and stress indicators, thereby offering insights into the growth and development of crops throughout their life cycle. Thermal infrared data are particularly useful for monitoring water stress in plants, as they help detect variations in surface temperature that can signal drought conditions or inefficient irrigation practices.

On the other hand, terrain indices – such as slope, elevation and aspect – significantly affect water runoff, soil erosion and microclimates, which directly impact agricultural productivity. Soil indices, including soil moisture, texture and nutrient availability, are vital for evaluating the suitability of land for various crops. By integrating satellite-derived data with physical soil and terrain models, these tools provide a comprehensive understanding of the natural conditions that drive crop productivity. This holistic approach enables farmers and land managers to make informed decisions that optimize soil health, enhance water management strategies and maximize crop yields. In summary, the synergy between climatic, multispectral, thermal, soil and terrain data allows for a more nuanced understanding of the agricultural landscape, ultimately promoting sustainable farming practices and improving food security.

Remote-sensing indices relevant to agricultural applications

A summary but far from exhaustive list of indices derived from remote sensing and impacting all the previous applications in agriculture is provided in table 2. As can be seen, remote

[89] Fischer, G., Nachtergaele, F.O., van Velthuizen, H.T., Chiozza, F., Franceschini, G., Henry, M., Muchoney, D. and Tramberend, S. 2021. Global Agro-Ecological Zones v4 – Model documentation. Rome, FAO.

[90] WaPOR, remote sensing for water productivity, www.fao.org/in-action/remote-sensing-for-water-productivity/en (accessed on 9/30/2024), FAO.

sensing can support a variety of downstream applications in agriculture, basing such information on different types of satellites, from multispectral low Earth orbit satellites to thermal infrared geostationary satellites. Even though more information can be found in specialized documentation,[91] this table should enable readers to understand the deep impact of remote-sensing data in downstream applications related to agricultural services, and how space-based systems are now an essential part of many applications used by private users, governmental entities, universities and research centres as well as international agencies.

Table 2. Examples of applications informed by remote-sensing indices in downstream segment

Applications	Example indices	Indices class	Satellite source
Assessing vegetation health and biomass.	NDVI, SAVI, EVI, GCI	Vegetation indices	LEO optical satellites (e.g., Landsat, Sentinel-2), GEO satellites (GOES, Himawari, Meteosat, INSAT)
Monitor water content	NDWI, SWI	Water content indices	
Crop canopy development	LAI	Leaf area index	
Estimating biomass production	GPP, NPP	Primary productivity indices	
Monitoring crop growth and harvesting activities	Interferometric SAR (InSAR), dual polarization ratios	SAR-derived structural indices	LEO SAR satellites (e.g., Sentinel 1)
Discriminating between different crop types	RVI, dual polarization ratios	SAR-based indices	
Monitoring water loss from soil and plants.	Actual evapotranspiration, SWI	Water productivity indices	LEO optical satellites (e.g., MODIS, Landsat), GEO satellites (GOES, Himawari, INSAT) and climatic models
Estimating water demand for crops	Potential evapotranspiration		

[91] M. Weiss, F. Jacob, G. Duveiller, "Remote sensing for agricultural applications: A meta-review", *Remote Sensing of Environment*, Volume 236, 2020, 111402, https://doi.org/10.1016/j.rse.2019.111402.

Table 2. Examples of applications informed by remote-sensing indices in downstream segment (*continued*)

Applications	Example indices	Indices class	Satellite source
Measuring rainfall amounts	Precipitation, drought severity index	Climate variables	LEO microwave and thermal satellites (e.g., GPM, TRMM, MODIS, Sentinel-3, Landsat), GEO satellites (GOES, Meteosat)
Quantifying surface temperature	Temperature		
Estimating incoming energy from the Sun	Solar radiation		
Determining water content in the soil.	Soil moisture	Soil and nutrient indices	LEO microwave satellites (e.g., SMAP, Sentinel-1), LEO optical satellites (e.g., MODIS), GEO satellites (GOES, Himawari, Meteosat)
Studying crop growth and soil processes.	Nitrogen content		
Monitoring carbon sequestration	Soil organic carbon content		
Assessing water runoff and erosion	Slope	Terrain indices	LEO radar and optical satellites (e.g., SRTM, ASTER)
Classifying agricultural areas based on altitude	Elevation		

Domain-specific standards

Referring to figure 8, downstream products relevant for agriculture (and not only) are subject to many relevant standards guaranteeing proper interoperability and exchange of information. For agricultural applications, domain-specific standards are essential to address unique needs such as land administration, land cover and land use. For example, the ISO 19152 Land Administration Domain Model supports effective land management by standardizing data related to land registration and spatial planning, while the ISO 19144-2 and ISO 19144-3 standards facilitate consistent classification of land cover and land use, crucial for land-related indicators and environmental monitoring. These standards provide a tailored framework to improve agricultural data exchange and ensure global interoperability, enabling more efficient, sustainable agricultural practices.

In support of United Nations efforts to achieve the SDGs, ISO has been collaborating with FAO to create domain-specific standards for agriculture and food security applications, mostly regarding land cover and land use.[92] Established in December 2020 in collaboration with FAO, the Advisory Group 13 (AG13) on land cover and land use under ISO/TC 211 aims to advise TC 211 on how the ISO/TC 211 standards can be applied in the context of land cover and land use in the United Nations and other transnational organizations and to coordinate in the context of broader United Nations initiatives for this purpose, including how it is being used in agricultural applications.

Such a standardized approach to creating a land cover and land-use map is key to optimizing interoperability and the sharing of land cover and land-use data from local to global, and global to local levels. Agricultural applications of land cover and land-use maps are of significant help for land monitoring and the evaluation of agricultural production, climate change and water resources modelling, and disaster management. Aside from country-level projects, FAO has also been contributing to various regional and global land cover monitoring efforts. One of the current technical limitations in developing these products are the challenges in consistency when data are integrated from multiple sources. One example could be when the data come from two different country data sets, or from different mapping scales. Establishing and adopting a standardized approach to the development of land cover and land-use maps such as classification, accuracy assessment and data-sharing can further improve interoperability and accessibility across different geographic levels and organizations.[93] For this purpose, FAO has developed tools such as land characterization system software to create land cover legends based on standards, for example, ISO 19144-2.[94] FAO has also developed an online catalogue and a land cover legend registry, for land cover information in different file formats. The aim of this registry is to provide a land cover legend that will support data interoperability between different land cover data sets at different geographic levels.[95]

These standards such as those related to land cover and land use are being used to support the broader objectives of the 2030 Agenda for Sustainable Development as reflected, for example, in the use of ISO 19144 by the United Nations Convention on Combating Desertification to integrate land cover information.

[92] ISO. undated. Support for United Nations activities, cited 8 January 2024, https://committee.iso.org/sites/tc211/home/standards-in-action/united-nations.html.

[93] ISO/TC211/AG13. 2022. *ISO/TC211/AG13 Interim Report on Land Cover and Land Use Use Cases.* ISO.

[94] ISO 19144-2:2023 - Geographic information — Classification systems - Part 2: Land Cover Meta Language (LCML) https://www.iso.org/standard/81259.html.

[95] Mushtaq F., Henry M., O'Brien C.D., Di Gregorio A., Jalal R., Latham J., Muchoney D., Hill C.T., Mosca N., Tefera M.G., et al. An International Library for Land Cover Legends: The Land Cover Legend Registry. *Land.* 2022; 11(7):1083. https://doi.org/10.3390/land11071083.

Global navigation satellite systems applications in agriculture

GNSS play a pivotal role in the space downstream segment related to modern agriculture, offering a range of applications that enhance productivity, sustainability and efficiency in farming practices. Below are some examples of the key applications of GNSS in agriculture:

- *Field data collection:* GNSS technology is essential for precise field data collection, enabling farmers, researchers and other stakeholders to georeference data accurately. This capability facilitates the gathering of information on soil conditions, crop health and yield variations across different field zones. By integrating GNSS with remote-sensing data, reliable information can be retrieved which helps in mapping field variability and informs targeted management practices.
- *Measuring the impact of extreme events:* GNSS can be employed to monitor and assess the impact of extreme weather events, such as droughts, floods and storms on agricultural lands. By providing precise location data, GNSS enables farmers, researchers and other stakeholders to analyse changes in land cover and crop conditions before and after such events. This information is critical for developing strategies to mitigate risks and enhance resilience against climate variability.
- *Evaluation of irrigation infrastructures:* The deployment of GNSS technology aids in evaluating the effectiveness of new irrigation infrastructures. By mapping the location and performance of irrigation systems, GNSS allows for precise locations of control areas where water application rates and soil moisture levels are measured. This information helps optimize irrigation management, ensuring that water resources are used efficiently and sustainably, ultimately improving crop yields.
- *Precision agriculture:* GNSS is a cornerstone of precision agriculture, a farming approach that utilizes technology to manage field variability in crops. GNSS-enabled machinery allows for accurate planting, fertilizing and harvesting by providing real-time location data. Farmers can apply inputs precisely where needed, reducing waste and enhancing overall farm efficiency. Additionally, GNSS supports variable rate technology, allowing farmers to tailor input application rates based on specific field conditions.
- *Real-time applications and mobile connectivity:* GNSS technology is increasingly integrated with real-time applications accessible via smartphones and tablets. These applications enable farmers to monitor field conditions, track equipment and manage operations remotely. Real-time GNSS data can inform decisions related to planting schedules, irrigation timing, productivity and pest management, enhancing overall farm management efficiency.

FRAMEWORKS GUIDING AGRICULTURAL INFORMATION FORMULATION

Having described the most relevant downstream applications of space-based data in agriculture, in accordance with figure 12, some of the main agricultural frameworks guiding agricultural information will now be detailed. In the field of agriculture, the development and utilization of information systems (indicators, applications, data sets, etc.) are guided by several key frameworks, each providing a unique lens through which agricultural data are gathered, processed and applied. A list of some representative frameworks is given below:

- *2030 Agenda for Sustainable Development:*[96] This comprehensive global agenda, spearheaded by the United Nations, includes goals that directly address agricultural productivity, food security and sustainable practices (particularly Goals 2, 12 and 15). Information derived from satellites and other geospatial tools is critical for monitoring progress on these goals, particularly in terms of agricultural outputs, land use and environmental impacts. Satellite data integration helps monitor food production systems and track progress towards sustainable land management and climate-resilient agriculture.
- *Essential agricultural variables*[97] *(EAVs):* EAVs for GEOGLAM are key Earth observation components designed to offer insights into agricultural land use, productivity and changes over time. These variables serve as foundational building blocks, which, when combined with other Earth observation data or non-Earth observation information, provide critical indicators for assessing the state and future trends of agriculture. Covering areas such as croplands, rangelands and fallow lands, EAVs help monitor agricultural practices and outcomes. EAVs are largely derived from satellite observations but are often complemented by field data for accuracy through calibration and validation (as in the context of the geospatial domain). Their primary role supports the mission of the agriculture community, while also aligning with broader policy initiatives such as the G20 Action Plan and the United Nations Sustainable Development Goals (SDGs).
- *Rio conventions:*[98] The Rio conventions, which include the United Nations Framework Convention on Climate Change (UNFCCC), the Convention on Biological Diversity, and the United Nations Convention to Combat Desertification (UNCCD), focus on sustainable land use and climate change mitigation. These conventions guide how satellite-derived data is applied to issues such as land degradation, desertification and agricultural biodiversity. Monitoring crop health, land cover changes and soil moisture via satellite data feeds directly into the objectives of these conventions, allowing nations to meet their commitments.

[96] The Sustainable Development Agenda, www.un.org/sustainabledevelopment/development-agenda/, United Nations.
[97] Essential Agriculture Variables and Agricultural Indicators for GEOGLAM, https://agvariables.org/, GEOGLAM.
[98] The Rio conventions, https://unfccc.int/process-and-meetings/the-rio-conventions, United Nations.

- *UN-GGIM:*[99] UN-GGIM plays a pivotal role in coordinating global geospatial data efforts, offering guidelines that shape how geospatial information is collected and used. Within agriculture, UN-GGIM encourages the integration of geospatial information to improve land-use planning, resource management and sustainable farming practices at the national and local levels. UN-GGIM frameworks also emphasize data interoperability, making it easier to integrate satellite data with other forms of geospatial information for comprehensive agricultural analysis.
- These frameworks serve as pillars, guiding how processed satellite and geospatial information can best be utilized in agricultural contexts. They ensure that the data are aligned with broader global objectives, such as sustainable food production, environmental protection and socioeconomic development, making the transition from satellite data to practical, on-the-ground agricultural applications more seamless and impactful.

OVERVIEW OF ESSENTIAL AGRICULTURAL VARIABLES

Essential variables (EVs) are defined as the minimum set of fundamental variables required to characterize state and change in a system. Various organizations around the world have been working together to define and discover EVs which bring huge value to how changes in different Earth systems are monitored. At present, different EVs have been developed for specific environmental domains and applications which also support the SDGs.

The concept of EVs spans different environmental domains. For climate monitoring applications, 55 essential climate variables (ECV) have been developed by the Global Climate Observing System (GCOS) to support the assessment of the Earth's climate status and provide risk mitigation measures.[100] Meanwhile, the Global Ocean Observing System has defined essential ocean variables covering the atmosphere, ocean and terrestrial scope, where it aims to aid in ocean forecasts and early warnings, as well as monitoring.[101] In the domain of biodiversity, essential biodiversity variables are identified by the Group on Earth Observations Biodiversity Observation Network, while essential geodiversity variables cover the geomorphology and pedology domain.

For the agricultural sector, the Group on Earth Observations Global Agricultural Monitoring (GEOGLAM) defines EAVs as "Earth observation-based 'building blocks' that in combination with one another or with other non-EO information provide insight into the GEOGLAM agricultural indicators". These are derived from satellite or Earth observation data and

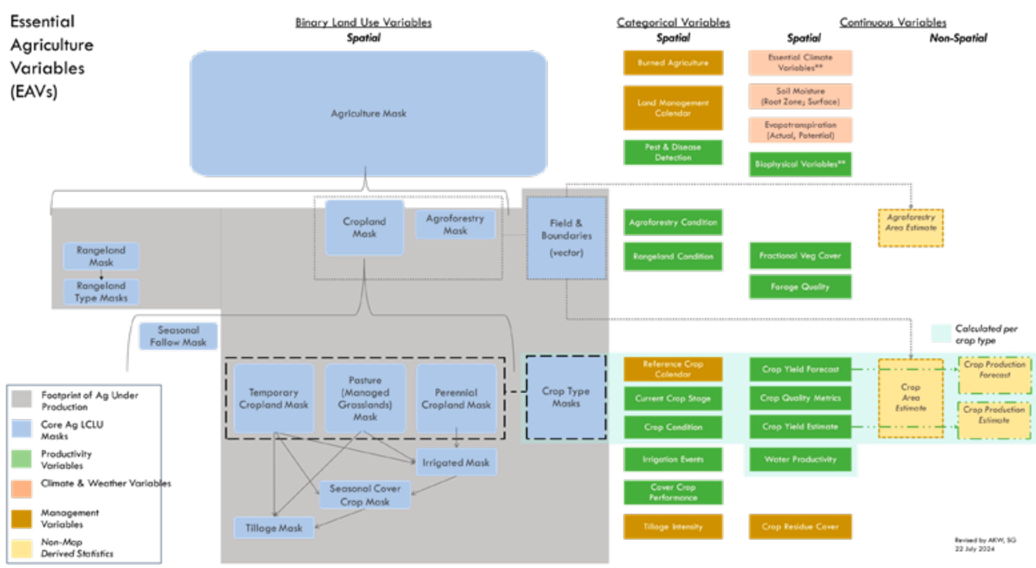
[99] UN-GGIM, https://ggim.un.org/.

[100] GCOS. 2023. About Essential Climate Variables. In GCOS, cited 22 February 2024, https://gcos.wmo.int/en/essential-climate-variables/about.

[101] GOOS. 2024. Essential Ocean Variables – Global Ocean Observing System. In: Essential Ocean Variables, cited 22 February 2024, https://goosocean.org/what-we-do/framework/essential-ocean-variables/.

are calibrated and validated through ground or field data.[102] EAVs would enhance the global, regional and national capacity to collect, develop and distribute accurate and timely information which is critical for agricultural use. GEOGLAM currently operates a specific working group focusing on the capacity-building, product development and protocol development for EAVs. The working group is working towards the creation of documentation for guidelines, validation protocols and standards related to EAVs. An overall picture of their work and methodology is shown in figure 12.[103]

Figure 12. Essential agricultural variable (EAV) hierarchy mapping



Source: GEOGLAM. 2023. Essential Agriculture Variables and Agricultural Indicators for GEOGLAM. In: AG Variables. Cited 21 February 2024. https://agvariables.org/

A full list of EAVs for land use, productivity and agronomic management is also published on the GEOGLAM website, where each EAV is defined and described by its application, frequency of update and spatial unit.[104]

EAVs, when developed, would provide key insights into crop and land conditions through Earth observation data. This structured approach ensures better data-driven decision-making, supports sustainable agricultural practices and contributes to global food security.

[102] GEOGLAM. 2023. Essential Agriculture Variables and Agricultural Indicators for GEOGLAM. In: AG Variables, cited 21 February 2024, https://agvariables.org/.

[103] GEOGLAM. 2023. EAV Product Priorities & Status Updates. In: AG Variables, cited 22 February 2024, https://agvariables.org/eav-product-priorities-status-updates.

[104] GEOGLAM. 2023. Full EAV table AgVariables, cited 21 February 2024, https://agvariables.org/full-eav-table.

By leveraging satellite and Earth observation data, EAVs enable effective monitoring and management of agricultural ecosystems, demonstrating their importance in advancing agricultural knowledge and practices.

EARTH OBSERVATION AND GLOBAL NAVIGATION SATELLITE SYSTEMS USER REQUIREMENTS FOR AGRICULTURAL APPLICATIONS

Specification requirements for both Earth observation and GNSS data vary depending on the agricultural applications or products. These requirements can differ in terms of sensor types, frequency of observation, spatial resolution or spectral range capability. GEOGLAM has defined a set of user requirements for their core EAV using Earth observation satellites, taking into consideration the scale of the agricultural area of interest. These user requirements are categorized by different spatial resolutions (coarse resolution sampling, moderate resolution sampling, fine resolution sampling), spectral range and observation frequency for each mapping product and attribute class.

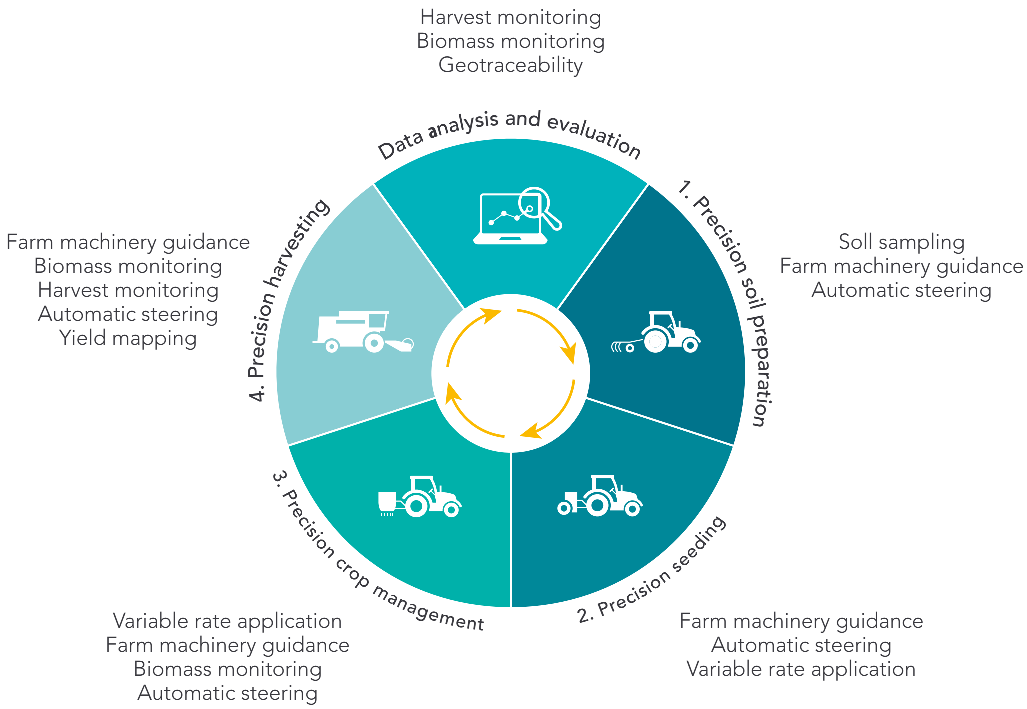
GNSS technology plays a crucial role in precision agriculture applications. Precise positioning data can be applied to every stage of the precision agriculture chain: from the initial stage of precision soil preparation to precision seeding, precision crop management and precision harvesting. All these stages require analysis and evaluation after data acquisition.

Given the wide range of application needs and requirements, GNSS performance and data specification need to be defined for each specific agricultural use case. In the table below, there is a comprehensive list of different precision agriculture applications and the corresponding GNSS data parameter requirements.

Beyond precision agriculture, GNSS technology also became a very useful tool for field data collection,[105] since GNSS allows field operators to collect precise geographic information, such as the location of specific objects in a field. Today, the design and operationalization of field data collection campaigns has been made easier by the availability of free applications for phones and computers.

[105] Petropoulos, George P., and Prashant K. Srivastava, eds. *GPS and GNSS Technology in Geosciences.* Elsevier, 2021.

Figure 13. Global navigation satellite systems applications in precision agriculture



Source: GSA (European GNSS Agency). 2018."Report on Agriculture User Needs and Requirements - Outcome of the European GNSS User Consultation Platform".

Table 3. GEOGLAM core essential agricultural variables and corresponding Earth observation data parameter requirements

GEOGLAM core essential variables

Req#	Resolution		When	Mapping					Attributes classes			
	Spatial	Spectral	Effective observation frequency (cloud free)	Agriculture mask	Rangeland mask	Crop mask	Crop type area and growing calendar	Field boundaries	Crop condition	Crop yield	Crop biophysical variables	Agricultural management practices
Coarse Resolution Sampling (>100 m)												
1	>500–2000 m	OP	D						■		□	
2	100–500 m	OP	2 to 5 per week	■	■	■	■	■	■	□	□	□
3	5–50 km	MW	D						■	■	■	
Moderate Resolution Sampling (10 to 100 m)												
4	10–70 m	OP	M (min 2 out of season +3 in season). Every 1–3 years.	■	■	■	▨	▨				■
5	10–70 m	OP	~W (8 days; min. 1 per 16 days)			■	■	▨	■	■	■	■
6	10–100 m	MW (DP)	~W (8 days; min. 1 per 16 days)	☁	■	■	■	▨	■	■	■	■

Fine Resolution Sampling (5 to 10m)												
7	5–10 m	VIS, NIR, SWIR	M (min. 3 in season)			■	■	■				
8	5–10 m	VIS, NIR, SWIR	~W (8 days min. 1 per 16 days)				■		■		■	■
9	5–10 m	SAR (DP)	M			■	■	■				■
Very Fine Resolution Sampling (<5 m)												
10	<5 m	VIS, NIR	3 per year (2 in season +1 out of season) Every 3 years			■	■	■				
11	<5 m	VIS, NIR	1 to 2 per month				■			■		■

OP, Optical; VIS, Visible; NIR, Near InfraRed; VNIR, Visible/Near InfraRed; SWIR, Short Wave InfraRed; MW, Microwave; DP, Dual Polarization; D, Daily; W, Weekly; M, Monthly.

Source: Ochiai, O., Poulter, B., Seifert, F.M., Ward, S., Jarvis, I., Whitcraft, A., Sahajpal, R. et al. 2023. "Towards a roadmap for space-based observations of the land sector for the UNFCCC global stocktake." *iScience*, 26(4): 106489. https://doi.org/10.1016/j.isci.2023.106489.

Table 4. Precision agriculture use and corresponding GNSS requirements

Application	Horizontal accuracy	Survey method and its relevance per app		Canopy	Availability	Robustness	Authentication	Integrity and reliability	Size, weight, autonomy	Fixing and convergence time
Farm machinery guidance	10-30 cm (pass-to-pass)	SBAS √√√, DGNSS √√√	RTK/N-RTK √ PPP/PPP-RTK √	No	High	Low	Low	High	NA	A few minutes
Automatic steering	Down to 2.5 cm (pass-to-pass)	RTK/N-RTK √√, PPP/PPP-RTK √√√		No	High	Medium	Low	High	NA	A few minutes
VRA-Low (spraying, spreading, harvesting bulk crops)	10-30 cm (pass-to-pass)	SBAS √√√ DGNSS √√	RTK/N-RTK √√√ PPP/PPP-RTK √√	No	High	Low	Low	High	NA	A few minutes
VRA-High (seeding/ planting)	2.5-10 cm (pass-to-pass)	RTK/N-RTK √√√, PPP/PPP-RTK √√		No	High	Low	Low	High	NA	A few minutes
Harvest/yield monitoring	Submetre	SBAS √√√ DGNSS √√	RTK/N-RTK √√√ PPP/PPP-RTK √√√	No	Medium	Low	Low	Medium	NA	A few seconds
Biomass monitoring	Submetre	SBAS √√√ DGNSS √√√	RTK/N-RTK √√ PPP/PPP-RTK √√	No	Medium	Low	Low	Medium	NA	A few seconds
Soil sampling	m-level / submetre	GNSS stand-alone √√ SBAS √√√ DGNSS √√√	SBAS √√√ DGNSS √√√	GNSS stand-alone √√√	Medium	Low	Low	Yes	> 8h	A few minutes
Livestock tracking and virtual fencing	m-level	SBAS √√√ DGNSS √√√	RTK/N-RTK √ PPP/PPP-RTK √	Yes	High	Low	Low	Medium	>24h	A few seconds
Precision viticulture (e.g., soil sampling, yield monitoring)	Submetre	SBAS √√√ DGNSS √√√	RTK/N-RTK √√ PPP/PPP-RTK √√	No	Medium	Low	Low	Medium	>8h	A few seconds
Precision forestry	Submetre	SBAS √√√ DGNSS √√√	RTK/N-RTK √√ PPP/PPP-RTK √√	Yes	High	Low	Low	Medium	>8h	A few seconds
Farm machinery monitoring and asset management	Metre-level / submetre	GNSS stand-alone √√√ SBAS √√√ DGNSS √√√	RTK/N-RTK √ PPP/PPP-RTK √	No	Medium	Low	Low	High	NA	A few seconds
Geotraceability	m-level	SBAS √√√ DGNSS √√√	RTK/N-RTK √ PPP/PPP-RTK √	Yes	High	Low	Low	Medium	NA	A few seconds
Field delineation	Submetre	SBAS √√√ DGNSS √√√	RTK/N-RTK √√ PPP/PPP-RTK √√	Yes	Medium	Low	High	Low	>5h	A few minutes

Source: GSA (European GNSS Agency). 2018. "Report on Agriculture User Needs and Requirements – Outcome of the European GNSS"

Note: As of December 2021, GSA was succeeded by the European Union Agency for the Space Programme (ESPA).

MONITORING PLATFORMS AND SYSTEMS FOR AGRICULTURE PRODUCTS

Agricultural monitoring systems aim to provide timely information for decision makers to support food security from local to global level. Currently, multiple agricultural monitoring platforms are in operation, which rely on the integration of satellite data and other sources. These platforms are developed through joint efforts and collaboration between various international organizations and government agencies, with the aim of addressing specific agricultural issues. They operate at different scales, ranging from local to regional and global, and come with specific objectives. For example, the Earth Observation for Sustainable Development (EO4SD) initiative is a collaborative effort between ESA and FAO. EO4SD brings together satellite data from ESA missions with other data sources to assess agricultural productivity, monitor water resources and provide insights into natural hazards affecting agriculture. This initiative specifically targets developing countries, helping them to implement sustainable agricultural practices and manage environmental challenges, such as droughts or floods, using geospatial information.

Another example of a comprehensive platform is the Agro-informatics Geospatial Platform under the FAO Hand-in-Hand Initiative. This platform integrates multiple sources of geospatial data, including satellite imagery, soil data, weather patterns and socioeconomic information, to guide investment decisions in agriculture and rural development. The platform supports precision agriculture by providing high-resolution, location-specific insights, such as identifying areas suitable for crop production or assessing the potential for land improvement. The data and insights generated are vital for addressing poverty and hunger, particularly in low-income countries, by fostering sustainable agricultural practices and improved land-use planning.

Table 4 reports details of some of the agricultural monitoring systems currently in operation, based on the input data and models used, the outputs produced and other characteristics such as the role of the analyst, their interaction with other systems and the geographical scale at which they operate.[106] The summary of the assessment of these monitoring systems is shown below. Included are the FAO Global Information and Early Warning Systems (GIEWS), Famine Early Warning Systems Network (FEWS NET), MARS Crop yield forecasting system (MCYFS), CropWatch, United States Department of Agriculture's Foreign Agriculture Service (USDA-FAS), GEOGLAM, World Food Programme (WFP) Seasonal Monitor, and Anomaly Hot Spots of Agricultural Production (ASAP). Additionally, GIEWS, ASAP and WFP contribute to the GEOGLAM Crop Monitor.

[106] Fritz, S., See, L., Bayas, J.C.L., Waldner, F., Jacques, D., Becker-Reshef, I., Whitcraft, A. et al. 2019. "A comparison of global agricultural monitoring systems and current gaps." *Agricultural Systems*, 168: 258–272. https://doi.org/10.1016/j.agsy.2018.05.010.

Although there are similarities among these monitoring components, such as types of data input from satellite data and target agricultural applications, the difference between stakeholders and target users defines the differences in their outputs and delivery mode. Understanding these differences is essential for optimizing the use of these systems and improving agricultural monitoring and decision-making processes.

Table 5. Comparison of different agricultural monitoring platforms and systems.

Agricultural monitoring systems	FAO GIEWS	FEWS NET	MCYFS	CropWatch	USDA-FAS	GEOGLAM	Seasonal monitor	ASAP
Products	Regular bulletins of food crop production and markets on a global scale, specific regional reports based on FAO regional and country offices	Specialized monthly reports on current and projected food security; provides timely alerts on emerging crises	Monthly MARS bulletins and maps for several weather and crop indicators	Bulletins with four spatial levels: global, regional, national (31 key countries including China), and subnational (for the nine largest countries)	Data visualization products, updated every two days and midseason to end-of-season yield estimates and maps	Two types of crop monitor bulletins (for AMIS and for early warning)	Region-specific reports with an approximate monthly frequency describing growing season conditions and providing an outlook for the months ahead	Early warnings issued every 10 days; frequent monitoring of hotspots of potential food security for 80 countries
Area covered by the system	Global	Sub-Saharan Africa, Central Asia, Central America and the Caribbean	Europe and neighbouring countries (China, Kazakhstan and Russian Federation)	Global for agro-meteorology, regional for farming, crop conditions, production, yield for 31 countries	Global	G20+7 Crop Monitor for AMIS; CMAEW for countries most at risk of food insecurity	WFP regions (near global)	10-day global automatic warning and hotspot assessment for 80 countries
Main customers of the system	FAO and FAO member countries	Food security analysts	DG AGRI, EUROSTAT, national stakeholders, agricultural ministries, insurance companies, international organizations, GEOGLAM, AMIS	State Grain Administration from China and other government departments but also other countries download the bulletins	International and domestic commodity traders, brokers, shipping, traders in the commodity food value chain	AMIS, national ministries of agriculture, international organizations, early warning community and authorities	WFP management and offices around the world, others	DG DEVCO, DG ECHO, EUROPEAN UNION delegations, but in general open to the food security analysis community
Interactions with other global agricultural monitoring systems	Uses information from FEWS NET. Contributes to GEOGLAM Crop Monitor	Contributes to GEOGLAM Crop Monitor	FAO and EC shared. Contribute to GEOGLAM Crop Monitor	Some baseline data from MARS and FAO are shared. Contribute to GEOGLAM Crop Monitor	If time permits, analysts review other systems. Ingest publicly available forecasts for data visualization of current and past crop status. Contributes to GEOGLAM Crop Monitor	Interactions with FEWS NET, GIEWS, USDA-FAS, China CropWatch, JRC MARS and national and regional monitoring systems	Contribute to GEOGLAM Crop Monitor	The information is the basis for the JRC contribution to the GEOGLAM Crop Monitor. There is also collaboration on methods for hotspot detection

Source: Fritz, S. et al, Adapted from Fritz, S. et al., "A comparison of global agricultural monitoring systems and current gaps."

A map showing Integrated Food Security Phase Classification (IPC) in the Central African Republic. IPC is an approach for classifying the nature and severity of food insecurity. © FAO

A United Nations/FAO climate change and disaster risk reduction specialist conducts on-the-ground training on the use of drones to gather visual data on recently damaged rice crops in Magalang, Pampanga province, Philippines

II.

CHALLENGES AND OPPORTUNITIES FOR ENHANCED SPACE-RELATED CAPABILITIES FOR AGRICULTURE AND FOOD SECURITY

The present chapter explores the hurdles faced by stakeholders in the space for agriculture domain across all three segments of the space sector – upstream, midstream and downstream – and identifies collaborative opportunities that can accelerate growth in the use of space benefits for achieving food security. It also delves into the challenges related to planning agriculture missions, promoting access to space-based data and creating value for agricultural applications. With examples of successful global partnerships, capacity-building initiatives and mission planning frameworks, this chapter highlights how nations can overcome obstacles and leverage international cooperation to build resilient space capabilities for agricultural applications.

CHALLENGES AND OPPORTUNITIES IN THE UPSTREAM SEGMENT FOR AGRICULTURE MISSIONS

DEVELOPMENT CAPACITY

Dependency on other countries

Within the last few years, there has been a noticeable increase in countries becoming more involved in space activities – from the establishment of national space agencies to the development of national satellite capacity. One theoretical framework, called the Space Technology Ladder[107] attempts to better understand the space technology capability of different nations according to four major technology categories – establishment of a space agency, development of LEO satellites, development of GEO satellites and capacity to launch (table 5). These are steps emerging spacefaring nations may follow.

[107] Wood, D. and Weigel, A. 2012. "Charting the evolution of satellite programs in developing countries – The Space Technology Ladder." *Space Policy*, 28(1): 15–24. https://doi.org/10.1016/j.spacepol.2011.11.001

Table 6. Detailed view of the space technology ladder

13	Launch capability: satellite to GEO
12	Launch capability: satellite to LEO
11	GEO satellite: build locally
10	GEO satellite: build through mutual international collaboration
9	GEO satellite: build locally with outside assistance
8	GEO satellite: procure
7	LEO satellite: build locally
6	LEO satellite: build through mutual international collaboration
5	LEO satellite: build locally with outside assistance
4	LEO satellite: build with support in partner's facility
3	LEO satellite: procure with training services
2	Space agency: establish current agency
1	Space agency: establish first national space office

Source: Wood, D. and Weigel, A. 2012. Charting the evolution of satellite programmes in developing countries – The Space Technology Ladder. *Space Policy*, 28(1): 15–24. https://doi.org/10.1016/j.spacepol.2011.11.001.

Although more nations are establishing their own national space agencies, most still rely on external support for building their own satellites. Currently, 102 member States belong to the Committee on the Peaceful Uses of Outer Space. Many, however, are still developing their local space capabilities and depend on external procurement.

Empowering all nations through global collaboration in satellite development

Global collaborations focusing on capacity-building for satellite development for developing nations are needed to support and improve the development of space capacities. The UNOOSA Access to Space for All initiative, conducted jointly with space agencies, research institutions and industry, aims at developing the technical know-how, engineering processes and infrastructure of United Nations Member States in the areas of hypergravity and microgravity, satellite development and space exploration. Several countries (Guatemala, Kenya, Mauritius and Moldova) have launched their first satellite thanks to the initiative. Another global initiative called the Joint Global Multi-Nation BIRDS Satellite project or BIRDS Project[108] has been providing space capacity-building for different developing nations through a programme for higher education at the Kyushu Institute of Technology, where they learn the know-how for designing, building and operating CubeSats. Country representatives for the BIRDS-1 project include student engineers from Bangladesh, Ghana, Mongolia and Nigeria and it has expanded to include Bhutan, Malaysia and Philippines in BIRDS-2, and Nepal and Sri Lanka in BIRDS-3.

[108] Kyushu Institute of Technology. 2017. BIRDS project, cited 1 July 2024, www.birds-project.com.

Capacity-building initiatives such as Access to Space for All and the BIRDS project are an initial step towards developing national capabilities which can be extended from gathering mission requirements for mission planning to satellite development, especially for missions focusing on agricultural applications.

Leveraging public-private partnerships for satellite development

For countries that are in the initial stages of the space technology ladder, specifically in building their own satellites, venture opportunities can be established between Governments and companies for the procurement or the development of satellites. The partnership of Thailand with Airbus[109] to build two Earth observation satellites, THEOS-1 and THEOS-2, is one example. This collaboration not only involves the development of satellites, but also a training programme for engineers working for the Geo-Informatics and Space Technology Development Agency in the design and testing of similar satellite types to enable them to develop and manufacture their own in the future.

MISSION PLANNING

Challenges of information gaps and stagnation in remote-sensing innovation

Most commercial satellite providers have been launching satellite constellations with identical specifications to increase global coverage and revisit for data acquisition. However, prioritizing the increase of observation frequency over technology developments could stop new monitoring technology from being developed and applied. This leaves the door open to having images acquired over an area with higher revisit than what is needed for agricultural applications but not enough data diversity to help develop new techniques. To address this, the planning of new missions should aim not only at expanding spatial coverage and revisit but also at ensuring that there is room for new sensors that could stimulate research by increasing the variety of data available.

Unlocking opportunities for multi-stakeholder collaboration in satellite development

Global collaborative efforts such as inter-agency collaboration, public-private-partnerships, and the involvement of the academic community and international organizations such as the United Nations in developing and launching satellites for agriculture applications can help support the development of both Earth observation and GNSS satellites with new

[109] Airbus. 2023. THEOS-2 Airbus-built satellite for Thailand successfully launched Airbus, cited 20 August 2024, www.airbus.com/en/newsroom/press-releases/2023-10-theos-2-airbus-built-satellite-for-thailand-successfully-launched.

remote-sensing capabilities. One example of this would be the multi-agency cooperation between NASA and ESA to develop and launch two satellites: the ESA Copernicus Hyperspectral Imaging Mission for the Environment (CHIME) and the NASA Surface Biology and Geology (SBG) satellite missions.[110] The cooperation between the two agencies covers the three segments: the upstream, the midstream and the downstream.

Enhancing satellite development through standardized agriculture-specific requirements

Meanwhile, the development of standardized agriculture requirements based on actual end-user needs for satellite development can help support mission planning when identifying mission requirements. In coordination with CEOS, GEOGLAM has created a framework for defining Earth observation requirements specific to cases of agricultural use. Their development of EAVs has helped advance this initiative as it incorporates space data-derived agricultural products in combination with in situ data. The articulation of required specifications for spatial, spectral and temporal requirements for a defined agricultural product can serve as a framework to guide mission planning and ensure that global agricultural information and gaps in coverage can be addressed.

Strengthening satellite missions through regulated end-user and stakeholder feedback

Setting up well-defined and regulated discussion media such as forums or regular consultation sessions between end users, national space agencies and commercial space companies will ensure that their actual user needs and requirements are fully captured and met. For the past few years, ESA has been releasing calls to Mission Advisory Group members for the development and implementation of the Sentinel satellite missions. A good example of such a multi-agency collaboration is the Joint Mission Advisory Group framework between ESA and JAXA within the EarthCARE mission project.[111]

Furthermore, the emphasis on capacity-building in the use of remote sensing for agriculture is crucial as this provides end users, from policymakers to small-scale farmers, with the knowledge of how space-based data can be useful and integrated into their work. This will help strengthen the feedback loop system from user requirements to satellite development.

[110] Boccia, V., Adams, J., Thome, K.J., Turpie, K.R., Kokaly, R., Bouvet, M., Green, R.O. and Rast, M. 2021. NASA-ESA Cooperation on the SBG and CHIME Hyperspectral Satellite Missions: a roadmap for the joint Working Group on Cal/Val activities,cited 1 June 2024, https://meetingorganizer.copernicus.org/EGU21/EGU21-15166.html.

[111] Katagiri, S., Oki, R., Shimizu, S., Kimura, T., Nakajima, T., Okamoto, H., ... and Hagihara, Y. (2010). EarthCARE science mission objectives. In *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Science* (Vol. 38, No. 8).

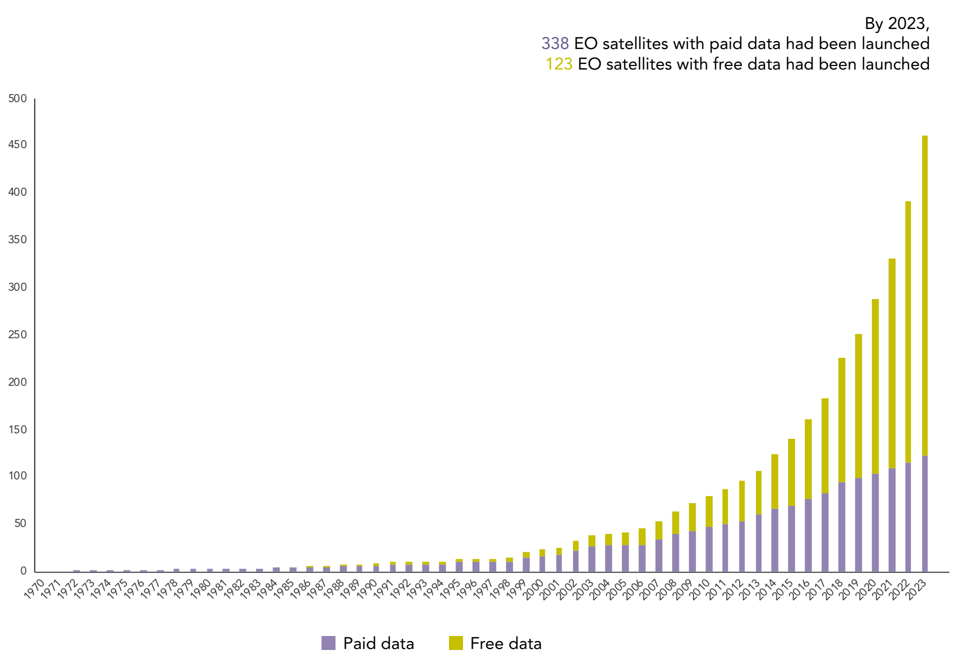
CHALLENGES AND OPPORTUNITIES IN THE MIDSTREAM SEGMENT

DATA ACCESS

Limited access to high-resolution Earth observation and global navigation satellite systems data

Based on the 2022 Joint Agency Commercial Imagery Evaluation – Remote Sensing Satellite Compendium database,[112] the ratio of the number of Earth observation satellites with data sets that can be freely accessed represents approximately half of the number of Earth observation satellites with commercial data. This shows an increasing imbalance in openly available satellite data for global use. However, although several space agencies offer vast amounts of free data, limitations persist regarding data specification and usability as free data are usually offered in medium and low resolution.

Figure 14. Comparison of free and paid data sets from all Earth observation satellites launched between 1970 and 2023



Source: Elaborated by the authors

[112] Ramaseri Chandra, S., Christopherson, J., Casey, K., Lawson, J. and Sampath, Aparajithan. 2022. *2022 Joint Agency Commercial Imagery Evaluation—Remote Sensing Satellite Compendium.* USGS Numbered Series. Circular. Reston, VA, U.S. Geological Survey. https://doi.org/10.3133/cir1500.

Indeed, most VHR satellites with a spatial resolution of 50 cm and 30 cm are only offered by private companies at high cost, limiting accessibility for developing countries and small-scale users, including those working small-sized crop parcels with multi-crops.. This represents a significant obstacle, specifically for precision agriculture, where metre or submetre resolutions are often required. In addition, finding a licensing scheme that allows groups of users or Governments to share and use commercial data remains a challenge. Moreover, the limited hardware infrastructure in developing countries creates an additional barrier to data accessibility.

Advancing agriculture and food security through enhanced multi-sector partnerships

Collaboration with satellite data providers and commercial satellite operators in return for agriculture-focused solutions and product development is one way to both allow open access to high resolution satellite imagery and advance agriculture and food security through innovative research and development. For example, Norway's International Climate and Forest Initiative (NICFI) partnership with Planet Labs, Airbus and Kongsberg Satellite Services gives free access to high-resolution satellite imagery for forest monitoring and environmental purposes.[113] The United Nations FAO SEPAL platform is one of the projects funded by NICFI.[114] Along with the open access public data from Landsat and the Copernicus programmes, the platform also utilizes cloud computing through collaboration with Google Earth Engine.

Enhancing data accessibility through open data initiatives

Following on from the Data FAIR (findable, accessible, interoperable and reusable) programme, GEO has designed a similar programme specifically to improve accessibility to and usability of Earth observation data. Lowering the financial barriers through open data access policies would democratize access to these kinds of data sets and will enable end users from government, academia and the general public to derive value from the data. A similar initiative by a global collaboration of agencies under IGS for GNSS data is also currently active and promotes an open data policy through providing freely available GNSS data, products and services. Similarly, the work of UN-GGIM on geospatial information management practices encompasses both Earth observation and GNSS Data FAIR use and contributes to the promotion of open data policies, standards and practices. Making Earth observation and GNSS data freely available would not only drive innovation in agriculture, but would also enable improved decision-making for policymakers and empower smallholder farmers.

[113] Kimbrough, L. 2020. New partnership brings high-resolution satellite imagery of the tropics to all. In: *Mongabay Environmental News*. [Cited 27 June 2024]. https://news.mongabay.com/2020/09/new-partnership-brings-high-resolution-satellite-imagery-of-the-tropics-to-all/.

[114] Planet Labs. 2019. Planet Satellites Bolster FAO's Geospatial Toolkit, cited 18 July 2024), www.planet.com/pulse/innovative-forest-monitoring-platform-sepal-2-1-goes-mobile/.

Additionally, the UN-GGIM initiatives include significant efforts related to the Global Geodetic Reference Frame (GGRF),[115] which is essential for ensuring the accuracy and consistency of geospatial data worldwide. The establishment of the United Nations Global Geodetic Centre of Excellence (UN-GGCE)[116] in Bonn, Germany, further strengthens these efforts by providing a focal point for geodetic collaboration, capacity-building and the long-term sustainability of the global geodetic infrastructure. These initiatives support a wide range of applications, from precise navigation to land management, reinforcing the critical role of open and reliable geospatial data in global development.

STANDARDIZATION AND ADOPTION

Challenges in standardizing and adopting Earth observation and global navigation satellite systems data

One of the key challenges in standardizing Earth observation and GNSS data is the inherent data heterogeneity due to diverse sources. Data sets often come from various platforms and sensors provided by different organizations, each with its own format and specifications, complicating integration and analysis, particularly for agricultural applications. A major obstacle for GNSS data has been the inconsistent adoption of a standardized geodetic framework, which further complicates the integration of data sets acquired from different sources and locations globally. However, significant progress was made when GGRF was officially endorsed by the General Assembly in 2015, as reflected in resolution A/RES/69/266 dated 26 February 2015. This endorsement marked a major milestone in overcoming challenges related to geospatial data integration by promoting a unified, accurate and consistent geodetic framework on a global scale.

Moreover, the work done by the United Nations Statistics Division through UN-GGIM on the Global Statistical Geospatial Framework (GSGF) represents a crucial advancement in integrating geospatial and statistical data and provides a standardized approach to combine location-based data with statistical information.[117] GSGF has direct relevance to monitoring agriculture, as it provides a mechanism to standardize the integration of statistical and geospatial data, enabling more accurate and efficient agricultural monitoring and decision-making processes. By aligning geospatial and statistical data, GSGF enhances the ability to track agricultural production, land use and food security trends, contributing to more informed policymaking at both local and global levels.

[115] www.iag-aig.org/topic/3

[116] https://unric.org/en/UN-GGCE/

[117] United Nations. 2019. The Global Statistical Geospatial Framework. https://ggim.un.org/meetings/GGIM-committee/9th-Session/documents/The_GSGF.pdf.

Despite the development of standards by international organizations such as ISO and OGC for geospatial information and agriculture use cases, their global adoption remains a challenge for institutions and organizations. The main obstacles include technical barriers, particularly for users without specialized expertise, and the cost and effort involved in implementing these standards. This issue is especially pronounced in countries with limited resources, which may hinder the successful adoption and implementation of such frameworks. Nonetheless, the endorsement of GGRF and the work on GSGF have laid the foundation for a more standardized and interoperable geospatial landscape, helping to mitigate some of these challenges.

Opportunities

Advancing innovation through global coordination in data standardization and capacity-building

Standardization of data, encompassing both Earth observation and GNSS, is essential for enhancing interoperability and facilitating seamless integration of data from various sources. This approach will accelerate innovation by promoting knowledge-sharing and collaboration among national agencies, researchers and developers, while also fostering partnerships with technology providers. By creating a unified framework for data exchange, stakeholders can more effectively leverage shared insights and resources, driving forward advancements in various fields, including agriculture, environmental monitoring and disaster management. Existing efforts in Earth observation and GNSS standardization and adoption include collaborative work by ISO and OCG in developing standards from formats and data quality to platforms and systems. IGS works on a global network of GNSS reference stations providing standardized GNSS processing and data distribution. UN-GGIM promotes the strengthening of national institutional arrangements on geospatial information management particularly for the achievement of the Sustainable Development Goals and the United Nations Integrated Geospatial Information Framework. The involvement of international organizations such as the United Nations, ISO and the Open Geospatial Consortium, in collaboration with the public and private sectors, promotes international cooperation and improves the adoption of existing standards, as well as the coordinated development of new ones.

EARTH OBSERVATION AND GLOBAL NAVIGATION SATELLITE SYSTEMS DATA PLATFORMS

Overlapping platforms for data access

The increase in available Earth observation and GNSS data sets was also followed by the rise of platforms to access them. However, this also comes with duplication of efforts and inefficient use of resources which could have been an opportunity for collaboration and synergy. The presence of multiple platforms could increase complexity for users. Since these platforms could host either the same or overlapping data, it also poses a potential problem of fragmentation of data sources, data inconsistencies and increased time to access up-to-date data which are relevant to their use.

Strengthening global data access through collaborative platforms

Initiatives from organizations such as the ESA Copernicus Open Access Hub and the NASA Earth data provide centralized access to different Earth observation data from multiple sources and providers. A more recent international collaboration between JAXA, NASA and ESA to create a tri-agency Earth observing dashboard is a good example of fostering collaboration and data-sharing. By reducing duplication, users can improve the efficiency of data access and use.

CHALLENGES IN VALUE CREATION FOR AGRICULTURE MONITORING IN THE DOWNSTREAM SEGMENT

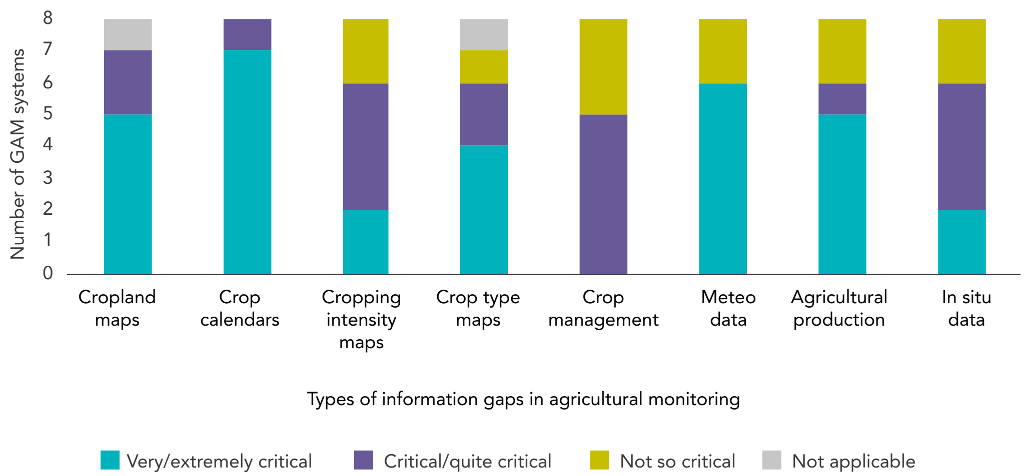
GLOBAL AGRICULTURE MONITORING INFORMATION

Addressing the information gap in global agricultural monitoring platforms

The availability of multiple agricultural monitoring platforms has benefited different types of users globally when it comes to providing timely agricultural products that facilitate decision-making. However, in an assessment report conducted on the eight global agricultural monitoring systems, some gaps persist in terms of agricultural data needs.[118] Information gaps in global agricultural monitoring systems are presented, with crop calendars being the most critical information gap, followed by meteorological data, cropland maps and agricultural production (figure 12).

[118] Fritz, S., See, L., Bayas, J.C.L., Waldner, F., Jacques, D., Becker-Reshef, I., Whitcraft, A. et al. 2019. "A comparison of global agricultural monitoring systems and current gaps." *Agricultural Systems*, 168: 258–272. https://doi.org/10.1016/j.agsy.2018.05.010.

Figure 15. Identified information gaps from different global agriculture monitoring systems



Source: Adapted from Fritz, S. et al., "A comparison of global agricultural monitoring systems and current gaps."

Advancing agricultural monitoring through innovative space missions and collaborative data-sharing

Ongoing and future collaborative space missions, as well as continuous innovation and the development of ground sensors as new sources of data, can potentially bring new value for agricultural monitoring. This enables new monitoring capabilities which could potentially fill in these information gaps. Collaborative sharing of standardized data, encompassing both remotely-sensed instruments and in situ measurements can drive innovations in utilizing space-related information, enhancing crop modelling and advancing agricultural products and services.

IN SITU DATA

Challenges in accessing high-quality in situ data for agricultural use

In situ data obtained from ground sensors through field collection is crucial in any analysis and modelling for agriculture-related applications as it complements remote-sensing data and provides critical input for model development, validation and verification. The lack of open access and high quality in situ data can be caused by its limited availability due to commercial or regulatory restrictions. There is also a considerably high cost in the collection of in situ data, as it involves logistic arrangements, capacity development, data management, labour and technology investments. This can be a challenge for countries with limited access to technical capacities and complex landscapes dominated by smallholder farms which can limit their access. In addition, the lack of knowledge and training in collecting and managing these types of data would also translate into issues of data quality and reliability.

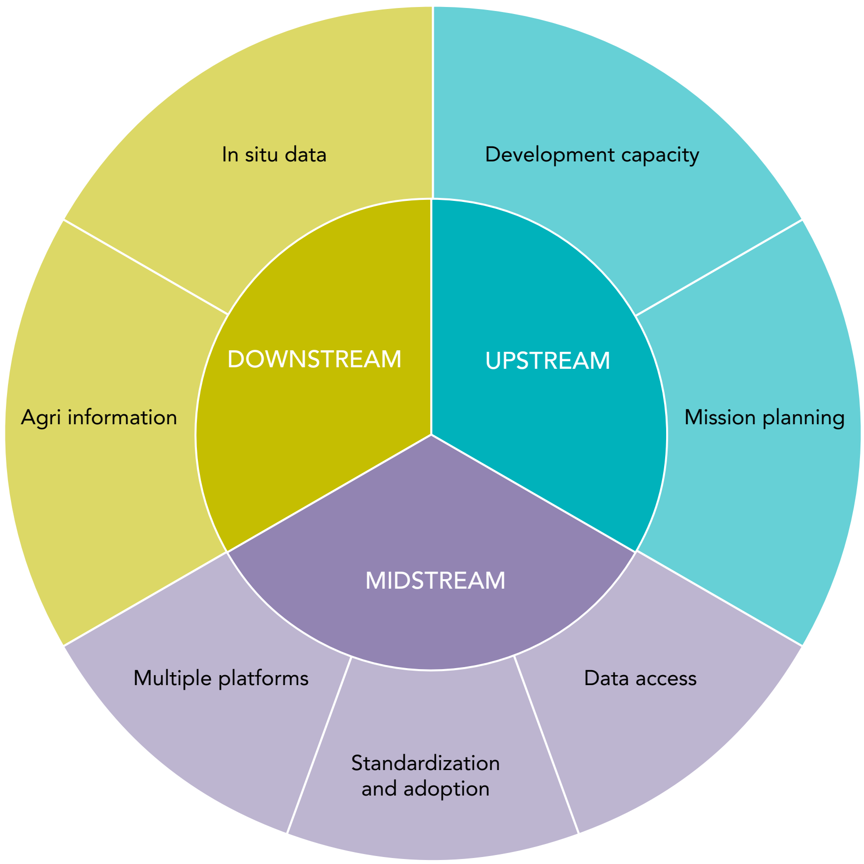
Global coordination for enhancing in situ data open access and collaboration

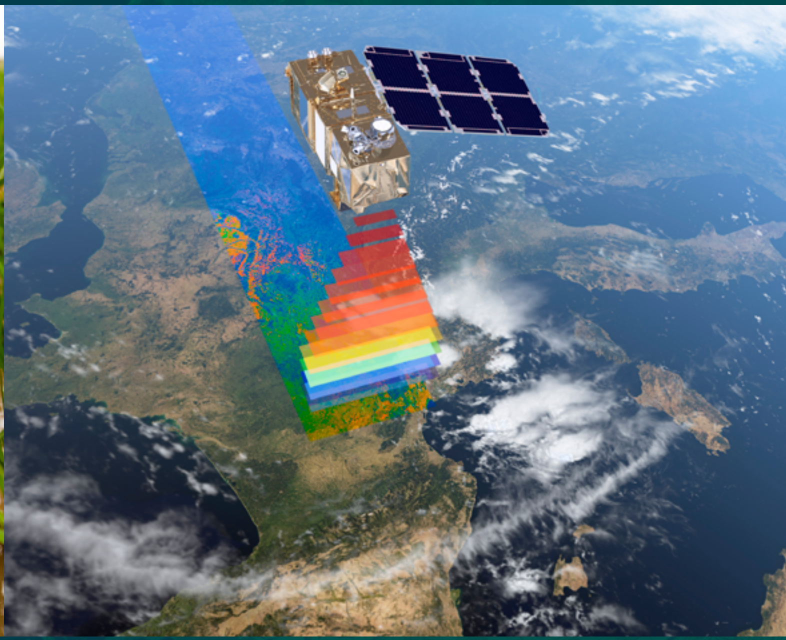
Several global initiatives improve the availability and access to in situ data for agriculture applications. GEOGLAM established a dedicated working group in 2021 to specifically address the existing gaps and create a framework to facilitate collaboration in the collection, sharing and use of in situ agriculture data. The ESA World Cereal programme aims at global in situ data collection, harmonization and standardization for agricultural monitoring.[119] WMO, through the Global Observing System (GCOS), promotes global terrestrial network stations for various essential climate variables such as for land surface and terrestrial observations. The NASA Earth Observing System Data and Information System (EOSDIS) is a central component of the Earth Science Data Systems Programme, offering comprehensive management of NASA Earth science data from satellites, aircraft, field measurements and other sources, including command and control, scheduling, data capture and initial processing for EOS missions.

The following figure summarizes the challenges and opportunities identified in this chapter, from the different segments used to make the analysis.

[119] *In-Situ Data for Global Crop Mapping | WorldCereal*. https://esa-worldcereal.org/en/situ-data-global-crop-mapping. Accessed 2 June 2024.

Figure 16. Identified challenges for each segment in the space technology for agriculture value chain





A woman farmer using a magnifying glass to check rice plants for insects. © FAO/Olivier Asselin

Sentinel-2, colour vision for Copernicus. ©ESA/ATG Medialab

III.

FUTURE OUTLOOK AND INNOVATION IN SPACE TECHNOLOGY FOR AGRICULTURE

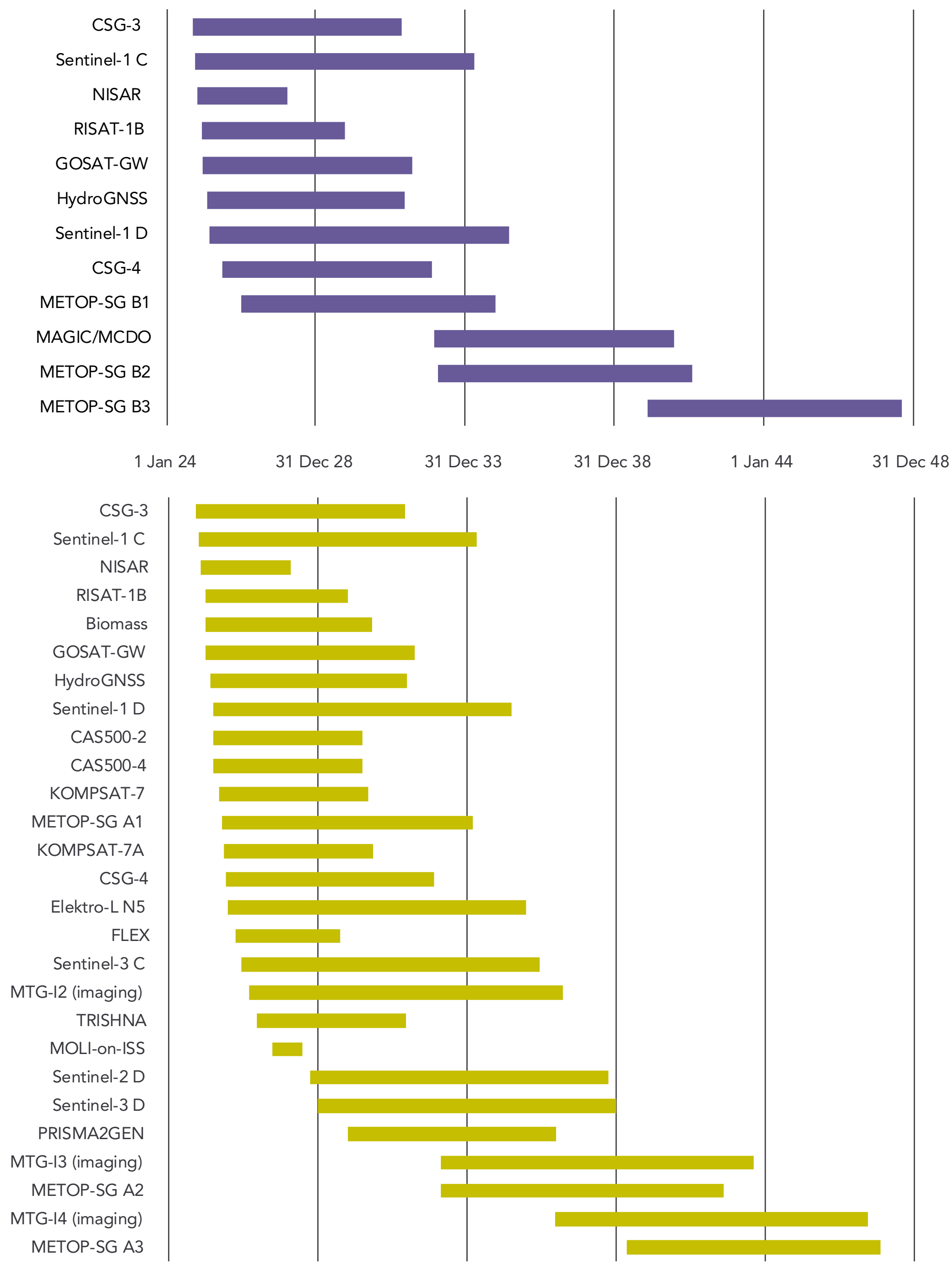
The future of agriculture is increasingly intertwined with advancements in space technology, particularly in Earth observation and GNSS. Over the coming decades, new space missions, supported by cutting-edge sensors such as optical, hyperspectral, infrared and radar technologies, are set to deliver real-time, actionable data that will play a critical role in transforming agricultural practices and improving global food security. The rise of space start-ups, innovative satellite systems and satellite edge computing further enhances these capabilities, offering faster data processing and on-the-ground impact. This chapter zooms in on the three key segments of the space sector: upstream – by exploring the future of space missions for agriculture; midstream – by delving into a new era of data management; and downstream – by looking at innovative solutions in space applications for agriculture.

FUTURE SPACE MISSIONS FOR AGRICULTURE

According to the CEOS Missions, Instruments and Measurements (MIM) database,[120] there are 27 future missions approved for vegetation and 12 for soil moisture (CEOS database consulted on 2 December 2024 for approved missions under those categories). Both types of mission can be utilized for agriculture technology development to achieve food security development goals (figure 13). The missions will employ a combination of GNSS technology and various Earth observation sensors, including optical/multispectral, hyperspectral, infrared and radar types, to achieve its objectives.

[120] CEOS. 2023. The CEOS MIM Database: Timelines - Measurement: Aerosols, cited 17 December 2023, https://database.eohandbook.com/timeline/timeline.aspx

Figure 17. Approved future missions focusing on agriculture applications such as vegetation and soil moisture set to be launched between 2030 to 2040



Source: Modified from CEOS. 2023. The CEOS Database: Timelines - Measurement: Aerosols, cited 9 October 2024. https://database.eohandbook.com/timeline/timeline.aspx

EMERGENCE OF NEW SPACE START-UPS

The emergence of new space start-ups has significantly impacted global space capabilities. Technological advancements have led to the development of smaller, more cost-effective satellites, sustainable launch options and more accessible sensor technology. Because of this, the possibility of launching dedicated satellite constellations driven by agriculture use cases is also now more feasible. New space start-ups have also announced plans to launch Earth observation satellites specifically for agriculture. As an example, EOSDA, a company from the United States, plans to launch seven Earth observation optical satellite constellations called EOS SAT by 2025,[121] with one of the mission objectives focusing on agricultural applications such as land-use monitoring, soil monitoring and the impact of climate change on agriculture production. The Polish start-up SatRev signed a deal with the National Support Center for Agriculture in early 2023 to develop a Satellite System Monitoring Agricultural Crops (S2MUR)[122] for the public sector and individual farmers. A German space start-up, ConstellR, supported by the ESA InCubed programme, is set to launch four high-resolution VEgetation (HiVE) satellites from 2024 to 2025, with a mission to monitor the surface temperature of agricultural land and improve crop health.[123]

SATELLITE EDGE COMPUTING

In a traditional ground-based processing operation, once a satellite captures an image of the Earth, it is then followed by downlinking the data through a ground station to enable the end user to receive the data, process it and turn it into useful information. Through satellite edge computing, this process is shortened by implementing on-board data processing and real-time data analytics.[124, 125] Edge computing could be used in different ways to optimize data flow from the upstream to the downstream segment. For instance, data could be pre-processed and optimized in terms of memory allocation requirements, thus potentially reducing the time needed to transmit large volumes of data during the downlink. Alternatively, on-board data could be pre-processed to provide real-time information for climate alerts, prompt disaster management, etc. Finally, on-board processing and the analysis of remote-sensing data can be coupled with innovative distributed satellite systems

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[121] EOSDA. 2022. EOS SAT Satellite Constellation to Serve Agricultural Needs, cited 14 December 2023, https://eos.com/eossat/.

[122] SatRev. 2023. News - SatRev sings 9 mln USD Earth observation data deal | SatRev, cited 14 December 2023. https://www.satrev.space/article/satrev-sings-39-mln-earth-observation-data-deal.

[123] ESA. 2023. HiVE Microsatellite Constellation – eoPortal, cited 17 December 2023, www.eoportal.org/satellite-missions/hive#space-and-hardware-components.

[124] G. Guerrisi, F. D. Frate and G. Schiavon, "Artificial Intelligence Based On-Board Image Compression for the Φ-Sat-2 Mission," in *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, vol. 16, pp. 8063-8075, 2023, doi: 10.1109/JSTARS.2023.3296485.

[125] I. Leyva-Mayorga et al., "Satellite Edge Computing for Real-Time and Very-High Resolution Earth Observation," in *IEEE Transactions on Communications*, vol. 71, no. 10, pp. 6180-6194, Oct. 2023, doi: 10.1109/TCOMM.2023.3296584.

(constellations, formations, etc.) to provide time-sensitive information for agricultural monitoring such as in the case of disaster events.[126]

A TECHNOLOGICAL REVOLUTION IN EARTH OBSERVATION AND GLOBAL NAVIGATION SATELLITE SYSTEMS DATA MANAGEMENT

DATA HARMONIZATION

Data harmonization in Earth observation refers to the process of aligning and standardizing data from different sources to ensure consistency and comparability, enabling more effective analysis and allowing interoperability between data sets, platforms and processes. Various standards have revolutionized data harmonization in the past decade. The adoption of these common standards has contributed to defining how data should be formatted, processed and exchanged to ensure compatibility across different systems. Their adoption, in support of data analysis processes, allows diverse data sets from various platforms, sensors and missions to be integrated and used together seamlessly. Data harmonization supported by standards includes, among many others, aspects related to units, dimensions, forms and projections.

DATA INTEGRATION AND INTEROPERABILITY

Combining two or more data sets contributes to maximizing the potential use of Earth observation data by integrating them into new derivative products.[127] In the context of Earth observation, harmonization of satellite imagery from multiple sources is likely to revolutionize the Earth observation industry as it is expected to address gaps in spatial, temporal or spectral coverage which have long been a challenge for end users. Improved integration and harmonization processes enhance the interoperability of data coming from diverse sources, maximizing downstream opportunities for processing, analysis, mapping and more.

One good example of data harmonization is the Harmonized Landsat and Sentinel-2 (HLS) initiative led by NASA in collaboration with USGS.[128] In this project, data from Landsat-8 and 9's Operational Land Imager and Sentinel-2A and 2B's Multispectral Instrument are

[126] Kathiravan Thangavel, Raja Pandi Perumal, Khaja Faisal Hussain, Alessandro Gardi, Roberto Sabatini, "Multidisciplinary design and optimization of intelligent Distributed Satellite Systems for EARTH observation", *Acta Astronautica*, volume 216, 2024, pp. 411-427, ISSN 0094-5765, https://doi.org/10.1016/j.actaastro.2023.12.055.

[127] www.nature.com/articles/s41597-024-02956-3.

[128] https://hls.gsfc.nasa.gov/.

combined and run through a series of processing methods: atmospheric correction and cloud masking, geographic registration and spatial resampling, and bidirectional reflectance distribution function normalization. The transformed product is a 30-metre seamless surface reflectance data with Universal Transverse Mercator projection and in Military Grid Reference System tiling system. Currently, it has global coverage, except for the region of Antarctica.[129]

In scenarios where cloud-free data with high temporal coverage is essential, such as in agricultural mapping and monitoring, the HLS product has proven valuable by increasing the capture frequency in the area of interest, compared to relying on a single satellite source.[130] This, in turn, can support decision makers in crafting science-based policies with accurate and reliable agricultural maps and data.

NEW DATA MANAGEMENT AND WORKING ENVIRONMENTS

The evolving landscape of space and Earth observation data management is increasingly characterized by the integration of cloud computing, standardized frameworks, advanced data analytical platforms and innovative dissemination tools. Cloud computing platforms such as the Google Earth Engine (GEE)[131] or SEPAL[132] platforms have revolutionized the way Earth observation data is stored, processed and accessed, enabling vast data sets to be managed efficiently and making high-performance computing resources available to a broader range of users. This shift, made possible by the adoption of international standards, facilitates real-time data processing and large-scale analytics, essential for timely decision-making in fields such as environmental monitoring and disaster response.

Data analytics platforms, often hosted on cloud infrastructure, provide users with powerful tools to analyse and visualize complex data sets. Platforms such as GEE and Amazon Web Services (AWS) offer scalable environments where users can apply machine learning, statistical models and other analytical methods to derive insights from large volumes of Earth observation data.

THE POTENTIAL OF QUANTUM COMPUTING IN DATA MANAGEMENT FOR REMOTE SENSING

Recent scientific literature has highlighted the current effectiveness and future potential of quantum computing, a revolutionary paradigm compared to traditional computing based on bits for binary processing.[133] Unlike conventional computing, quantum computing utilizes

[129] https://lpdaac.usgs.gov/documents/1698/HLS_User_Guide_V2.pdf.
[130] https://ainfo.cnptia.embrapa.br/digital/bitstream/doc/1143597/1/AP-Exploring-harmonized-Landsat-2022.pdf.
[131] https://earthengine.google.com/.
[132] https://sepal.io/.
[133] Sukhpal Singh Gill, Rajkumar Buyya, "Transforming Research with Quantum Computing." *Journal of Economy and Technology*, 2024, https://doi.org/10.1016/j.ject.2024.07.001.

qubits, which can exist in multiple states simultaneously, allowing for parallel processing at unprecedented scales.[134]

Today, many researchers and tech companies are actively working to demonstrate the quantum advantage – the notion that a programmable quantum computer can solve specific problems faster than any classical computer, regardless of the practical utility of the task. While this so-called "quantum advantage" has not been conclusively proven for real-world problems, several cases have shown notable computational efficiency through quantum computing. These include achievements in foundational work in quantum computing[135] as well as emerging applications in areas such as remote sensing and classification problems.[136, 137]

If ongoing research in quantum computing successfully proves a measurable advantage over classical computing, it could significantly enhance big data management in Earth observation. This might optimize various pre- and post-processing tasks, including improving the evaluation of Level 1 and 2 remote-sensing data or enhancing the generation of auxiliary information, such as land scene classification or land cover data.

ADVANCEMENTS IN EARTH OBSERVATION AND GLOBAL NAVIGATION SATELLITE SYSTEMS ANALYSIS FOR AGRICULTURE SOLUTIONS

IMPROVED AVAILABILITY OF GROUND-TRUTH DATA

One of the key advancements expected in the near future is the improved availability of ground-truth data through simple, user-friendly smartphone GNSS-based applications for the collection of field data. These applications will allow farmers, international agencies and governmental bodies, among others, to easily collect and upload real-time data from agricultural land, such as soil health, crop conditions and pest activity, directly from their mobile devices.

[134] Nielsen, M. A., and Chuang, I. L. (2010). *Quantum Computation and Quantum Information: 10th Anniversary Edition.* Cambridge: Cambridge University Press.

[135] Arute, F., Arya, K., Babbush, R. et al. "Quantum supremacy using a programmable superconducting processor." *Nature* 574, 505–510 (2019). https://doi.org/10.1038/s41586-019-1666-5.

[136] A. Sebastianelli, D. A. Zaidenberg, D. Spiller, B. L. Saux and S. L. Ullo, "On Circuit-Based Hybrid Quantum Neural Networks for Remote Sensing Imagery Classification", in *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, vol. 15, pp. 565-580, 2022, doi: 10.1109/JSTARS.2021.3134785.

[137] E. Pasetto, M. Riedel, K. Michielsen and G. Cavallaro, "Kernel Approximation on a Quantum Annealer for Remote Sensing Regression Tasks", in *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, vol. 17, pp. 3262-3269, 2024, doi: 10.1109/JSTARS.2024.3350385.

By utilizing GNSS technology, these apps can precisely geolocate data points, ensuring that the information is highly accurate and linked to specific areas of the farm. This ground-truth data is invaluable for improving the accuracy of remote-sensing models and enhancing predictive analytics, as they provide a direct, real-time view of conditions on the ground.

In the near future, the volume of high-quality, real-time data available for analysis is expected to increase significantly. International and governmental agencies should aid in the free dissemination of these data to help and accelerate technological improvements based on the connection of remote-sensing and ground-truth data. This will not only benefit individual farmers by providing more tailored insights but also contribute to the development of larger agricultural data sets, improving the overall effectiveness of precision agriculture solutions and climate-resilient farming strategies. These tools will bridge the gap between field-level realities and remote-sensing technologies, helping to drive smarter, more sustainable farming practices.

ARTIFICIAL INTELLIGENCE FOR AGRICULTURE

The rapid evolution of artificial intelligence (AI) technology presents a transformative tool for enhancing the efficiency, equity and environmental sustainability of agricultural practices. This comes at a crucial time when global progress is imperative to meet the targets set by the international community.[138] Recent scientific breakthroughs, coupled with the success of specific applications, have thrust AI into the spotlight as a powerful ally in the agrifood sector.[139]

AI encompasses a family of technologies that empower computers and machines to perform tasks previously considered reliant on human experience, creativity and ingenuity. It enables machines to function autonomously, learning from vast data sets without explicit programming for a given task. In most AI systems, learning occurs through continuous adjustment of parameters based on training data, employing machine learning algorithms and, more recently, deep learning. This approach mirrors natural learning processes, wherein knowledge and skills develop through continuous trial and error. Key advantages include overcoming challenges in developing multivariable algorithms for complex tasks, allowing for greater versatility and agility of the algorithms.[140] Typically, both Earth observation and GNSS data are essential for AI applications in agriculture. Earth observation provides imagery data, both optical and radar, which serves as a source of raw information for AI systems, while GNSS is used to accurately geolocate field data for training models. For supervised machine learning algorithms, field data remains one of the best sources of labels, although very high-resolution imagery can also be used for label collection.

[138] Digital agriculture in action: Artificial intelligence for agriculture, FAO-ITU.
[139] Artificial intelligence in the agri-food sector, European Parliament.
[140] *Artificial Intelligence: A Modern Approach*, 4th United States ed. by Stuart Russell and Peter Norvig.

The versatility of AI is evident in its ability to expedite time-consuming tasks at a fraction of the time and effort required by humans, especially when combined with other technologies. For instance, while a human specialist may take several days to manually survey 1,400 acres of farmland to identify areas with insufficient hydration or fertilization, an AI system can rapidly pinpoint these areas by analysing real images captured by drones. This enables targeted resource utilization for optimal agricultural outcomes.[141]

AI applications in agriculture span various domains, including crop, soil and land monitoring, pest and disease detection, weather and temperature forecasting, predictive analytics, and irrigation facilities analysis. These technologies can significantly enhance land-use planning by optimizing crop management, enabling the efficient use of land in mixed farming systems with livestock, and guiding sustainable practices for better resource allocation and environmental conservation. The use of AI in these areas not only accelerates decision-making processes but also enhances precision, enabling more sustainable and resource-efficient farming practices.[142]

The most recent advances in the application of AI for agricultural practices showcase an exciting trajectory towards even greater precision and innovation. Cutting-edge developments include the integration of AI-driven autonomous vehicles equipped with advanced sensors for real-time data collection in the field. These vehicles, ranging from smart tractors to drones, facilitate unparalleled efficiency in monitoring crop health, identifying anomalies and implementing targeted interventions. Moreover, the use of machine learning algorithms has evolved to handle complex and dynamic agricultural ecosystems, enabling farmers to gain valuable insights into optimizing crop yields while minimizing resource usage. In parallel, advancements in computer vision and image recognition technologies empower AI systems to discern subtle nuances in plant health, aiding in early disease detection and prompt mitigation strategies. These recent breakthroughs underscore the transformative potential of AI in reshaping traditional farming paradigms and ensuring sustainable agricultural practices for the future.

The current landscape and future possibilities of AI-based applications for farmers hold tremendous promise in revolutionizing agricultural management and decision-making processes. Presently, AI-driven apps are emerging as indispensable tools for farmers, providing real-time insights into crop health, weather patterns, and optimal planting and harvesting schedules. These applications leverage machine learning algorithms to analyse historical data, satellite imagery and local weather forecasts, offering personalized recommendations for irrigation, pest control and fertilizer application. As technology continues to advance, the potential for AI-based apps to become even more intuitive and user-friendly grows

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[141] Digital agriculture in action: Artificial intelligence for agriculture, FAO-ITU.

[142] N. C. Eli-Chukwu, "Applications of Artificial Intelligence in Agriculture: A Review", *Eng. Technol. Appl. Sci. Res.*, vol. 9, no. 4, pp. 4377–4383, Aug. 2019.

exponentially. Future iterations may integrate features such as predictive analytics to foresee market trends, enabling farmers to make informed choices for crop selection and pricing strategies. Additionally, the integration of AI in agriculture is key to fostering sustainable practices, ensuring efficient resource utilization, and ultimately contributing to global food security. The ongoing evolution of AI-based apps for farmers reflects a transformative shift towards precision agriculture, empowering farmers with the tools they need to navigate the complexities of modern agriculture with greater efficiency and sustainability.

Recent advances in AI technologies hold tremendous promise for revolutionizing agriculture by making processes more efficient, sustainable and adaptive to the evolving needs of the sector. Delving deeper into the capabilities of AI, its integration into agricultural practices stands to contribute significantly to the global pursuit of food security and environmental stewardship.

INNOVATIVE SOLUTIONS FOR FARMERS

The rapid advancement in remote-sensing technology is transforming the agricultural sector by making sophisticated monitoring tools more accessible. User-friendly smartphone applications will soon enable farmers to monitor their fields with real-time satellite data, providing essential information for optimizing various farming practices such as irrigation, seeding and crop health management. These applications are designed to allow farmers with minimal technical knowledge to understand and use information based on Earth observation data. Through these tools, farmers can receive timely alerts about potential issues such as drought stress, pest infestations or nutrient deficiencies, all of which contribute to improving yields and resource efficiency. Moreover, the integration of field-specific recommendations tailored to local weather and soil conditions ensures that farmers can take swift and accurate action to improve productivity.

IRRIGATION OPTIMIZATION

Efficient water management is critical in agriculture, particularly in regions where water scarcity is a growing concern. Remote sensing combined with GNSS technology enables precise monitoring of water use, ensuring that irrigation is optimized. This technology helps farmers reduce water wastage by delivering water exactly where it's needed, in the right amounts, and at the right time.

Advances in remote sensing, such as microwave and SAR technologies, have improved the ability to monitor soil moisture in real-time. These technologies can penetrate through cloud cover, making them ideal for continuous monitoring, even during adverse weather conditions. Access to accurate soil moisture data helps farmers make informed irrigation decisions, enhancing water-use efficiency and promoting sustainable farming practices.

AUTOMATED MACHINERY AND PRECISION AGRICULTURE

Incorporating GNSS into farm machinery enables precision farming, where every seed, fertilizer drop and pesticide application can be fine-tuned to the needs of the land. Autonomous tractors, guided by GNSS and supported by remote-sensing data, ensure that farming inputs are applied with high accuracy, reducing waste and lowering costs.

Precision agriculture technologies, such as variable rate technology, allow farmers to optimize inputs according to spatial variability within their fields. These tools, combined with Earth observation data, can significantly improve crop yields while conserving resources such as water, fertilizers and fuel.

UN-SPACE

"The United Nations Inter-Agency Meeting on Outer Space Activities (UN-Space) is the formal inter-agency mechanism aimed at enhancing coordination of space-related activities within the United Nations system."

IV.
CONCLUSION AND RECOMMENDATIONS

With the increasing challenges facing the agricultural sector, the ability to make informed decisions is vital for effective agricultural monitoring and management. With the integration of satellite imagery, GNSS and advanced data management, agriculture can evolve towards more sustainable and precise practices. This makes timely, continuous and sustained availability of, and access to, local, regional and global spatial data for agricultural applications critical. However, alongside these opportunities comes the need for efficiency and sustainability in space infrastructure development.

Analysing the past experiences of United Nations entities and international collaborations and programmes, backed up by expert interviews and questionnaires with diverse stakeholders, this report demonstrates the importance of space technology, data and applications for sustainable agriculture and presents opportunities and challenges for upstream, midstream and downstream segments. Throughout the preparation of this report, various recommendations for each of the aforementioned segments were formulated.

STRENGTHENING GLOBAL CAPACITIES IN THE USE OF SATELLITE DATA FOR AGRICULTURE

Enhanced engagement, capacity development and knowledge-sharing at local, regional and global levels are key to demonstrating and promoting the importance of a space-based approach to agriculture monitoring. Targeted capacity-building programmes, in particular for developing countries and vulnerable areas, should be expanded and scaled-up, as should the training of local experts in, inter alia, satellite data analysis and the development and use of agricultural applications. Improved data literacy and data management are key to strengthening the technical capacity needed, which then informs strategic policy and decision-making. At the same time, global initiatives aimed at enhancing knowledge-sharing to better understand needs and gaps, along with strengthening connections across different segments of the space sector, hold the potential to improve access to space data and applications for agriculture, while also optimizing the efficient allocation of resources for space sustainability.

INCREASING INTERNATIONAL COORDINATION FOR INCLUSIVE COLLABORATION ON AGRICULTURE-FOCUSED SATELLITE MISSIONS

Taking into account the diverse stakeholders in the space technology for agriculture ecosystem (see, for instance, figure 18 below, which focuses on users), strategic and technical collaboration, and the leveraging of related advantages can be achieved through existing or new coordination and cooperation mechanisms. The upstream, midstream and downstream segments of space technology must be continuously enhanced through global collaboration, capacity-building and improved data management systems. International cooperation is essential to developing space-based agricultural solutions that meet the needs of both developed and developing countries. Initiatives that promote coordinated satellite development programmes, shared infrastructure and assets, data standardization, and greater access to satellite information will not only increase the efficacy of agricultural monitoring but also reduce duplication of efforts and operational costs. Through the sharing of resources, investment in satellite development is maximized. Costs may be also be reduced through the optimization of the overall space segment for agriculture. This also promotes the safe and sustainable use of space by maximizing missions and reducing potential sources of space debris.

IMPROVING ACCESSIBILITY AND INTEROPERABILITY BETWEEN SPACE DATA AND SERVICES

Currently, Member States derive significant benefits from space data for various applications. However, the lack of coordinated approaches sometimes results in costly and inconsistent processes. Single-use licences and duplicated efforts, in particular among United Nations entities or different ministries within a specific country, can result in increased costs, lower efficiency and limited collaboration. Furthermore, coordinated Earth observation imagery procurement, for example through a United Nations-centralized imagery procurement hub, would have the potential to increase synergies, reduce duplication and result in benefits for multiple United Nations programmes and countries. In parallel, efforts to promote the use of open-access platforms, standardized data formats and recognized methods can contribute to increased interoperability, increased ownership and customized applications that address user-specific or country-specific needs for their food security and sustainable agriculture needs. With regard to the adoption, adaptation and feasibility of innovative approaches, data and services, promoting public-private collaborations has the potential to increase piloting data and services and the availability of customized innovative services, for example building on emerging AI, sensors, technical approaches and standards.

ADDRESSING GAPS IN SPACE APPLICATIONS FOR AGRICULTURE

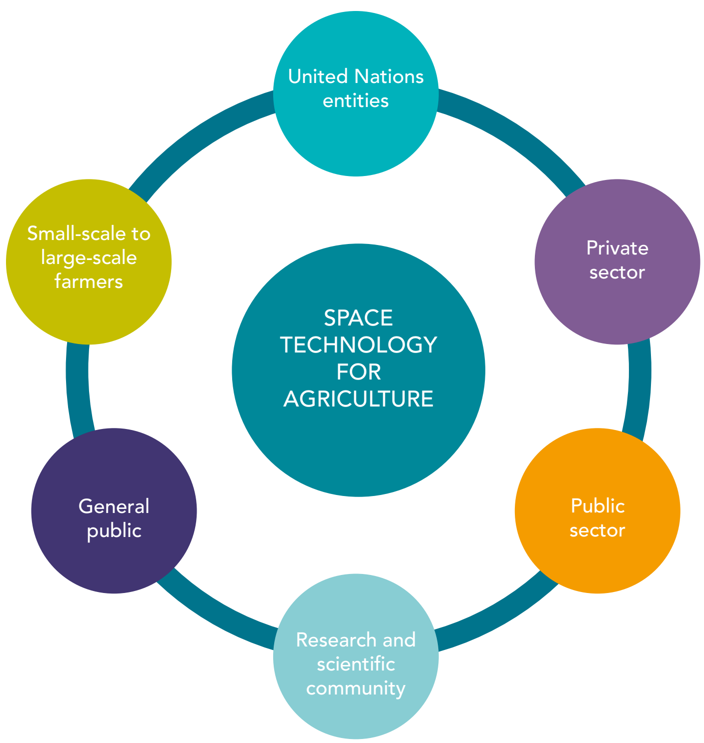
Stakeholders should consider ways to fill gaps in the existing use of space technology intended for agricultural applications to achieve food security goals, aiming to strengthen collaboration and promote space sustainability by sharing resources from space segment to user segment infrastructure.

In this vein, FAO and UNOOSA, in particular, should deepen their collaboration, working to improve their understanding of the needs of agriculture, considering the wide diversity of local to global needs and gaps. They should also support the scaling-up of integrated capacity-building and technical assistance efforts in satellite data utilization, such as with targeted training programmes, data-sharing initiatives and knowledge transfer mechanisms; build upon existing collaboration to support the improvement of access to satellite-based data and services; and maximize efforts to foster innovation, including through multi-stakeholder partnerships, in particular with new actors providing available data and services. As an example, strengthening public-private partnerships and making the best use of transformative innovations, such as AI with new sensors and ground information, will improve alignment between segments, as well as the capabilities of the commercial and public sectors.

Collaboration could also be extended, in the future, to cover thematic areas such as the management and protection of ocean and marine zones, which are also critical for food security and environmental sustainability.

Through continuous investment in space technology, international partnerships and sustainable practices, the agriculture sector can be better equipped to tackle the mounting pressures of population growth, resource constraints and environmental change. This transformation is essential for meeting global food security goals and achieving sustainable development for 2030 and beyond.

Figure 18. Space technology user ecosystem for agriculture



ACRONYMS AND ABBREVIATIONS

AGRA	Alliance for a Green Revolution in Africa
AI	Artificial intelligence
ARD	Analysis ready data
BDS	BeiDou system
CEOS	Committee on Earth Observation Satellites
CHIME	Hyperspectral Imaging Mission for the Environment
EAV	Essential agriculture variables
ESA	European Space Agency
EVI	Enhanced vegetation index
FAIR	Findable, accessible, inter-operable and reusable
FAO	Food and Agriculture Organization of the United Nations
GCI	Green chlorophyll index
GEE	Google Earth Engine
GEO	Geostationary orbit
GEOGLAM	Group on Earth Observations Global Agricultural Monitoring
GKI	Geospatial Knowledge Infrastructure
GLONASS	The Russian Federation Global Navigation Satellite System
GNSS	Global Navigation Satellite Systems
GPP	Gross primary productivity
GPS	Global Positioning System
GSDI	Global spatial data infrastructure
HiH	Hand-in-Hand
HiVE	High-resolution VEgetation
IFAD	International Fund for Agricultural Development
IGS	International GNSS Service
InSAR	Interferometric synthetic aperture radar
INSPIRE	Infrastructure for SPatial InfoRmation in Europe
ISO	International Organization for Standardization
JAXA	Japan Aerospace Exploration Agency
LAI	Leaf Area Index
LEO	Low Earth orbit
LiDAR	Light detection and ranging
MEO	Medium Earth orbit
NASA	National Aeronautics and Space Administration of the United States
NDVI	Normalized difference vegetation index
NDWI	Normalized difference water index
NICFI	Norway's International Climate and Forest Initiative
NPP	Net primary productivity
NSDI	National spatial data infrastructure

OGC	Open Geospatial Consortium
PAMS	Precision agriculture management system
PRISMA	Hyperspectral Precursor of the Application Mission satellite
RVI	Radar vegetation index
SAGI	Satellite, aerial and ground integration
SAVI	Soil Adjusted Vegetation Index
SAR	Synthetic aperture radar
SDGs	Sustainable Development Goals
SDI	Spatial Data Infrastructure
SDO	International Standards Development Organization
SEPAL	System for Earth Observation Data Access, Processing and Analysis for Land Monitoring
SWI	Soil water index
UAV	Unmanned aerial vehicle
UN-GGIM	United Nations Committee of Experts on Global Geospatial Information Management
UNICEF	United Nations Children's Fund
UN-IGIF	United Nations Integrated Geospatial Information Framework
UNOOSA	United Nations Office for Outer Space Affairs
UNRCC-AP	United Nations Regional Cartographic Conference for Asia and the Pacific
UN-Space	United Nations Inter-Agency Meeting for Outer Space Activities
USDA	United States Department of Agriculture
VHR	Very high resolution
WFP	World Food Programme
WFS	Web Feature Service
WHO	World Health Organization
WMS	Web Mapping Service

ANNEX

This publication aims to assess the current state of the use of space technology in agriculture and identify challenges faced by different users and stakeholders from upstream, midstream and downstream segments of the space value chain. To complement desk research, a questionnaire was circulated to stakeholders from the public, private and not-for-profit sectors. Stakeholder interviews were also conducted with representatives of different space agencies and international organizations.

Sixteen stakeholders were interviewed and 24 questionnaire responses received.

STAKEHOLDER INTERVIEWS

The interviews solicited opinions about current initiatives and use cases, challenges and recommendations.

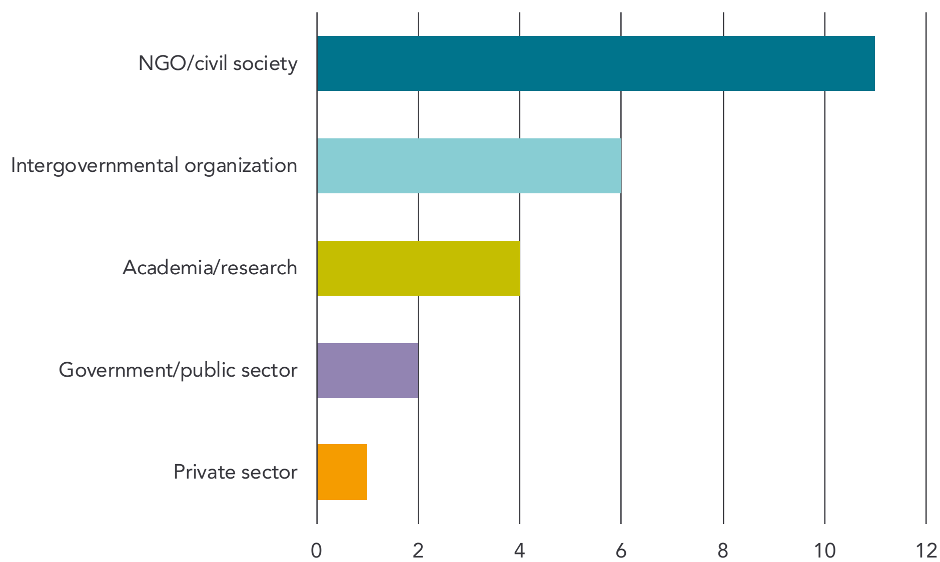
Space value chain segment	Interviewee's organization/entity
Upstream	ESA, CEOS
Midstream	ESA, CEOS, OGC, ISO, FAO (CSI)
Downstream	ESA, CEOS FAO, UNOOSA (UN-SPIDER), GEO (GEOGLAM)

QUESTIONNAIRE

The purpose of the questionnaire was to gather information on the three space value chain segments: upstream, midstream and downstream.

SAMPLE QUESTIONS AND HOW THEY ARE USED IN THE PUBLICATION

Sample questions	Relevance to publication
Upstream: Would you see any value in having United Nations entities involved in mission development and operations for requirement definition and refinement?	The answers to this question are used to determine potential opportunities for the United Nations to support the development of agriculture-focused space missions
Midstream: Are there challenges in accessing satellite-based Earth observation and GNSS data required for your agricultural use case? Please identify the challenges encountered, if there are any.	The answers to this question are summarized and assessed to understand the state of accessibility of space data, specifically for Earth observation and GNSS data, from the perspective of different types of users.
Downstream: Please provide recommendations, if there are any, on how to improve further and expand collaborative efforts focused on agricultural applications	The answers to this question are used to define opportunities for collaboration and provide recommendations and future action items.



Respondents were from diverse geographic areas.

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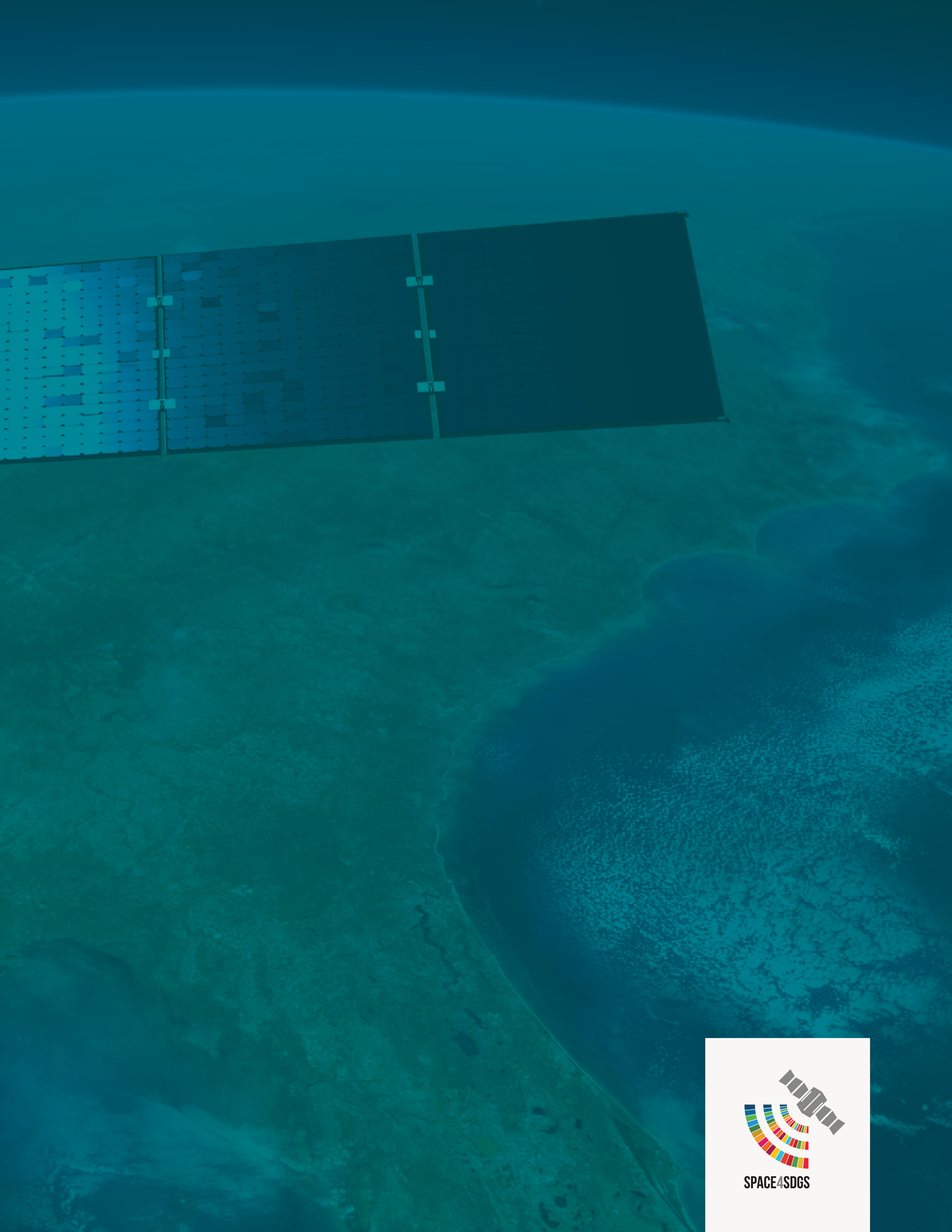
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