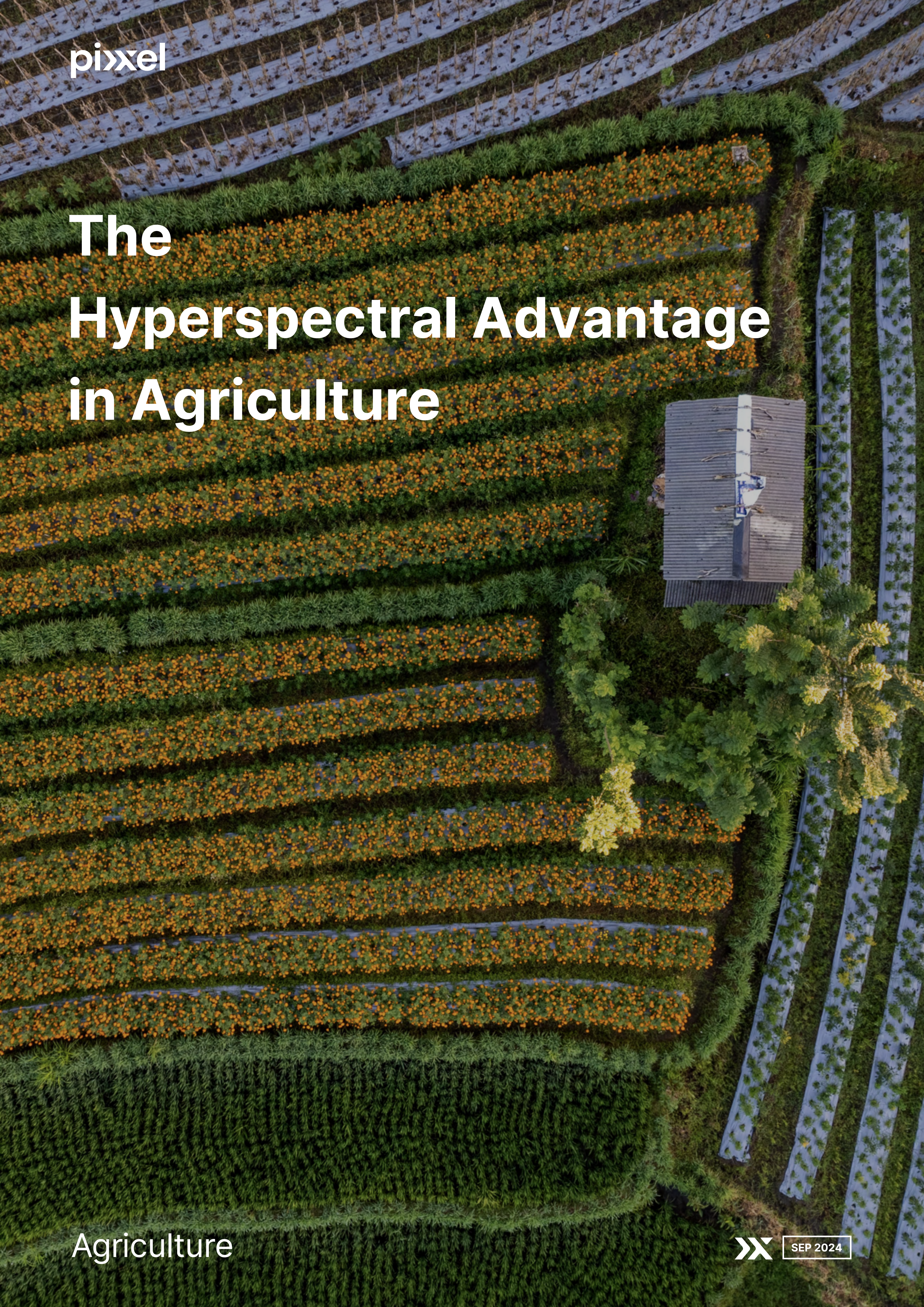


pixxel

The Hyperspectral Advantage in Agriculture

Agriculture

SEP 2024

Contents

Introduction

This whitepaper illustrates the applications and benefits of hyperspectral imaging (HSI) satellites in agriculture. It outlines the challenges the industry faces when limited by conventional datasets and how this novel technique can overcome them. By comparing traditional methods with the advanced capabilities of HSI, this paper highlights the benefits and properties that contribute to more efficient and comprehensive agricultural strategies.

Motivation: The rise of precision agriculture

Efficient agricultural practices are crucial for addressing the challenges of a growing population, declining resources, and inefficiencies in current agricultural methods. Modern technological advancements within the agricultural field offer solutions to these pressing issues.

Precision agriculture, or **precision farming**, is a broad term to describe an approach to agricultural management that utilises technology and data-driven techniques to optimise various aspects of crop production. In particular, remote sensing techniques may be applied to precision agriculture efforts, which, combined with data analytics, aim to optimise various aspects of farming, including cropping, irrigation, fertilisation, and pest control. By precisely targeting inputs and resources, agricultural operators can increase productivity while minimising excess waste and environmental impacts.

Precision agriculture techniques may result in:

- Maximised resource efficiency: By accurately mapping soil properties and crop requirements, farmers can target their resources effectively, reducing unnecessary inputs (including fertilisers, pesticides, and irrigation) while minimising environmental pollution and contamination of water bodies.
- Increased crop yields: By effectively monitoring crops and their requirements, organisations can see higher yields, which, in turn, helps meet the food demands of a growing global population.
- Sustainable land management: By adopting practices that prioritise soil health, biodiversity, and ecosystem services, organisations can maintain long-term productivity in their lands while also preserving natural habitats and reducing greenhouse gas emissions.

Various countries and regions have implemented frameworks to promote coordinated action between agriculture and broader land-use objectives. These frameworks often include government incentives and support programs to encourage the adoption of precision agriculture, helping farmers invest in the necessary technologies and training to implement these practices effectively.

Notable initiatives and organisations supporting such efforts include:

- World Health Organization (WHO) Guidelines on Pesticide Use: The WHO provides guidance on reducing pesticide residues in food, promoting alternatives to chemical measures, and improving pesticide management practices.
- The Food and Agricultural Organization (FAO) of the United Nations: The FAO provides guidelines on best practices and supports initiatives such as agroecology, integrated pest management, and soil conservation.
- The European Union Common Agricultural Policy (CAP): This policy encompasses various measures promoting sustainable agriculture, biodiversity conservation, and environmental protection, including subsidies for farmers who implement practices such as crop diversification.
- Convention on Biological Diversity (CBD): As an international treaty, the CBD conserves biodiversity by encouraging traditional farming practices, conserving wild crop relatives, and preserving pollinator habitats.

Given the necessity for comprehensive management strategies in agriculture, robust monitoring is essential for gaining reliable insights into the state of farmlands. This includes the impacts of crop health and biodiversity conservation efforts, such as precision farming techniques, land rehabilitation, and soil restoration projects.

Traditionally, assessing agricultural land has been costly and laborious, involving highly specialised expertise.These limitations result in infrequent evaluations of cropland conditions, failing to provide a thorough understanding of the dynamic and diverse nature of such areas. Additionally, conventional methods often fail to promptly detect and report on critical factors and events, like pest infestations, soil degradation, and water scarcity.

Recognising this urgency, the emergence of Pixxel's hyperspectral satellites offers a promising solution. With their advanced spectral, spatial, and temporal capabilities, these satellites are set to reveal previously unseen insights.

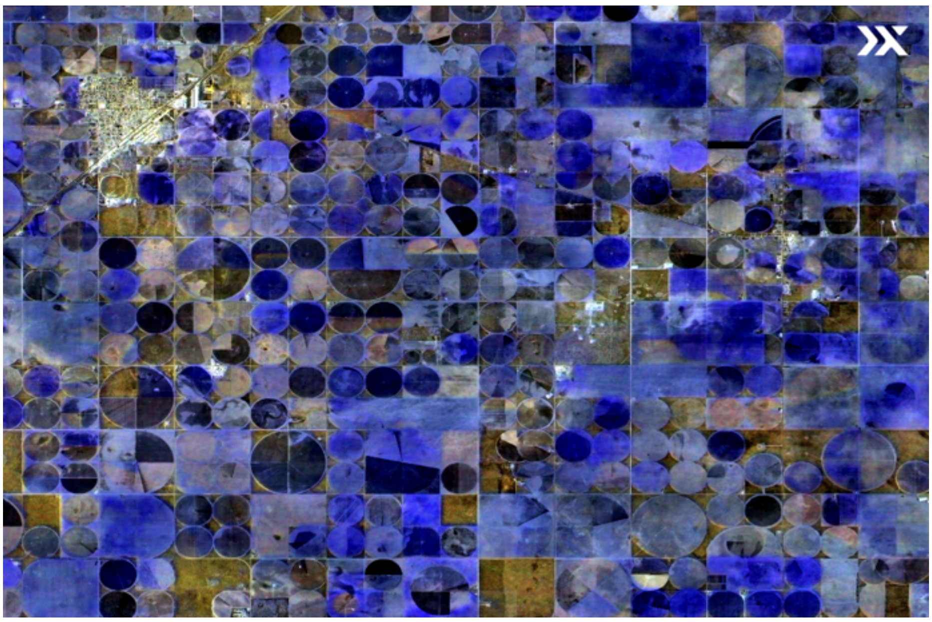
This whitepaper showcases the competitive advantages of Pixxel's HSI solutions, welcoming a new era in how stakeholders perceive and manage vital agricultural lands.

What is Hyperspectral Imaging?

HSI is a cutting-edge technology that significantly aids in analysing agricultural lands. Unlike the 5-15 bands typically captured by multispectral imaging (MSI) satellites, hyperspectral sensors split the electromagnetic spectrum into many narrow bands, each with a bandwidth of less than 10nm. HSI sensors detect unique spectral signatures of small features through the reflected light from ground objects. This capability enables unprecedented precision, capturing details beyond the visible spectrum and into the infrared range. A comparative analysis of the three most popular optical satellite imaging techniques used to monitor ground activities is shown below.

A comparison of RGB, multispectral, and hyperspectral imagery.

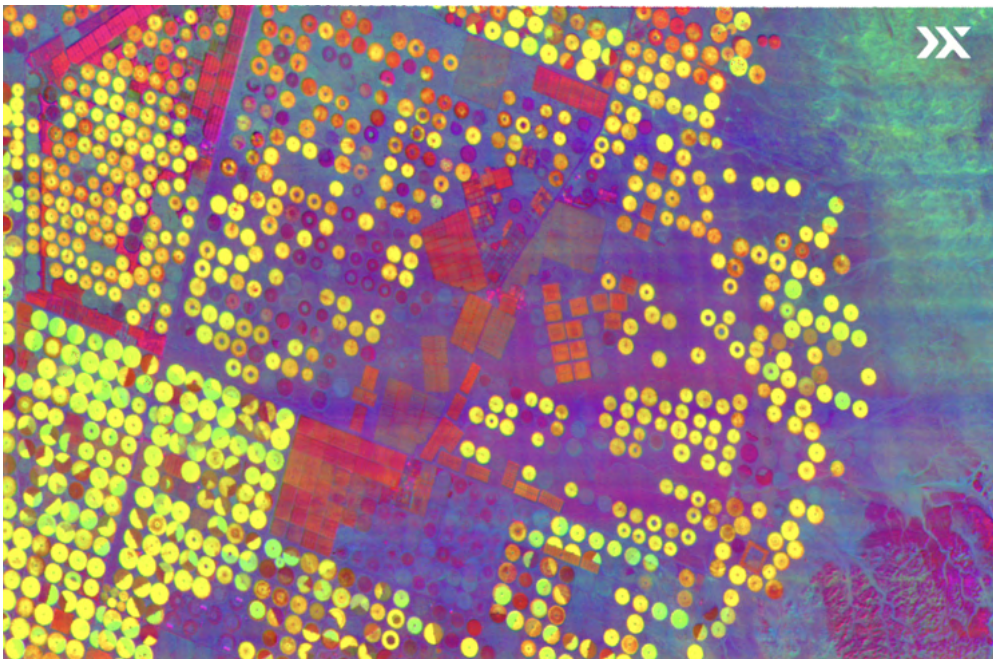
Type	# of bands	Bandwidth (FWHM)	Wavelength Range
RGB	3	~50-70 nm	635 nm-700 nm (Red) 520 nm-560 nm (Green) 450 nm-500 nm (Blue)
Multispectral	4-20	~15-35 nm	400-1000 nm
Hyperspectral	100+	<10 nm	400-2500 nm



Synthetic 5m image of agricultural fields primarily growing cotton near Seminole, Texas (U.S.A.)

HSI provides informative and voluminous datasets, combining conventional imaging, radiometry, and spectroscopic principles. While multispectral imagery offers insights, its limited spectral resolution and dependence on ground infrastructure constrain its applications. Furthermore, the widely spaced bands in multispectral imaging can run the risk of averaging out values or incorrectly classifying properties, potentially missing specific details.

In contrast, hyperspectral imagery's extensive spectral resolution, encompassing over 100 narrowly spaced bands across the electromagnetic spectrum, surpasses any other satellite imagery dataset. For example, when analysing crop health, MSI might produce a smoother spectral curve, obscuring finer details on vegetation stress factors. Meanwhile, HSI would reveal intricate details by highlighting specific spectral characteristics associated with different stressors. This distinction highlights the superior capability of HSI in detecting subtle variations and threats invisible to current Earth-orbiting satellites, providing invaluable agricultural monitoring and management insights.



A false colour composite applied over hyperspectral imagery extracts detailed insights over agricultural fields due to their many very narrow bands (Tubarjal, Saudi Arabia).

Challenges in Agricultural Practices

Ensuring the health and productivity of agricultural lands is crucial for sustaining food productivity and livelihoods. However, the agricultural sector encounters numerous challenges, impeding its efficiency and sustainability. This section highlights agricultural organisations' prevalent challenges and issues, underscoring the need for data-driven solutions.

Inefficient resource allocation: Efficient allocation of resources, including water, land, and energy, is critical for sustainable agriculture. However, organisations often need more information on crop performance to estimate the required inputs. This has both financial and environmental consequences, resulting in lower yields and wasteful applications of fertilisers, water, and pesticides. Innovative technologies like remote sensing and HSI hold the potential to significantly improve data collection and analysis, thereby enhancing resource optimisation and supporting agricultural productivity.

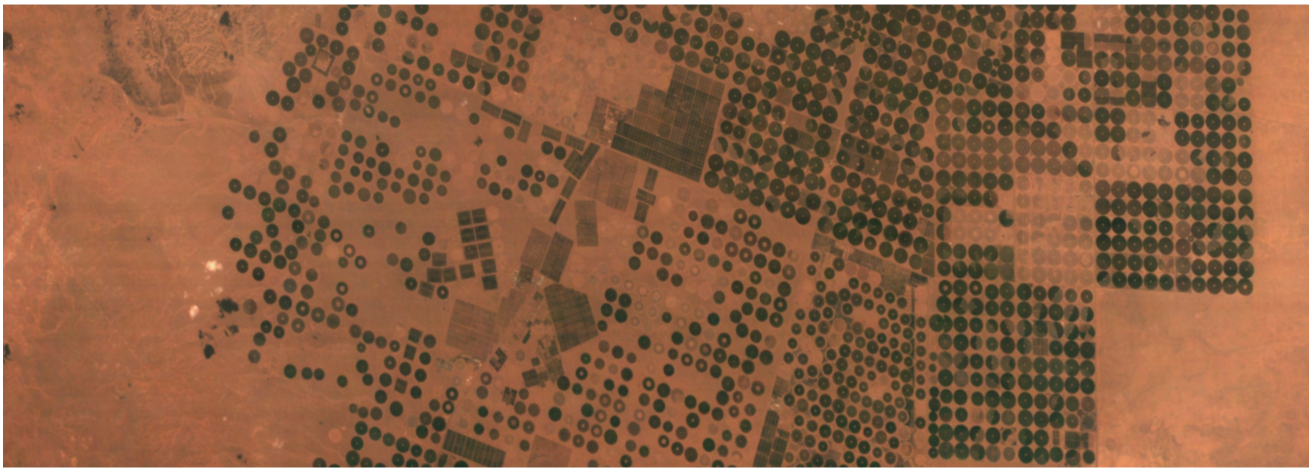
Environmental degradation and contamination: Agricultural activities contribute to various forms of contamination, harming ecosystems and agricultural productivity. Yet, organisations must improve when implementing sustainable farming practices due to inadequate technological infrastructure and limited access to frequent and consistent agricultural data. This limits their ability to mitigate contamination, further worsening environmental and public health concerns. Organisations can proactively monitor and address contamination risks using advanced monitoring techniques and spectrally enhanced datasets.

Disease and pest outbreak: Infestations significantly threaten crop yields and food security, leading to substantial economic losses for farmers and disruptions in global food supply chains. Climate change and globalisation contribute to the spread of pests and diseases, exacerbating the risk of outbreaks.[1, 2] However, the lack of timely and accurate infestation data hinders proactive intervention efforts, leaving crops vulnerable to outbreaks. Integrating data-driven practices that utilise enhanced spectral features empowers organisations to anticipate and mitigate pest and disease risks effectively, thereby safeguarding agricultural yields and enhancing food security.

Soil degradation: Nutrient depletion, erosion, and compaction undermine the long-term productivity of agricultural lands. Intensive farming practices, including monoculture and excessive tillage, exacerbate soil health issues, decreasing crop yields and increasing vulnerability to environmental stressors.[3] The absence of high spectral fidelity imagery impedes organisations' ability to assess soil health parameters. Adopting remote sensing data like hyperspectral imagery enables organisations to optimise soil health monitoring and conservation efforts, supporting precision agricultural practices and resilience against stressors.

Extreme weather events: The increasing frequency and intensity of extreme weather events, such as droughts, floods, and storms, threaten agricultural production. However, organisations often struggle to implement climate-resilient agricultural practices due to the lack of robust data and forecasting tools, leaving agricultural systems vulnerable to extreme weather events. Integrating remote sensing technologies and climate forecasting models can empower organisations to develop proactive adaptation strategies that enhance agricultural resilience.

Agricultural fraud: This refers to deceptive actions by organisations, such as falsely claiming to plant specific crops to avoid fees or gain financial subsidies[4]. Traditional monitoring methods often fail to detect discrepancies, leaving the sector vulnerable to manipulation. Advanced satellite imagery with high spectral resolutions enhances crop detection accuracy, ensuring transparency and accountability across the agri-food



RGB imagery captured over Tubarjal, Saudi Arabia using Pixxel's HSI satellites.

[1] Gullino, M. L., Albajes, R., Al-Jboory, I., Angelotti, F., Chakraborty, S., Garrett, K. A., Hurley, B. P., Juroszek, P., Lopian, R., Makkouk, K. M., Pan, X., Pugliese, M., & Stephenson, T. S. (2022). Climate change and pathways used by pests as challenges to plant health in agriculture and forestry. Sustainability, 14(19), 12421. https://doi.org/10.3390/-su141912421

[2] Singh, B. K., Delgado-Baquerizo, M., Egidi, E., Guirado, E., Leach, J. E., Liu, H., & Trivedi, P. (2023). Climate change impacts on plant pathogens, food security and paths forward. Nat Rev Microbiol, 21(640–656). https://doi.org/10.1038/s41579-023-00900-7

[3] United States Department of Agriculture [USDA]. (2019). Soil management and conservation. In D. Hellerstein, D. Vilorio, & M. Ribaudo (Eds.), Agricultural Resources and Environmental Indicators, 2019. EIB-208, U.S. Department of Agriculture, Economic Research Service. https://www.ers.usda.gov/webdocs/publications/93026/eib-208.pdf

[4] Agri-Food fraud: What does it mean? European Commission. (n.d.). European Commission. Retrieved April 26, 2024, from https://food.ec.europa.eu/safety/eu-agri-food-fraud-network/what-does-it-mean_en

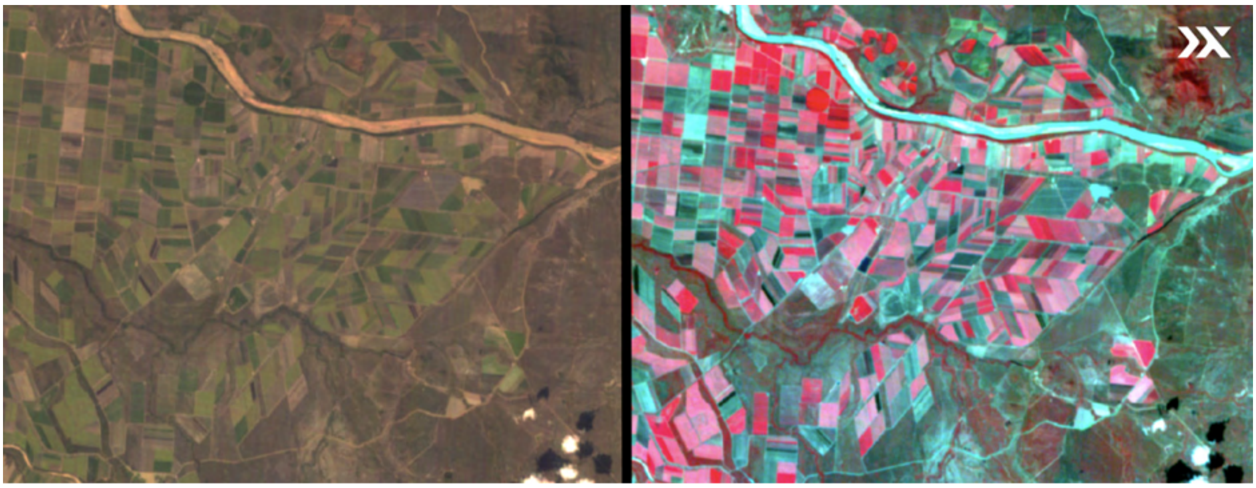
Hyperspectral Imagery in Action

Integrating hyperspectral imagery into agricultural management practices presents a solution to address the sector's challenges. By harnessing the spectral information provided by HSI, organisations can execute crucial tasks that contribute to enhanced farming techniques and methods.

Hyperspectral imagery enables organisations to accomplish three critical tasks:

- Detection: Monitoring crops and identifying potential issues and abnormalities in agricultural fields.
- Classification: Categorising agricultural features facilitates a deeper understanding of the intricate dynamics and relationships between agricultural systems and their surrounding environments.
- Quantification: Measuring various agricultural parameters, including crop density, biomass, and soil nutrient levels, offers valuable insights into the overall health and productivity of agricultural lands.

High-resolution satellite imagery can offer the narrowband spectral information required to effectively monitor and assess the health of croplands through minor variations in health parameters. HSI satellites present voluminous datasets, allowing for precise monitoring and comprehensive analysis of agricultural systems.



The power of HSI becomes apparent when compared with multispectral imaging. The hyperspectral image (right) highlights the superior level of detail, capturing vast information beyond what is possible with MSI (left). This capability enables precise pest detection and analysis, invasive species and disease detection, soil health and nutrient content determination, and chlorophyll content, empowering farmers with comprehensive insights for efficient decision-making in precision agriculture.

Band Group	Wavelength (nm)	Parameters	Significance
Blue	375	Leaf water content, fraction of photosynthetically active radiation (fPAR)	Indicates leaf water levels and photosynthetic activity
	466-490	Chlorophyll-a and b	Detects chlorophyll levels, ripening, or browning of vegetation
Green	515	Leaf nitrogen	Measures photosynthetic activity, nitrogen content in leaves
	520	Pigment, biomass changes	Reflects changes in leaf pigments and biomass
	550	Total chlorophyll	Indicates overall chlorophyll content in leaves
Red	675	Chlorophyll absorption	Measures reflectance due to chlorophyll absorption
	682	Biophysical quantities and yield	Assesses leaf area index, grain yield, crop type
Red Edge	700-720	Vegetation stress and chlorophyll	Indicates plant stress, particularly due to nitrogen
NIR	845	Biophysical quantities and yield	Assesses leaf area index, vegetation vigour
	915-975	Moisture, biomass	Reflects moisture and biomass content in vegetation
FNIR	1100-1215	Biophysical quantities, moisture, water sensitivity	Indicates vegetation properties and sensitivity to water changes
SWIR	1300-1400	Water content, lignin, cellulose	Asesses moisture content and plant vigour
	1500-1600	Plant stress, protein, lignin	Detects plant stress and growth parameters
	1650-1750	Leaf water content, soil moisture	Supports irrigation practises and water usage
	2100-2300	Nitrogen, protein, cellulose, lignin	Assesses soil fertility and plant nutrition

NIR: Near-Infrared bands
FNIR: Far-near Infrared bands
SWIR: Short-wave Infrared bands

Hyperspectral vs Multispectral Imaging in Agriculture

HSI sensors offer exceptional accuracy when compared to traditional imaging techniques. The captured imagery contains data in hundreds of spectral bands across the electromagnetic spectrum, enabling the extraction of more precise insights into agricultural lands and practices.

Parameter	Multispectral Imaging	Hyperspectral Imaging
Yield prediction	Suitable for general yield estimation	Provides detailed information for accurate yield prediction
Cropland inventory	Valid for basic land-use and land-cover maps	Enables precise identification of crop species and detailed cropland inventory
Vegetation stress	General indication of stress based on simple indices, such as NDVI	Detailed, early stress detection using narrowband indices
Disease and pest detection	Detection of significant outbreaks and infestations	Enhanced detection and identification of pre-symptomatic outbreaks and infestations
Nutrient benchmarking	Basic assessment of nutrient levels	Detailed evaluation and mapping of nutrient distribution in soils
Moisture content	Basic estimation of leaf moisture content	Precise measurement of moisture levels, including early signs of drought
Agricultural land health status	Basic assessment of land health	Provides in-depth analysis of land health through a combination of narrowband indices
Soil properties analysis	General soil type and texture classification	Detailed mapping of soil properties, including organic matter and mineral content
Weed detection	Identification of significant weed infestations	Precise detection and classification of various weed species

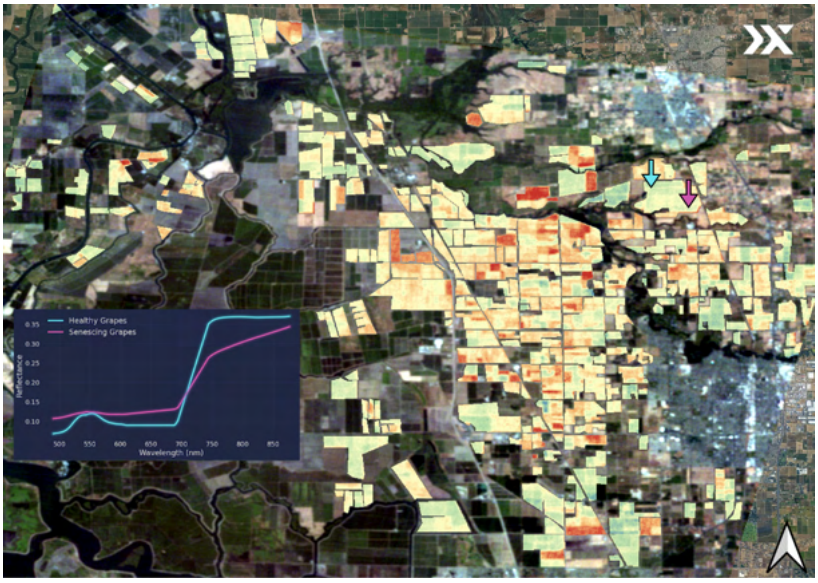
Parameter	Multispectral Imaging	Hyperspectral Imaging
Crop phenotyping	Basic phenotypic traits measurement	Detailed phenotyping, including biochemical composition and physiological traits
Irrigation management	Basic irrigation planning based on general moisture content	Optimised irrigation scheduling using precise soil and plant water status
Harvest time optimisation	General recommendations for harvest timing	Accurate prediction of optimal harvest time based on crop maturity indices
Post-harvest quality assessment	Basic quality assessment of harvested crops	Detailed quality evaluation, including nutrient content and disease presence
Climate impact assessment	General assessment of climate impact on crops	In-depth analysis of climate effects on crop health and yield
Precision agriculture	Basic implementation of precision agriculture practices	Advanced precision agriculture techniques with detailed site-specific management

Use Cases in Agriculture

HSI provides high-level insights across several agricultural applications. This section highlights a non-exhaustive list of hyperspectral imagery use cases.

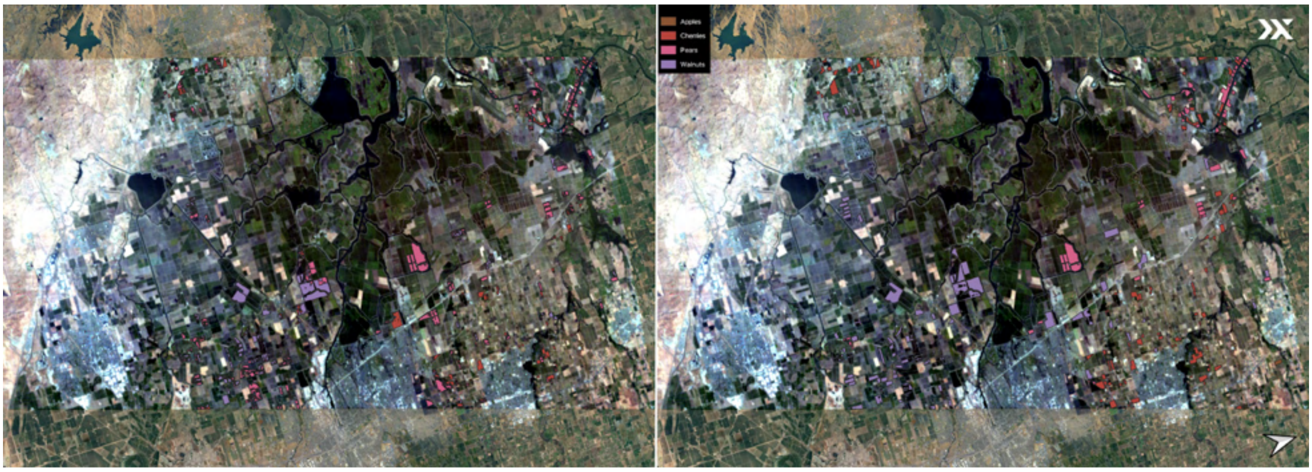
Vegetation and crop health monitoring

- Agricultural land health status: HSI is a powerful tool for assessing agricultural land health, especially for detecting vegetation stress. The high spectral fidelity helps identify subtle changes in vegetation health and soil composition. In particular, narrowband indices enable the detection of senescence, a process where plant cells stop dividing and start breaking down, leading to ageing and eventual death. This capability supports timely interventions to address issues to improve agricultural productivity and sustainability. Moreover, HSI satellites facilitate the detection of abiotic stressors, like adverse winds, temperature, and water availability. While these stressors may arise due to locality, environment, or climate change, early detection enables proactive measures to mitigate their impact on crop health and productivity.
- Canopy structure analysis: Hyperspectral imagery enables the examination of plant canopy structure and density. The spectral detail highlights variations that may indicate different growth stages and stress conditions and identifies potential issues. For instance, dense canopies may indicate overcrowding, resulting in competition for light and nutrients among plants, ultimately impacting overall crop health and yield. Conversely, sparse canopies might indicate underdevelopment or pest damage. Understanding these variations allows for management decisions like thinning to enhance light penetration and air circulation, optimising crop health and productivity.
- Early disease and pest detection: HSI satellites offer applications for the early detection and monitoring of diseases and pests affecting crops. In particular, this involves their capability to detect subtle anomalies in vegetation reflectance associated with disease symptoms or pest infestations. This early detection enables the implementation of timely control measures, reduction of crop losses, and minimisation of chemical pesticides.
- Crop physiology and photosynthesis monitoring: VNIR bands in hyperspectral imagery can provide insights into plant health and vigour monitoring by accurately detecting subtle variations in chlorophyll concentrations. This offers organisations a detailed understanding of crops' photosynthetic efficiency and physiological status. For instance, a decline in chlorophyll content may signal nutrient deficiencies or disease onset, prompting timely interventions. This VNIR-based capability enables healthier and more resilient crops, supporting sustainable practices and ultimately increasing productivity and profitability.



Plant Senescence Index applied to Pixxel's hyperspectral imagery over vineyards in Central Valley, California (U.S.A.). Crop areas with a high senescence index (red) indicate high vegetation stress or ripening, enabling targeted interventions. The spectral signatures further highlight the differences between healthy (blue) and senescing (pink).

- Crop phenotyping: Hyperspectral imagery's high spectral fidelity enables precise quantification of phenotypic traits like leaf area, colour, and canopy cover across growth stages. For instance, variations in leaf area and colour can provide insights into plant health, vigour, and stress responses. This comprehensive data provides insights into plant health and stress responses, supporting breeding programs by identifying superior traits for developing more resilient crop varieties.



Analysis of orchard crops over Central Valley, California (U.S.A.) shows the superiority of hyperspectral imagery (right) over multispectral imagery (left). When validated with ground-truth datasets from the USDA 2022 Crop Map, hyperspectral imagery had an overall classification accuracy of 89.9% compared to the 24.9% accuracy using seven bands from Landsat (30 m) imagery.

Resource management and efficiency

- **Precision irrigation and fertilisation:** Hyperspectral imagery's high spectral resolution enables the assessment of soil moisture and plant health indicators. SWIR bands are particularly effective at detecting soil moisture content, helping to identify areas of water stress. Meanwhile, VNIR bands analyse chlorophyll content and photosynthetic activity, offering insights into crops' nutritional status and overall health. The integration of this data enables optimised irrigation and fertilisation, enhancing resource efficiency, supporting sustainable practice, maximising yield potential, and contributing to more efficient and effective agricultural operations.

- **Yield prediction:** With many narrowband indices, hyperspectral imagery provides valuable data for accurately predicting crop yields by pinpointing stress indicators like variations in chlorophyll content, leaf moisture, and canopy reflectance. Agricultural organisations can utilise spectral information to adjust the concentrations and frequency of inputs such as irrigation, fertilisers, and pesticides, ultimately enhancing overall productivity and profitability.

- **Yield quality forecasting:** Hyperspectral sensors capture a wide range of wavelengths, allowing for precise detection and quantification of crop health and quality indicators. In this case, VNIR bands monitor plant health parameters, while SWIR bands assess water and nutrient content in soil and plants. For example, optimal chlorophyll and moisture levels predict higher yields, while stress indicators prompt early interventions. By analysing these indicators, organisations can gain insights into factors that ultimately contribute to yield quality and, thus, accurately predict outcomes.

Nutrient and soil analysis

- **Nutrient benchmarking:** HSI enables accurate mapping of nutrient distribution by analysing spectral signatures associated with nutrient concentrations in soil and vegetation. This information informs nutrient cycling, availability, and overall health, optimising fertiliser application across vast agricultural landscapes.

- **Soil biochemistry analysis:** By analysing spectral signatures associated with soil organic matter and nutrient content, HSI offers comprehensive insights into soil composition and biochemistry. This valuable data supports sustainable soil management practices, such as cover cropping, crop rotation, and organic amendments to improve soil health and productivity.

- **Moisture content assessment:** HSI accurately identifies and monitors moisture levels in soils and leaves, aiding in plant water content assessment and irrigation management. This spectral analysis promotes sustainable water use, minimises water stress, and enhances crop quality and yield.

- Crop residue and cover crop monitoring: SWIR bands in hyperspectral imagery effectively differentiate crop residues, cover crops, and bare soil due to their sensitivity to moisture content and organic material. Organisations can use this data to accurately map the distribution and coverage of ground cover types, evaluate the success of conservation efforts, and make informed decisions to optimise soil management strategies.

Analysis of rice and corn fields over Central Valley, California (U.S.A.) shows the power of hyperspectral imagery (right) over multispectral imagery (left) in distinguishing species. When validated with ground-truth datasets from the USDA 2023 Crop Map, hyperspectral imagery had an overall classification accuracy of 91% compared to the 65% accuracy using seven bands from Landsat (30 m) imagery.

Cropland classification and inventory management

- Crop species classification: HSI sensors on Earth observation satellites capture data across hundreds of narrow wavelength bands, detecting unique spectral signatures influenced by biochemical and biophysical properties. This enables accurate classification of crop species and varieties, often with just a single image. Unlike traditional methods needing time series data, HSI can differentiate similar-looking species, which is crucial for precision agriculture. This precise identification supports transparent cropland inventories, discourages misrepresenting or falsifying crop types (and yields) for financial gain, enhances trust and accountability across agricultural supply chains, and safeguards against practices that compromise market integrity and
- Carbon sequestration monitoring: Unlike MSI, hyperspectral imagery offers detailed spectral information for precise analysis of soil organic matter and vegetation health. This level of precision accurately detects changes in carbon stocks over time. Also, when coupled with conservation practices like reduced tillage and cover cropping, HSI evaluates their success, helping optimise land management strategies and enhance carbon sequestration potential, contributing significantly to climate change mitigation strategies.

Operational Benefits

Comprehensive data for informed decisions: Hyperspectral imagery provides detailed information about crop species, health indicators, and soil composition, allowing for informed decisions and tailored management strategies.

Environmental insights: This technology enables the early detection of crop stress and diseases, facilitating timely intervention and prevention measures to ensure productivity and sustainability.

Efficient resource allocation: HSI facilitates efficient resource allocation by offering improved accuracy compared to traditional sensors, optimising agricultural practices such as irrigation, fertilisation, and pest management.

Cost-effectiveness: The ability to cover large areas in a single image, coupled with its ability to provide scalable, objective, and consistent monitoring, contributes to sustainable and economically viable agricultural management strategies.

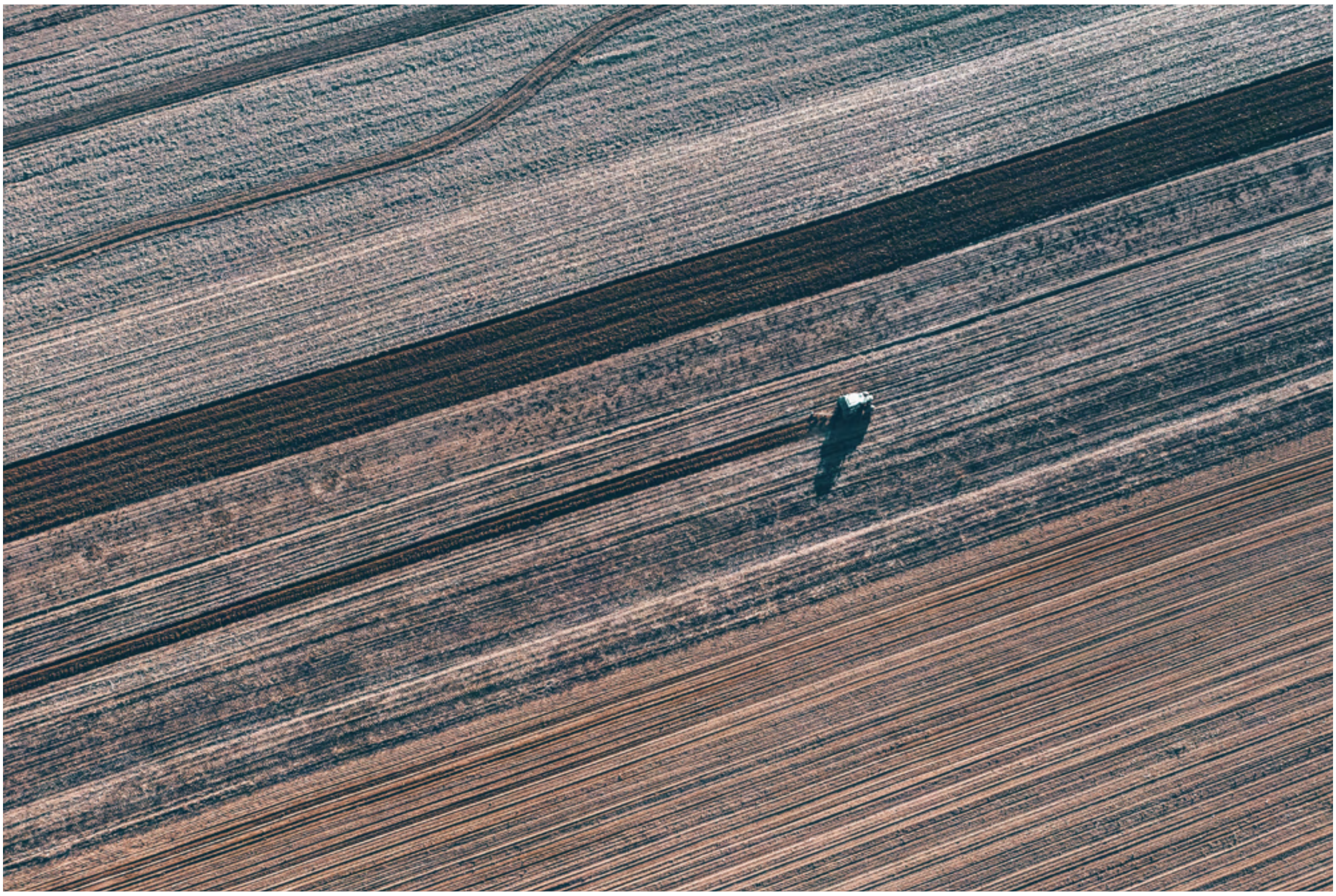
Inherent Product Properties

Detailed spectral signatures: Hyperspectral imagery exhibits continuous spectral coverage and can discriminate fine spectral features, allowing for precise identification and mapping of various agricultural parameters.

Data richness and accessibility: Hyperspectral imagery is commercially available and provides comprehensive information, aiding in crop identification and mapping for informed agricultural decision-making.

Enhanced image quality: Hyperspectral imagery's high resolution facilitates the identification of subtle differences in crop health and soil conditions, enabling a better understanding of agricultural ecosystems and their dynamics.

Improved insights and analytics: HSI offers an enhanced foundation for in-depth analysis, enabling a deeper understanding of the intricate relationships between crop health, environmental factors, and productivity, fostering effective management practices.



About Pixxel

Pixxel is a space technology company building a constellation of the world's highest-resolution hyperspectral imaging satellites, which will help us see the unseen problems plaguing Earth today. Pixxel also supports the visualisation and analysis of datasets through its in-house Earth observation studio, Aurora. With its unique technology and first-mover advantage, Pixxel is on a mission to build a health monitor for the planet.

Pixxel's hyperspectral satellites capture up to 50x richer detail of our planet than multispectral and other satellites currently in orbit. The constellation is designed for 24-hour revisit anywhere on Earth, helping detect, monitor and predict critical global phenomena across agriculture, oil and gas, mining, environment and other sectors.

Pixxel's Earth observation studio suite, Aurora, provides customers with a fast and easy way to extract insights from diverse Earth observation datasets, including hyperspectral imagery, by creating reports, generating alerts and integrating them into existing workflows and software.

Pixxel has over 50+ customers across industries, including the global mining company Rio Tinto, the Agritech company DataFarming, and 90+ resellers across all major geographies.

Pixxel has successfully launched and operated three pathfinder hyperspectral satellites with 10-30 meter spatial resolution, already demonstrating the impact that hyperspectral imagery can have. Pixxel will launch six satellites in 2024 that will enable global daily access and 18 satellites are planned to be launched by 2025-26. Pixxel is also launching numerous satellites to enable global daily access, including those with VSWIR capabilities to expand its spectral capacities.

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