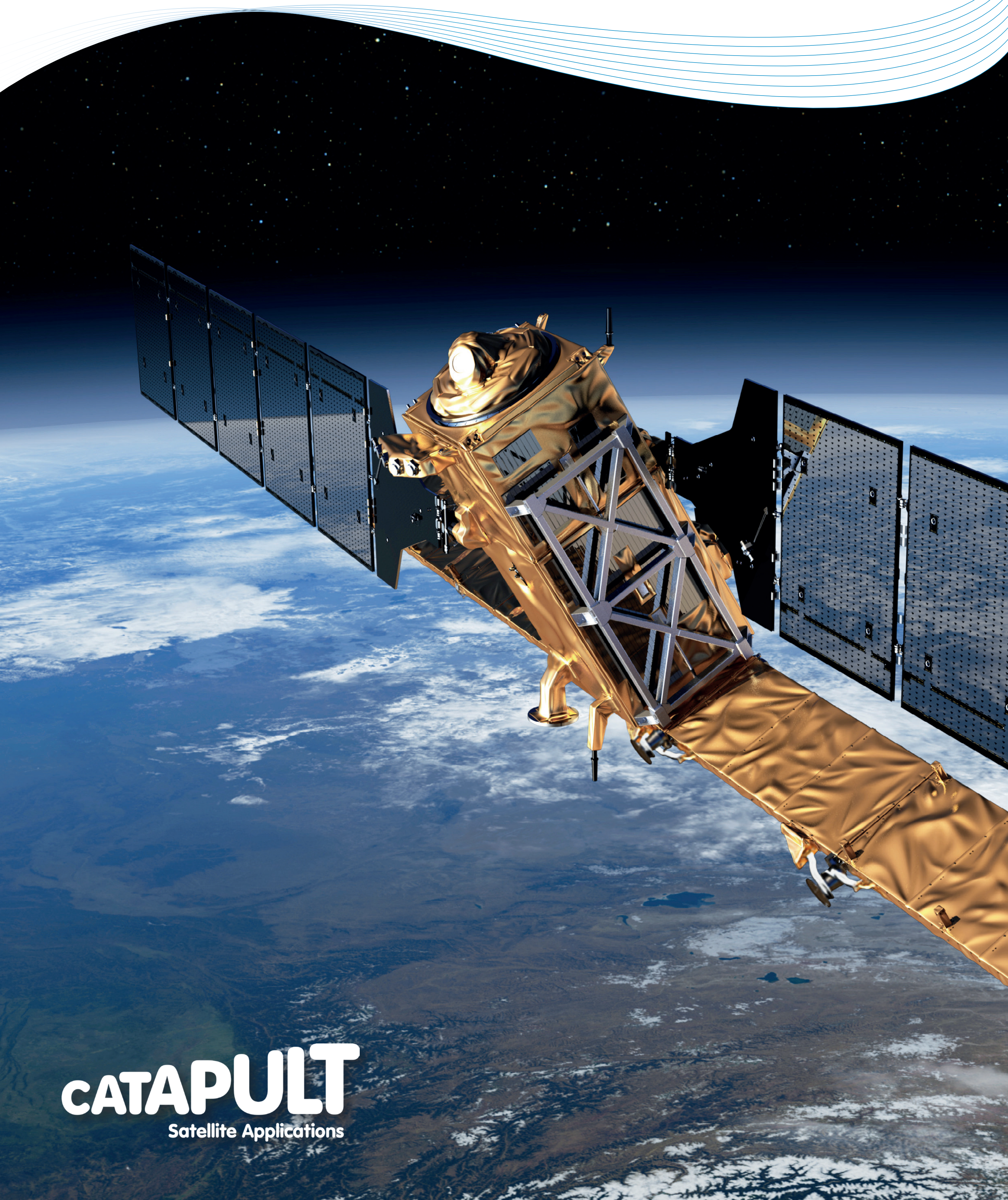
Satellites for agriculture



CATAPULT Satellite Applications

Contents

Introduction

This review is a collaboration between AHDB and the Satellite Applications Catapult to provide an overview of the current status of satellite technologies available for agricultural applications. The main focus within this review will be Earth observation (EO), but satellite communication (Satcom) and global navigation satellite systems (GNSS) technologies will also be covered, where appropriate.

Much is promised with regards to the use of new technologies, such as those offered through satellites, to assist growers with estimating the timing of harvest, predicting in-season yields, detecting and controlling pests and disease, understanding water and nutrient status, planning crop nutrition programmes and informing in-season irrigation. Developments in satellite constellations, payloads and launch are enabling increased connectivity and observational capability. Coupling these developments with ‘smarter’ computing, data infrastructures and analytics is increasing the possibilities for the use of satellite technologies across the agricultural sector. While this creates new possibilities for products, services and decision support, it also presents a challenge for the agricultural sector to ensure that the latest technology is linked appropriately with production challenges and, therefore, can be used to deliver the gains required to meet the societal, economic, political and environmental needs.

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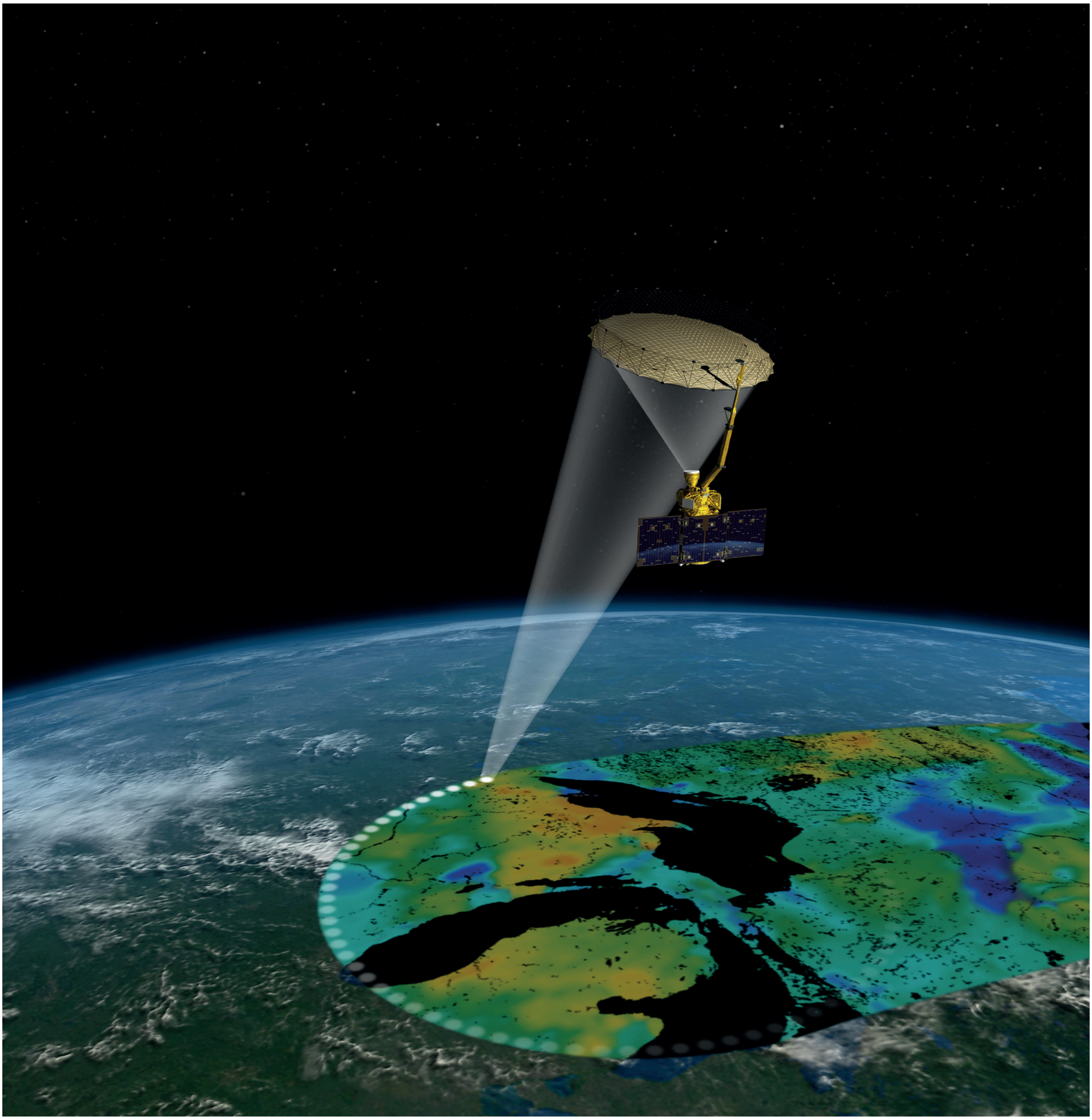
Front page: Sentinel 1, image credit: ESA Contents page image credit: NASA

Earth observation satellites (EOS)

Satellite EO is a form of remote sensing focused on obtaining information about the Earth's surface and atmosphere from platforms up to 36,000km away in space. The derived information does not originate from a single satellite mission but a whole range of satellites with different instrumentation and mission objectives. The target application determines the choice of EOS mission and instrumentation.

EOS have been in orbit since the early 1970s, with state-of-the-art spatial resolution – the level at which surface details may be depicted is down to 0.25 metres from very high-resolution commercial satellites. Comparatively, publicly owned satellites provide freely available imagery down to 10-metre spatial resolution. Higher spatial resolution is typically associated with smaller area coverage and on-demand data acquisition (ie typically, data is not systematically collected). There is a wide variety of both commercial and open-source satellite data available for different spatial/temporal resolution and associated costs.



NASA's Soil Moisture Active Passive (SMAP) satellite, collecting global soil moisture data.

Image credit: NASA

EOS agricultural measurements

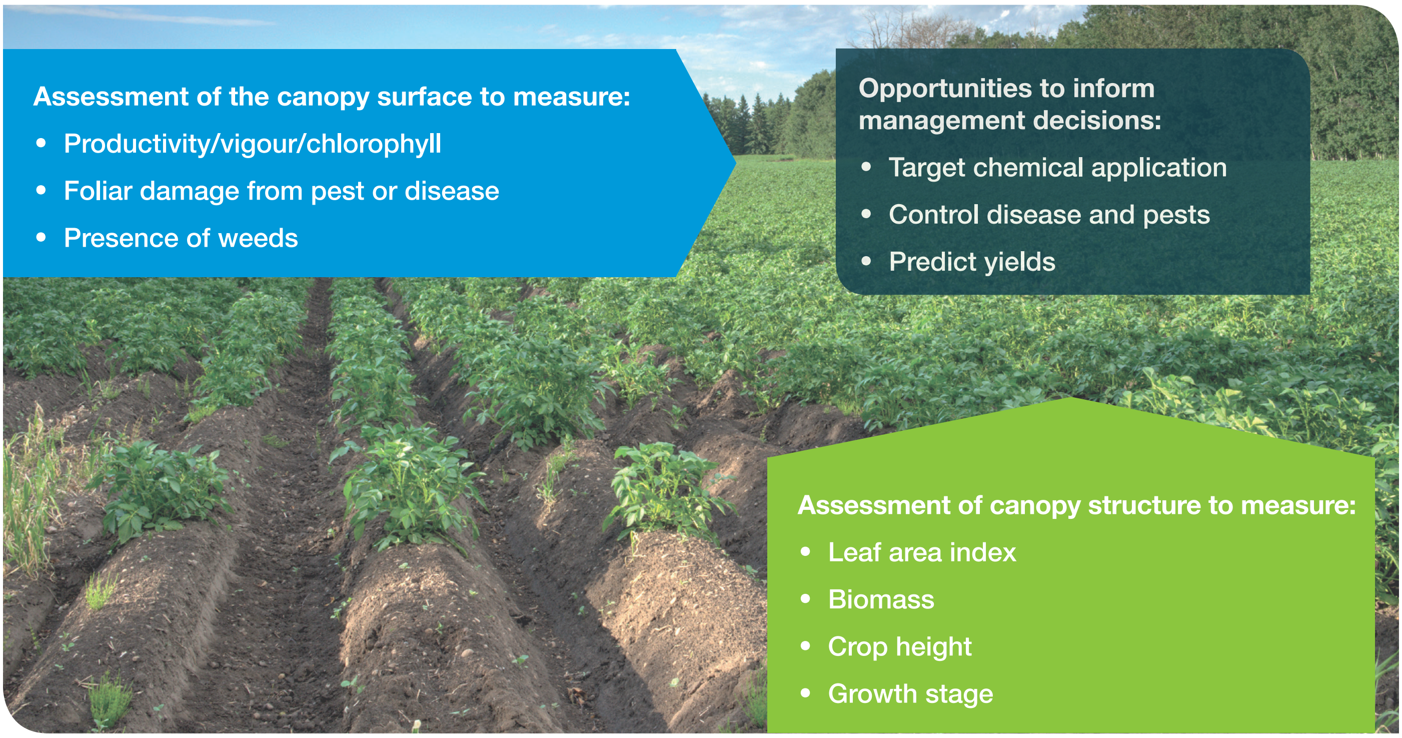


Figure 1. Understanding of crops through EO

Image credit: Satellite Applications Catapult

Spatial information is key to improving the management of crops and their inputs. Up-to-date mapping of crops provides opportunities for government and research organisations to monitor agricultural activities and for growers to understand crop status, predict yields and target application of inputs, such as fertiliser, growth regulator or fungicide. EO measurements are increasingly used to deliver such spatial information on a timely, within-season basis. EO measurements, whether captured from satellite, aircraft or unmanned aerial vehicle (UAV), can provide information on the canopy surface and/or its structure. Canopy surface measurements include greenness and chlorophyll content, damage from disease and pests or the presence of unwanted species, such as weeds. Canopy structure measurements can include leaf area index (LAI), biomass or crop height. Taken together, these different measurements can be used by growers to inform their management decisions, as illustrated in Figure 1.

This section will detail how EOS data can be exploited for measurements related to in-season agricultural support and crop identification. EOS data can provide some direct agronomic measurements when analysed, but to maximise the value and information attainable, the data should be coupled with other data sets, information sources, models and advice to create the agricultural intelligence that enables actionable decision-making.

EOS for in-season agricultural decision support

As outlined previously, EOS sensors provide measurements of crop reflectance and structure that can be related to biophysical properties, such as LAI, height, yield and growth stage (Figure 2). However, it is important to note that EOS rarely provides direct measurements of these biophysical properties; instead, it is common to exploit EOS data within a data science approach and use crop models to link EO measurements to crop dynamics of interest (Figure 3).

Yield prediction is a major area of interest within agriculture and numerous models have been developed for crops including wheat, maize, sugar beet and potatoes. Typically, a series of direct ground measurements of the crop are recorded throughout the year, such as tiller number, leaf area index, crop height, weed infestation, and are used to monitor production. Yield is then usually forecast using regression against previously measured

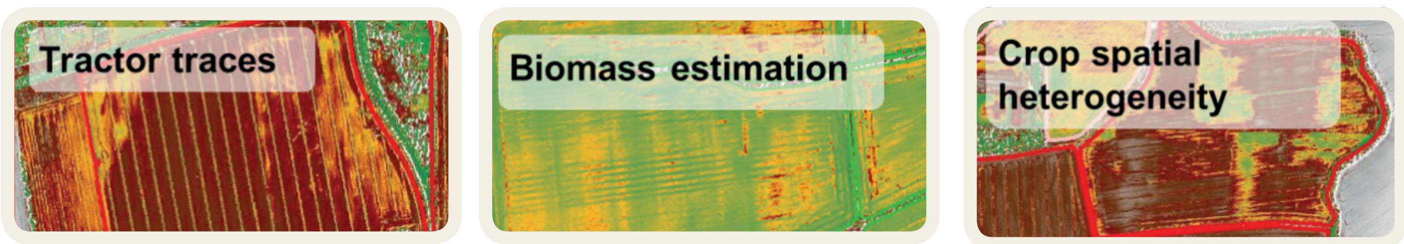


Figure 2. Example measures derivable through assessment of EO data (Imagery Source – Planet)

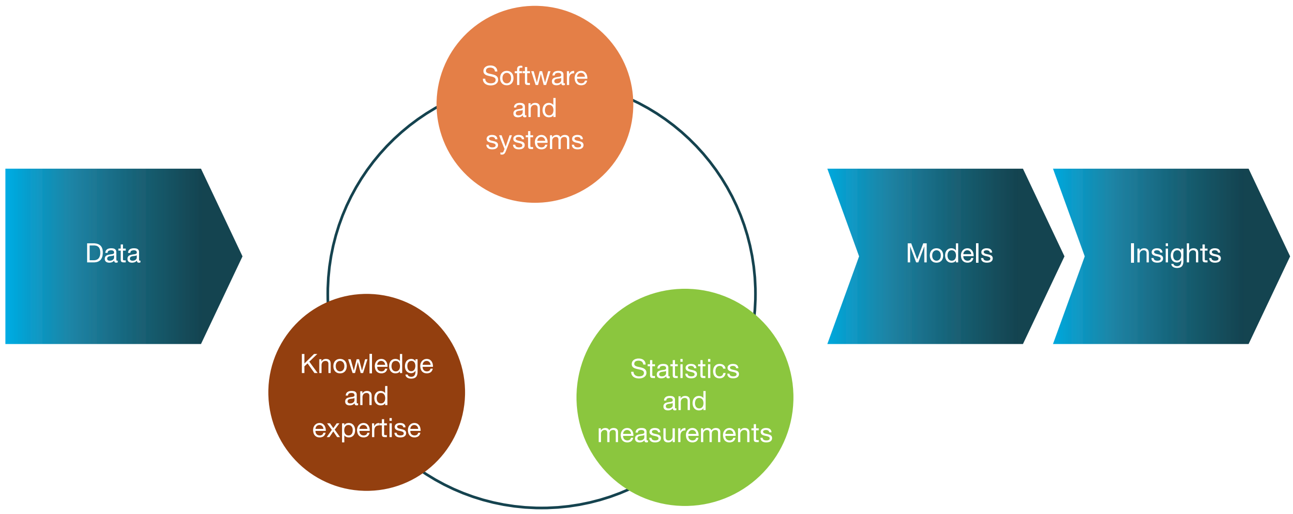


Figure 3. System integration required to turn data into knowledge

yield data. Key parameters that can be estimated from EO are increasingly incorporated into yield models, for example weed infestations from high spatial resolution data or vegetation indices used to infer LAI. The main advantage of EO in this context is the ability to rapidly assess parameters over far larger spatial areas than can be recorded on the ground.

EO data can also be incorporated with more complicated numerical crop models that use agro-meteorological parameters (eg temperature, rainfall, radiation, crop type, soil type, nutrient availability) to estimate crop biomass, health and yield. EO data can be directly fed into these models, providing spatial and temporal data necessary to update the model during the season and improve predictions. These systems can operate at local scales, such as Fruitlook (**www.fruitlook.co.za**), which is a pre-operational service offering South African grape and deciduous tree growers weekly estimates of eight crop parameters to inform them on crop growth, water use and nutrient status, together with a forecast of soil moisture content. Fruitlook obtains its estimates by directly feeding EO data into energy and water balance algorithms.

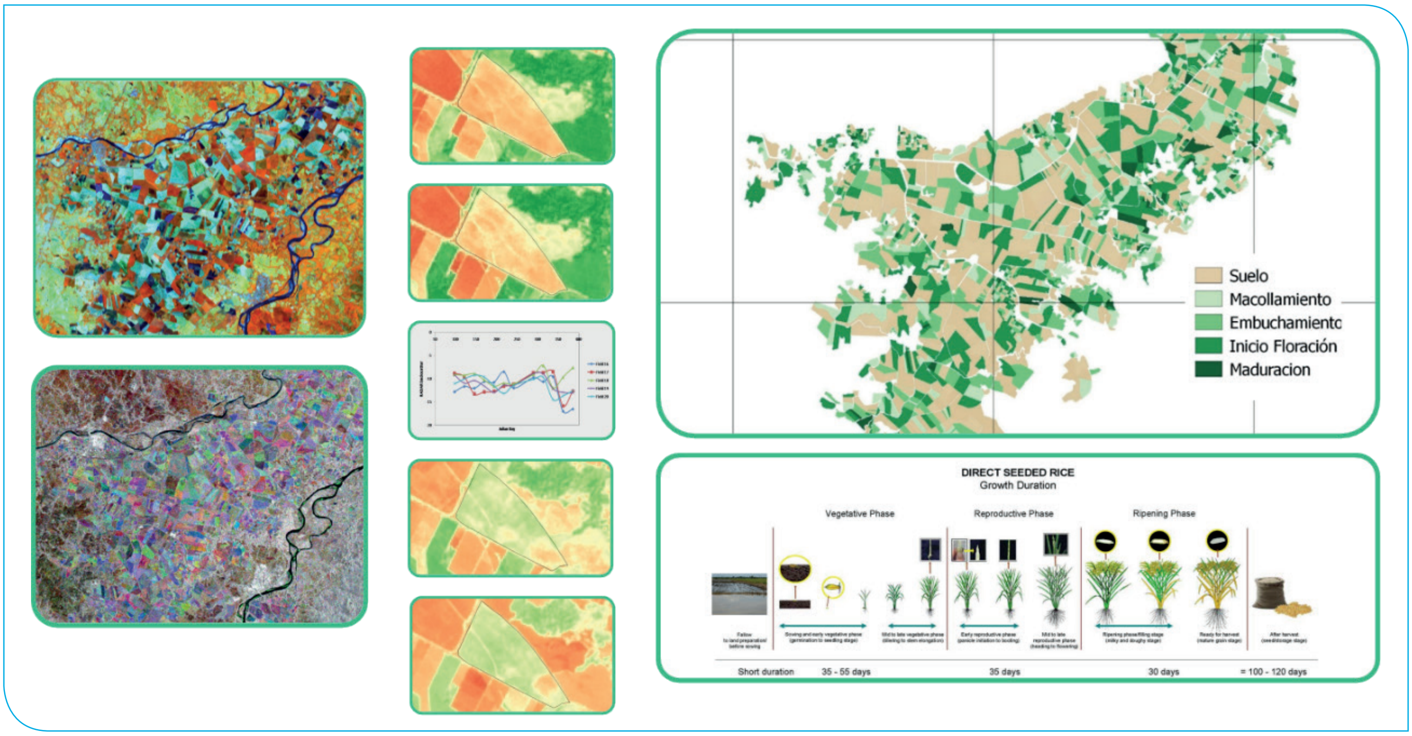


Figure 4. An example of how EOS optical and SAR data can be used within a growth model to monitor regional rice growth stage variations and predict potential yield across the growing season
Image credit: ESA

Alternatively, such systems can operate at regional and global scales, such as the MARS (Monitoring Agricultural Resources) crop monitoring service (**https://ec.europa.eu/jrc/en/mars**) supervised by the JRC. MARS provides the EU with up-to-date information on crop production within the EU to support the Common Agricultural Policy and also covers Russia/Kazakhstan, China, India, South America, Africa and is a global window for aiding an understanding of global food security. The system is based on static data, such as soil maps, crop parameters and administrative regions, and is updated in near real time by including weather observations, weather forecasts and other remote sensing data to provide end-of-season yield forecasts.

At the simpler end of the scale, crop management systems are increasingly being used by growers to record and map their crops both within and between seasons. They are able to overlay different layers containing soil, crop and yield information into their crop management system, allowing them to inform and improve management techniques, better target inputs and plan for harvest (Figure 5). This move towards the use of digital data is a necessary development as growers face increasing pressure to reduce production costs, optimise yields, while maintaining a high quality at the same time as being constrained by strict environmental, health and safety regulations.

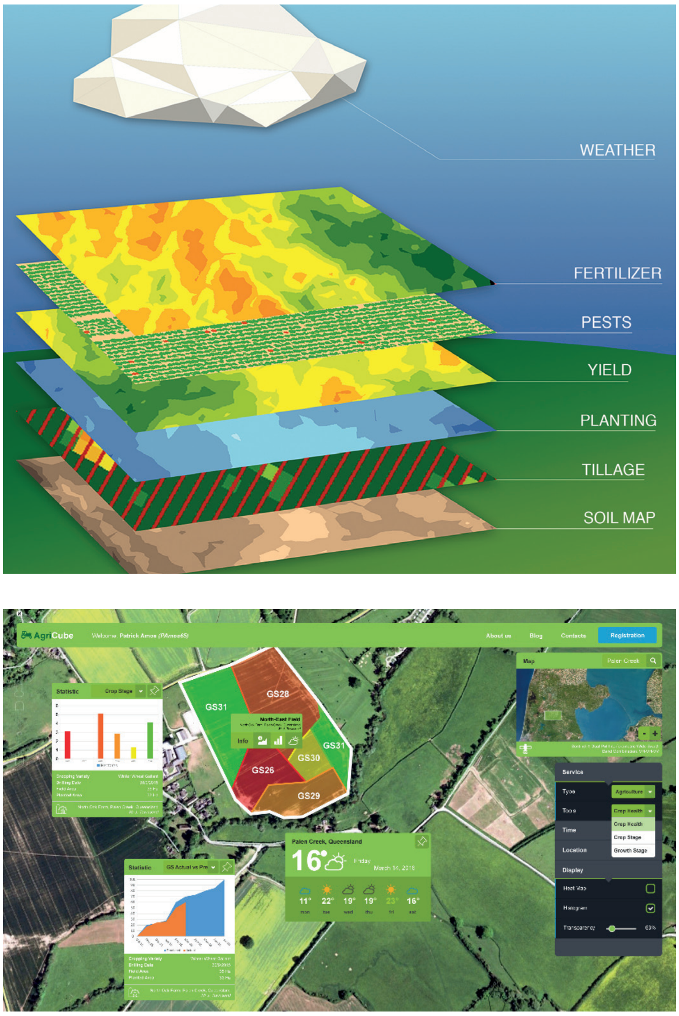


Figure 5. Example data layers (top) stored and accessible within a typical online farm management system (bottom)

The availability of higher spatial and temporal EO data combined with the widespread use of in-field sensors, smartphones and mapping portals represents a step change in the way growers are implementing precision farming and on-farm decision-making, at the field level down to plant-scale management (Figure 6). Flat-rate inputs onto variable fields will only produce variable returns. The ability to now characterise a field at multiple scales enables users to better understand variations, measure them and then correct and balance them. Expected proliferation in the use of in-field sensor networks providing real-time measures will take this even further and enable leaf-scale monitoring and management.

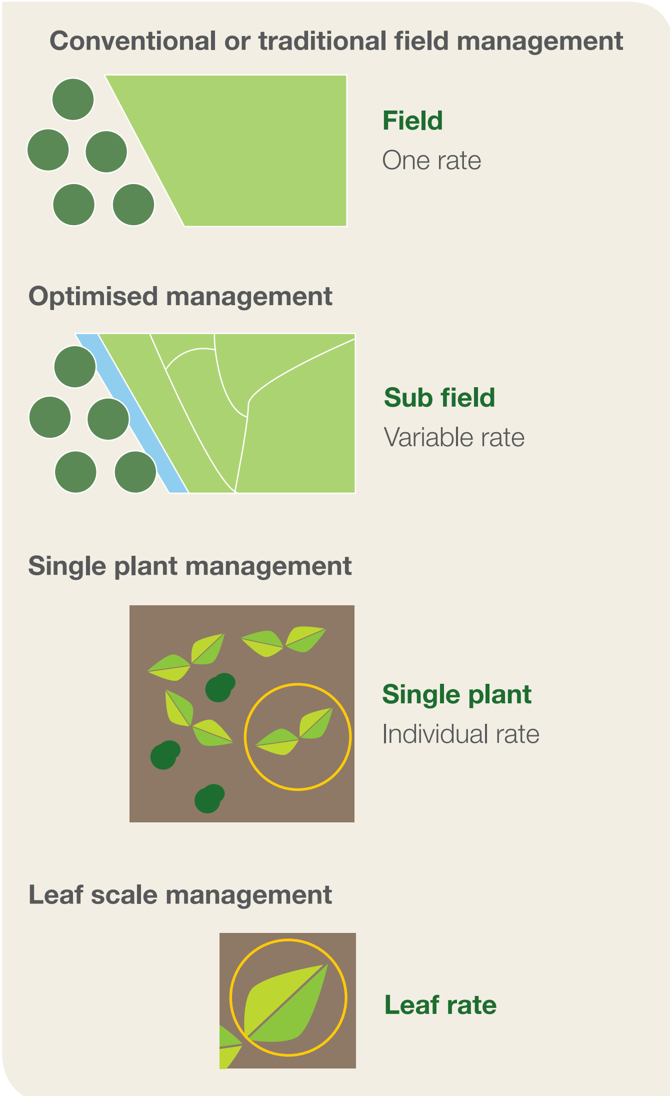


Figure 6. Precision agriculture – applicable at different scales
Source: Satellite Applications Catapult

Example of an integrated EOS market solution for in-season decision support

There are an ever-increasing number of market products and services available to the agricultural sector exploiting EOS data alongside satellite and other terrestrial EO technologies (eg UAV, IoT in-field sensors). In the UK, traditional market farm management offerings available to farmers have been forced to diversify their products either through internal developments, strategic linkages or market acquisitions to enable harnessing of the exponential growth of crop spatial information available from different EO and in-field sensor technologies.

Increasingly cloud-based, these farm management systems store, integrate and enable analysis of different data layers (eg EO, IoT, farm, weather) to produce in-season decision support data sets (eg nutrient map) and visualisations to the farmer, accessible anywhere. These are beginning to enable real-time field assessments for input or feed allocation, as well as enhancing grazing management through bringing together EO, weather and live animal tracking data to better advise the farmer on pasture rotation (Figure 7).

A new breed of non-traditional agricultural businesses proposing advanced data-intelligence capabilities to farmers are emerging and challenging the more established agronomy, precision farming and farm management businesses. These companies are adapting developments in computer vision and big data analytics to harness this surge in data availability to increase the speed, quality and variety of products and services available to farmers. These include:

- Real-time updates on current field, soil and crop conditions
- Real-time decision support (eg when to irrigate)
- Precision profit mapping
- Disease and pest identification
- Immediate alerts to canopy conditional change (eg water stress)
- Harvest forecasting (Figure 8)
- Hyper-localised weather
- Fleet management and performance tracking
- Animal tracking and monitoring
- Enhanced field planning – eg field profiling and variety selection
- Visualisation and augmented reality (Figure 9) to enable direct in-field assessment of live operational and historical issues

Current UK market leaders exploiting EOS data for in-season agricultural decision support are advertising an average yield benefit of between 3 and 8% over the farmers' traditional best practice when used for input applications. Figures such as these, though, are not often readily available to farmers when justifying the potential purchase of new technologies. A trawl of most of the service operators provides limited justifications as to the absolute benefits of using their technologies/systems.

Figure 7. Example of an online farm management platform that exploits computer vision and crop modelling to integrate EOS, weather and field data to automatically assess each field across the whole farm for grass biomass and grazing readiness. Utilising a grass wedge, fields in green are shown to the farmer as being suitable for grazing, while those in red require further growth

Source: Satellite Application Catapult

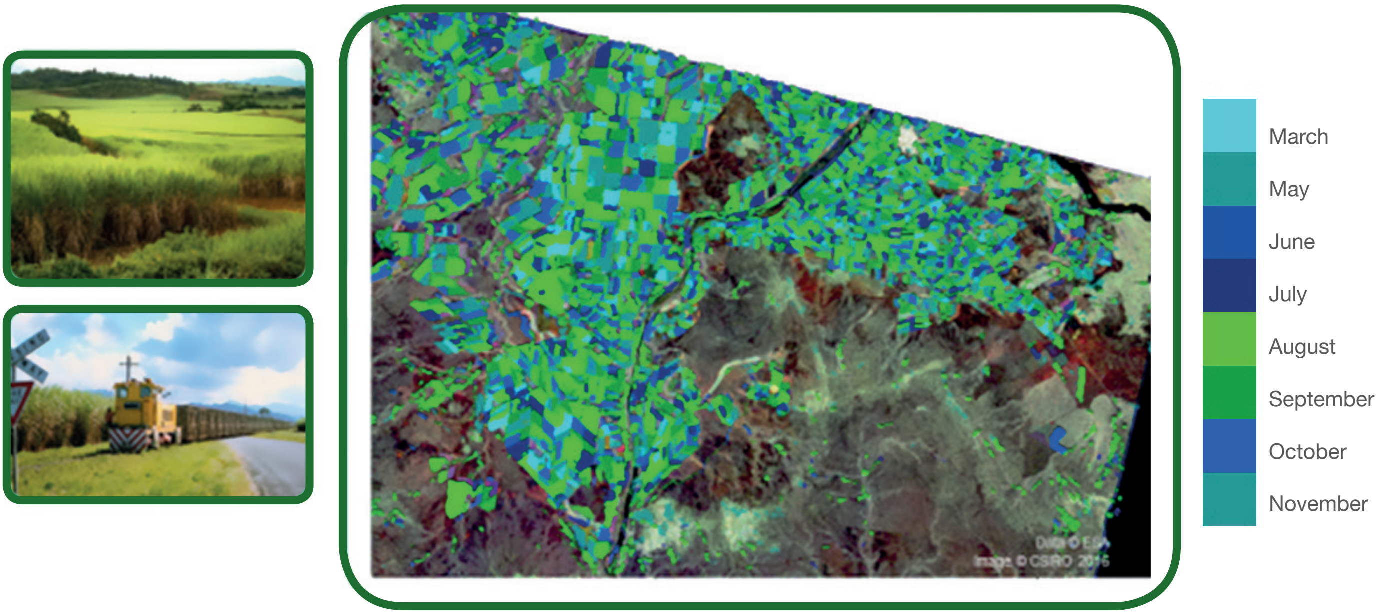


Figure 8. An example of how EOS data can be used to enable farmers to understand harvest readiness. In this example, for the sugar cane industry in Australia, in-season and historical EOS data were used alongside weather and planting data to estimate at a field level across the growing season which fields were ready for harvest in which months. This was required to plan train timings to remove the harvested sugar cane and transport the mills for processing

Source: Data: ESA Image: CSIRO 2015

Figure 9. An example of augmented-reality farming solutions displayed on a regular handheld device

EOS for crop identification

Stakeholders from across the agricultural sector have an interest in where and how much of each type of crop is being grown. Analysis of EOS data is a novel tool to generate accurate geospatial information associated with cropped areas, rather than the statistical information which has been traditionally obtained via census returns and other sampling methods.

National and regional crop-type mapping is being carried out in many parts of the world using freely available EOS data, such as from Landsat and Sentinel. For instance, in Canada an annual crop map has been produced for several years using a combination of Landsat and Radarsat data (**www.agr.gc.ca/atlas/agrimap/**). In the UK, a land cover and crops product, based on Sentinel 1 & 2 data, is available and has been developed by the Centre for Ecology and Hydrology (CEH) and Remote Sensing Applications Consultants Ltd (RSAC Ltd) (Figure 10) **www.ceh.ac.uk/crops2015**.

The Land Cover *plus* crop map is based on the UK Land Cover Map (LCM) parcel framework and is produced following the end of the current growing season. For the crop map, every parcel larger than 2 ha is categorised as arable/horticultural or improved grassland parcels and coded with crop-type information. Where parcels contain

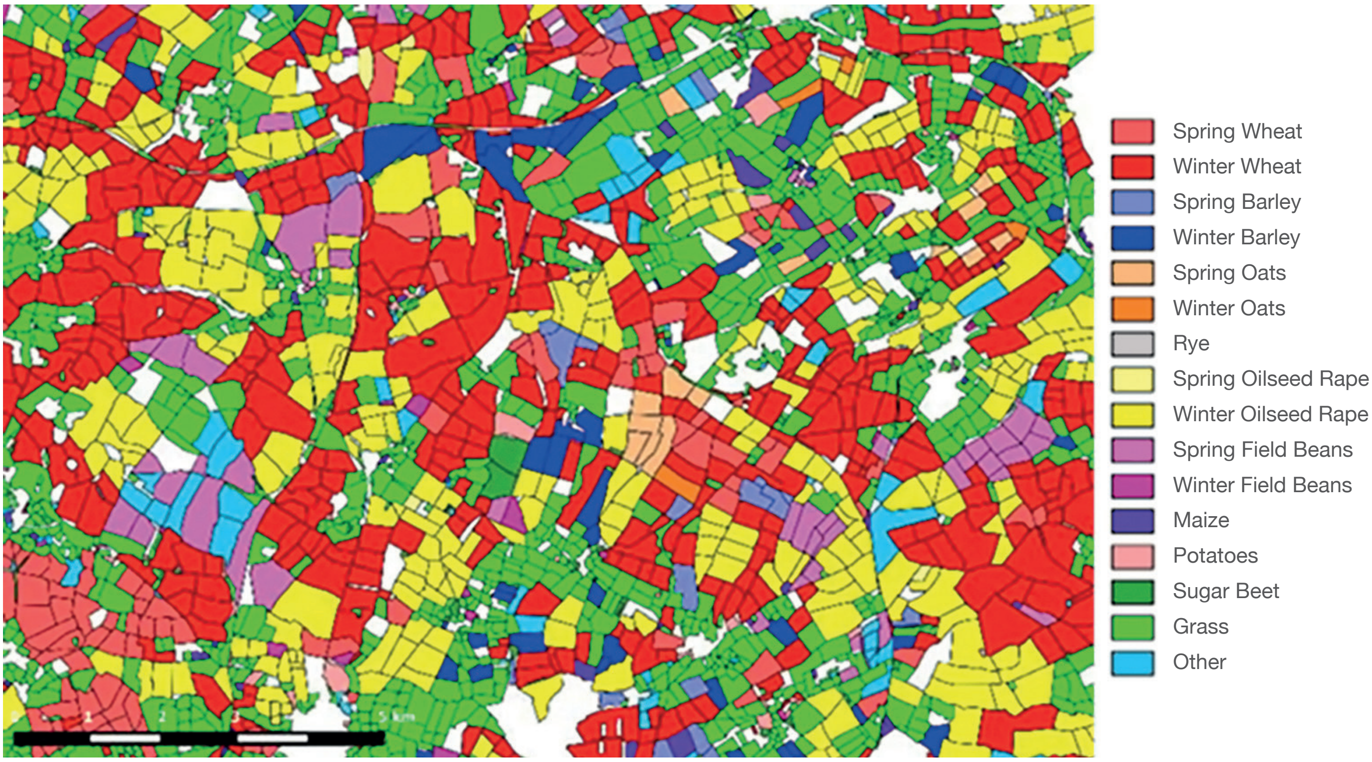


Figure 10. Land Cover plus Crops - Annual national crop map addition to UK Land Cover Map
Source: CEH and RSAC Ltd

two or more crops, preliminary processing has been applied to subdivide parcels into separate cropping units. The crop classes generated in 2016 were winter wheat (including oats), spring wheat, winter barley, spring barley, oilseed rape, field beans, potatoes, sugar beet, maize and improved grass. Other cereals, peas, early potatoes, early maize and vegetables are grouped in a class called ‘other’, together with a small number of parcels which could not be classified.

Often, three or four image dates are needed to map a range of different crop types and as per the CEH Crop Map, limiting its production until the end of the growing season or even into the following year. Even with large numbers of optical satellites, it is often not possible to guarantee the required images because of unpredictable cloudy weather. For this reason, there is a lot of interest in SAR EOS data – as images can be acquired regardless of cloudy weather conditions.

Figure 11 shows crop phenological change between four Sentinel 1 SAR data sets acquired during March/ April 2016 and the growth profile for oilseed rape. Through characterising the crop growth curve for each crop type and using a classification approach, a crop map can be produced.

Historical challenges related to separating certain crop types and early-season identification within the growing season still remain when looking to exploit EOS data. The nature of EOS data is still failing to provide the spectral detail required to differentiate between crops that have a similar physical appearance (eg sugar beet and red beet).

Developments in computer vision and machine learning are increasing the potential to distinguish between crops with similar spectral characteristics. Through utilising EOS data from multiple seasons alongside historical field data sets (eg crop records) to generate training data sets, predications can be made on the likely crop being grown. Through exploiting these developments, new possibilities will be opened up, relating to:

- Chemical inputs to catchment modelling
- Contamination mitigation
- Flood risk analysis
- Support for catchment-sensitive farming
- Production forecasting
- In-season input sales
- Multi-scale disease/pest and weed profiling

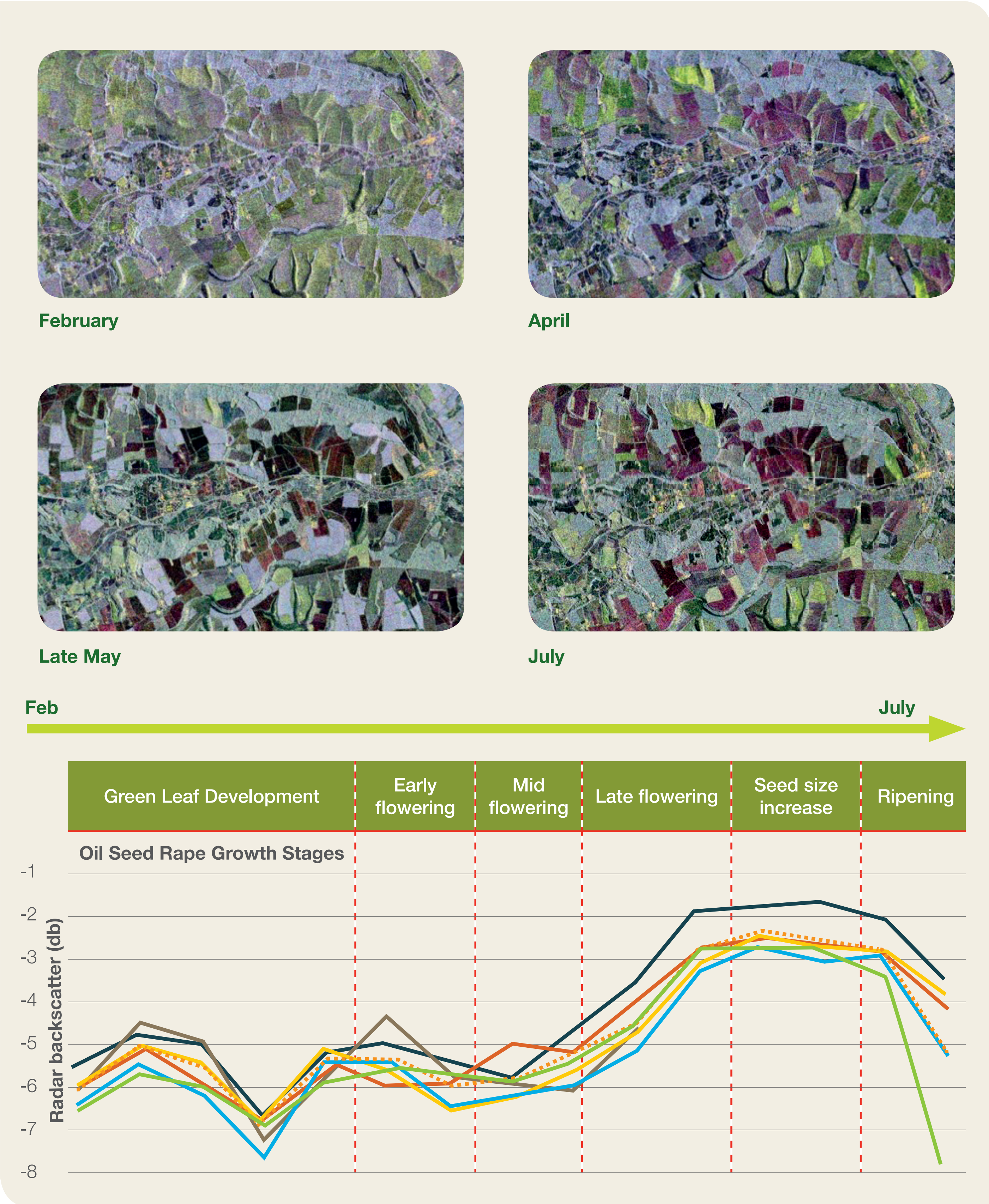


Figure 11. The use of SAR data to characterise a growth profile for OSR for crop mapping. Images in the upper part are colour composites using different SAR polarisations, each from a different date to show changes in crop growth. The plot below shows the backscatter trend for selected fields from which phenological growth stages can be inferred (Data source: ESA)

Table 1. Crop identification using EOS, current ease of differentiation between crop types (green = good, yellow = moderate, red = poor)

Crop	Ease of identification	Considerations
Wheat		Possible to differentiate between spring and winter wheat if seeding and emergence dates are known Differentiation is achievable with confidence before May, particularly if splitting using difference in crop cover between fields planned for veg/salads
Barley		Differences in spectral responses is achievable between wheat and barley Not possible to identify between varieties
OSR		OSR has a very different spectral response to both wheat and barley Use of imagery during flowering is a clear differentiator Structural differences between cereals and OSR make SAR an appropriate data source
Potatoes		Possible to identify potato crops with relative ease, but spectral response can be very similar to sugar/red beet crops and other veg/salad crops depending upon time of year, stage in growth cycle, location and if recently irrigated It is not possible to distinguish between different types of potatoes unless ground data is provided to aid potential identification
Sugar / red beet		As with potatoes, it is possible to identify sugar/red beet crops with relative ease, but spectral response can be very similar to potatoes/other veg/salad crops depending upon time of year, stage in growth cycle, location and if recently irrigated It is very challenging, if not impossible, to differentiate between sugar beet and red beet using spectral signatures alone and, thus, ground data sets will be required to train classifiers
Maize		The structural nature of maize makes it easier to identify as the growing season progresses, particularly from SAR Identification earlier in the crops' growth cycle can be more challenging given the presence of such a broad range of other cereals, vegetables and salads currently in their growth cycles
Beans / peas		The nature of these crops makes them appear similar in appearance to other veg/salad crops within EOS data Ground data should be acquired to aid potential identification Identification of flowering from satellite EOS data in vining peas is not possible
Grassland		Identification of grassland areas, like cereal crops, is relatively simple given the fact that vegetation is present all year around There can be confusions between grazing grasslands and managed grasslands for recreational purposes which appear highly productive Grazing also impacts upon the spectral responses attainable given the frequent changes in biomass levels
Salads		Highly challenging to separate between salads and other vegetable crops given their appearance in EOS data. Increasingly more difficult with decreasing EOS resolutions Possible to use locational factors to reduce confusions, eg soil type or growing region
Field vegetables		Possible to use growth cycle characteristics of certain vegetable/salad crops to aid identification, eg lettuce have short growth cycles With some salad/fruit crops being grown indoors or under covers, these cannot be identified using EOS
Orchards		Orchards are highly identifiable given the nature of the appearance within EOS data. However, they can easily be confused spectrally with hedgerows, scrubland and other areas of woodland Fruit walls are more challenging to identify than traditional orchards given their structure, although the use of a wire may be used to identify them in higher-resolution SAR data
Other top fruit		With some top fruits being grown indoors, these cannot be identified for obvious reasons Like field vegetables and salads, their appearance within EOS data can appear very similar

EOS for monitoring environmental parameters

The power of EO lies in its ability to monitor large areas of land and atmosphere consistently and regularly. Different EOS sensors can be exploited to monitor common environmental parameters used within an Environmental Impact Assessment, including atmospheric variables, land/soil properties, vegetation and hydrological parameters. For an appraisal of the suitability of EOS for monitoring environmental parameters, see Table 2.

Atmosphere

Atmospheric parameters such as aerosols, water vapour, dust, ozone and trace gases can be routinely monitored from different satellite sensors. The majority of these aerosols can be subdivided into coarse PM10 (2.5–10 µm diameter) and fine PM2.5 (<2.5µm diameter) particles – both of which are routinely measured by different satellite EO sensors. The MODIS instruments on board the NASA satellites Terra and Aqua are one of the leading providers of particulate measurements. Once the European Copernicus Programme is operational, Sentinel-4, 5 and 5P will also offer aerosol monitoring. Typically, these satellites will have a revisit time of 1–2 days.

EOS are the perfect tool to carry out regular monitoring of atmospheric water vapour and dust on regional scales. A wide range of sensors are available to measure water vapour and dust, from microwave imagers to traditional optical imagers from both low earth orbit and geostationary earth orbit platforms.

Land

The monitoring of land surface temperature is key to modelling an area's climatic and meteorological conditions. EOS enable land surface temperature monitoring at a temporal resolution and with wide area coverage not matched by other data sources. The use of thermal infrared EO techniques allow the estimation of land surface temperature (LST) on a global scale. LST can be estimated from various satellites at different spatial resolutions – providing that the sensors acquire data in the thermal infrared region of the electromagnetic spectrum (eg Landsat TM/ETM+).

Retrieval of soil moisture from EOS can be undertaken using visible, infrared, thermal and microwave data techniques. Each of these techniques has advantages and disadvantages, based on how sensitive the soil surface is to electromagnetic radiation. Thermal infrared data from satellites (ranging from 3–14 µm wavelength) is best suited for soil moisture estimation (eg Landsat-8 TIRS). The following parameters may be considered as indicators of soil moisture: vegetation indices, surface radiant temperature measurements and classification of land parameters. Active EO techniques using SAR data include the use of backscatter models. Simplistically, the lower the moisture content of a surface, the stronger the radar backscatter value will be under the same land-cover conditions. SAR has the ability to penetrate the sublayer under soil surface area. However, it is highly sensitive to soil roughness and vegetation cover. When considering monitoring soil moisture depth, previous research has shown success in estimating measurements up to a depth of 5 cm from the top soil surface for bare or sparsely vegetated soils. Longer wavelengths give greater penetration.

Hydrological parameters

Both optical and SAR EOS sensors can be used to monitor a variety of hydrological parameters including water-surface area (streams, rivers, lakes, reservoirs), water quality (organic or inorganic constituents), water surface temperature, snow surface area and water depth, to give wide-scale observations over large geographic areas. Pure water (free from organic and inorganic compounds) is characterised by the least amount of absorption and scattering of incident light that takes place in the blue wavelength region. In contrast, almost all incident radiance is absorbed in the near- and middle-infrared (MIR) regions, meaning water often appears very dark in infrared imagery. This characteristic is particularly useful when discriminating water from land, as land surfaces scatter radiance in the NIR and middle infrared regions of the electromagnetic spectrum. While multispectral techniques for water delineation, such as the Normalised Difference Water Index (NDWI), are dependent on weather conditions, SAR EO offers an all-weather method for measuring standing water. This trait makes SAR particularly useful for mapping flood events as these typically occur during times of dense cloud cover. SAR response from water bodies is unique due to their textural characteristic (smooth), facilitating limited scattering of energy back towards the sensor (eg Sentinel 1 A/B, Cosmo SkyMed).

EO techniques can be used to monitor numerous water quality parameters including temperature, suspended sediments (turbidity) and chlorophyll concentrations, which can in turn be used as indicators of ecosystem health or as an indication of ecosystem contamination. The spectral reflectance of pure water changes when suspended substances are introduced into the water body. EO of water quality is dependent on the ability to measure these spectral signature changes and relate them to empirical or analytical models to infer knowledge of water composition. In short, it is possible to infer water quality using water colour. In most cases, it is not possible to directly measure a specific chemical compound present in the water. However, it is possible to measure other indicators, which act as proxies for these reactions. For example, increased chlorophyll concentrations can indicate harmful algal blooms, potentially caused by eutrophication resulting from increased levels of nitrogen. Similarly, reduction in the attenuation coefficient can indicate turbid waters, inferring presence of suspended sediments. The use of narrowband sensors is recommended where possible to assist with spectral discrimination. Sensors such as MODIS offer this narrowband capability, however, with a trade-off against spatial resolution (500m).

While EO cannot be used to measure subsurface groundwater directly, numerous techniques exist to map proxy indicators of groundwater presence. Such indicators include previously discussed parameters including vegetation, soil, surface water, land cover, land use and leaf area index. SAR techniques can also be used to measure changes in groundwater level.

Table 2. An appraisal of the suitability of EOS for monitoring environmental parameters

Measurement	Description	Sensor(s)	Ground resolution	Temporal resolution	Application considerations
Aerosol monitoring (including water vapour)	Measure changes in composition of key atmospheric gases including nitrogen dioxide, sulphur dioxide, ozone, carbon monoxide and carbon dioxide	Very low resolution multispectral (eg MODIS, Sentinel-4/5/5P; SMM/I, AVHRR or MERIS from LEO platforms or SEVIRI from GEO)	100s of metres to kilometres	1–2 days	There is a general trade-off between spatial and temporal resolution. While satellites in geostationary orbit stay in the same place relative to Earth, giving a high temporal resolution and a low ground resolution, satellites in polar/ sun-synchronous orbit scan across the entire Earth's surface
Dust monitoring	Routine measurements of PM2.5 and PM10 for regional-scale analysis	Medium resolution visible or multispectral (eg GOES, Landsat TM)	30 m to 100s of metres	15 minutes – 2 weeks	
Land surface temperature	Local changes to land surface and atmosphere (eg land cover change, dust presence) can alter land surface temperature affecting local habitats and ecosystems	Thermal sensors (eg Landsat TM/ ETM+, Landsat TIIRS, ASTER, MODIS and AVHRR)	90 m–100s of metres	1–2 days or 8 days depending on the sensor	
Surface water	Remote sensing can be used to identify water bodies	High/Medium resolution multispectral sensors and SAR (eg Sentinel 1A/B, Sentinel 2)	0.25 m–30 m	6–12 days	Most effective on larger water bodies such as major lakes and rivers. Satellite information can only be used to inform water quality for a limited number of parameters (ie turbidity, and presence of algae blooms). As such, this application is likely only complementary to in-situ monitoring with current technology Commercial alternatives such as Cosmo-SkyMed can give spatial resolution down to 1m and a near-daily revisit
Surface water quality	EO can be used to monitor water quality	Low resolution narrowband multispectral (eg MODIS)	500 m	1–2 days	
Ground water	EO cannot be used to measure directly subsurface groundwater. Total water storage changes over large scales can be estimated using in-situ observations coupled with satellite observations of gravity	GRACE/GOCE only (Microwave/gravity gradiometer)	300–400 km	Monthly	Numerous techniques do exist to map proxy indicators of groundwater presence, such as land cover, soil moisture etc. Modelling from satellite-derived products including DEMs, soil maps, and geology maps can also provide estimation of groundwater potential
Soil moisture	Satellites can be used to derive regional soil moisture levels	High/Medium resolution SAR (eg SMOS)	35 km	3 days	Regional soil mapping typically still requires complementary field mapping to identify specific soil types, but EO-based modelling techniques can allow rapid wider delineation. See also Hazards section for benefit of monitoring soil moisture
Soil type	Satellites can be used for monitoring exposed soil, differentiating between broad exposed soil types				

SatComs for agriculture

A new wave of smart machines and digital technologies developed by the agri-tech industry promise to revolutionise existing farm management practices. Access to objective information about the real-time status of soil, water, crops, pasture and animals will optimise operational planning and decision making and facilitate significant productivity gains across the farming sector. Adoption of precision farming technologies and decision support tools is vital to the UK agricultural industry due to limited land resources, increased risk of food insecurity and obligations to global climate change treaties.

Operational considerations in arable farming – such as water management, input application and crop performance – could now be supported by a wealth of real-time digital information. With the advent of low-cost microelectronics and ultra-low power wireless communication technologies, it is now technically possible to deploy ground-based remote sensing networks across farmland to monitor key agronomic parameters such as soil moisture and incident sunlight. Other sources of objective information with relevance to arable farm management include micro-scale weather forecasts, predictive yield models and real-time sensor telemetry captured by agricultural machinery.

A multitude of software and hardware tools which integrate rapidly expanding flow of digital information with in-field farming operations are now commercially available. The development of agricultural machinery equipped with variable rate application technologies has already yielded productivity gains in the arable farming sector. Utilising latest in-situ monitoring information, farming inputs – seedlings, irrigation water, fertiliser and pesticides – may be optimally targeted with square metre accuracy to account for natural variability in growing conditions/crop production across a field.

Technologies now exist to remotely actuate digital control systems such as control valves on irrigation pipelines – publicly available information such as field soil type and historical climate information may be retrieved instantly at the click of an icon.

While development of precision agricultural systems has primarily focused on the arable farming sector, digital technologies are now becoming more widely utilised by livestock industries. Digital technologies now enable farmers to monitor numerous attributes of individual animals such as reproductive state, weight gain, feed conversion ratios and killing-out percentages to guide farm management decisions and long-term strategies. Other applications for precision-based systems include intelligent feeding stations which allocate appropriate quantities and qualities of feed based on different classes of stock and growth cycles. Ground, airborne and spaceborne remote sensing systems may also monitor soil fertility and grass growth rates in grazing pastures, while guiding variable rate application of fertilisers to optimise biomass production. Abnormal animal behaviour indicating poor health/stress may be rapidly identified by sensors embedded inside wearable collars.

While productivity gains are achievable at a local level, the true value of digital agriculture is fully realised by assimilating objective information captured on a large number of farms into centrally managed ‘expert decision systems’. Intelligence of decision support tools is maximised by fusing real-time situational awareness with analysis of comprehensive historical time series of meteorological, geophysical and agronomic information captured during previous growing seasons. As an example, data analysis of wheat yield output over the previous decade – with coincident soil type and climate information – can enable farmers to select the best variety to their specific location and growing conditions.

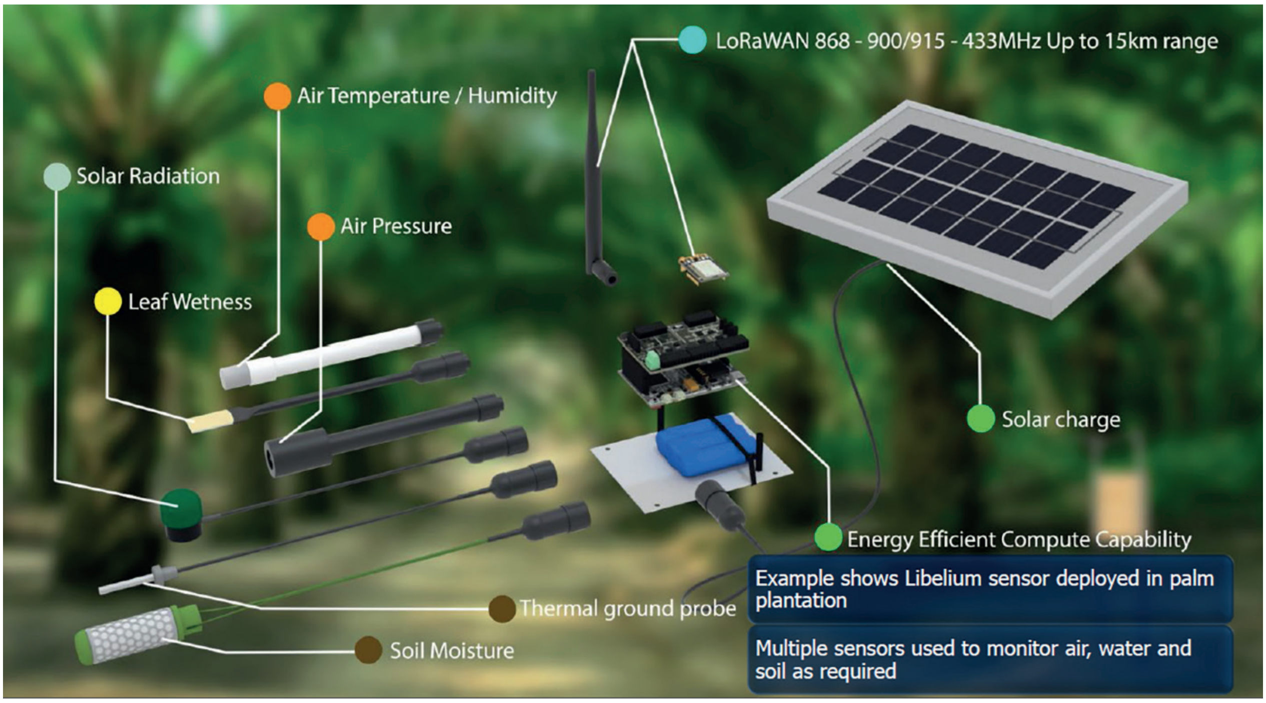


Figure 12. Wireless sensor node
Image source: Inmarsat (2017)

Figure 13. Data transfer from field to internet – Image source: Inmarsat (2017)

IoT technologies will play a vital role in the digital agricultural revolution – facilitating the deployment of low power, long range (>10 km) wide area network (LoRaWAN) wireless sensing and actuation systems into local farming ecosystems and optimised transfer of in-field digital information to cloud-hosted data management platforms.

A typical wireless sensor node is shown in Figure 12 (courtesy of Inmarsat). It is an integrated unit, combining a range of sensors with a LoRaWAN radio unit. The operation of the sensor node is overseen by a microcontroller, which could process the sensor data before it is transmitted to the internet via LoRaWAN link, if necessary.

When there is more than one wireless sensor node in the field, a communications gateway is used to facilitate data exchange between the nodes and the internet (see Figure). When mobile phone signal coverage is weak or non-existent, a gateway (blue box in the figure) could be connected to a satellite communications terminal (white unit in the figure) to provide the required data flow. As farms and the complete food supply chain become more connected, IoT will help capture the flow of food products from agriculture through the food industry ('agri-food logistics') to the consumer as the final customer ('food awareness').

Satellites for agriculture – Future vision

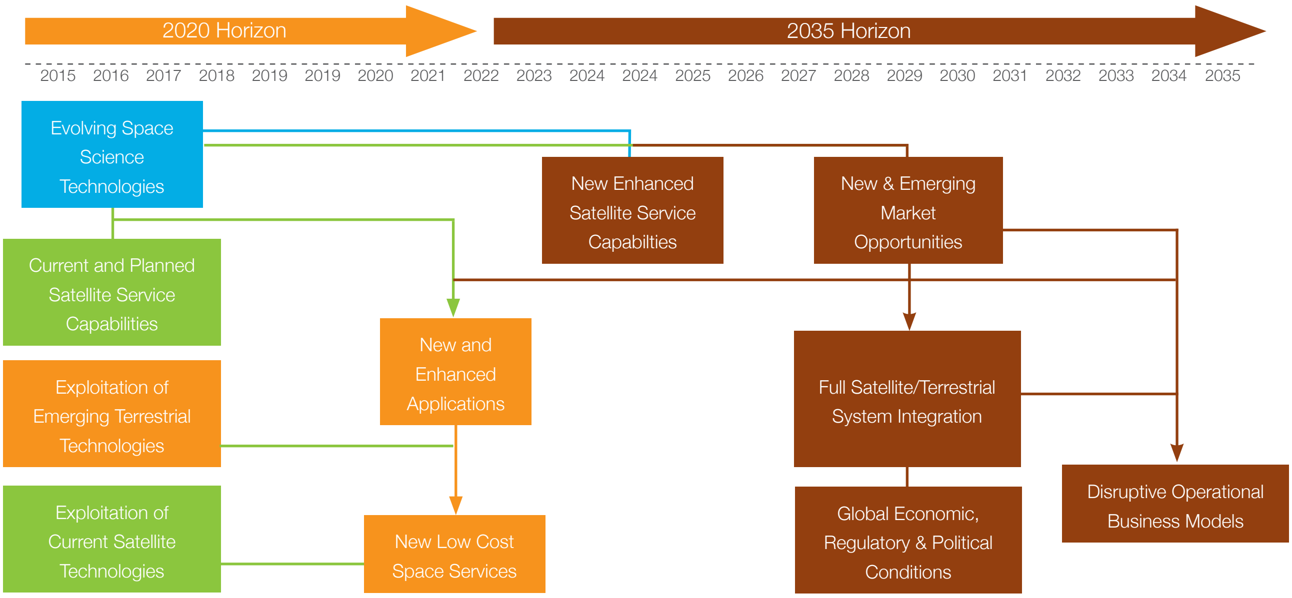


Figure 14. Simplified logic used to determine how inputs will be used to derive a view of the satellite landscape within the two time horizons: now to 2020 and then to 2035
Source: Satellite Applications Catapult

The Satellite Applications Catapult periodically undertakes research to create technology roadmaps aimed at facilitating the understanding of future technological innovations in the satellite industry. The innovations identified in this work will have positive impacts on the agriculture industry, particularly around frequency, cost and detail of information available both spectrally and spatially.

For the purpose of this study, the innovation time horizon is divided into short-term (until 2020) and long-term (2020–2035) developments. Figure 14 illustrates the logic that is used to determine how the various inputs and activities have been used to derive a view of the evolving satellite technology landscape to each of these horizons.

The 2020 and 2035 visions for the use of EO can be split into two subcategories – the upstream technology advancements, followed by the improvements in the downstream data analytics and commercial models. Improvements in the upstream technology will increase satellite technical specifications, such as spatial and temporal resolution, and innovations in the downstream industry will facilitate the exploitation of data through advances in IT infrastructure.

The vision to 2035 is largely underpinned by technological advances highlighted in the technology roadmaps by NASA[1] and ESA[2]. These innovations are currently a very low Technology Readiness Level (TRL). Other innovations are currently in early development, such as deployable optics, High Altitude Pseudo-Satellites (HAPS) and on-board processing. These innovations have been noted within the 2035 time frame as this is when it is believed there will be uptake and commercial exploitation on a large scale as testing of some of the technology has already begun to take place.

Planet Inc. small satellite constellation

The EO landscape is evolving rapidly – Planet Labs Inc design and launch miniature satellites (mass between 1 and 100kg) called Doves which continuously scan Earth and form a satellite constellation that provides a complete image of Earth daily at 3–5 m optical resolution. Planet have also acquired RapidEye, ex-Google subsidiary Terra Bella and its SkySat satellite and now own the largest constellation ever put into orbit - nearly 300 satellites. Planet imagery is available online and some is accessible under an open data policy.

Planet's daily satellite imagery - such as that now available from Planets - can reveal patterns in rapidly changing infrastructure, stockpiles and water resources, identifying areas of risk and opportunity. This data can be used in many ways, including the construction industry where systematic tracking of development is key to monitoring areas, and for financial analysts who are gathering research for investments.

Dual-use satellites

EO data is at its most powerful when analysed in the presences of auxiliary data sets. Missions such as NovaSAR will see complementary payloads, AIS and S-band SAR, put on the same satellite bus to increase the satellite's productivity and commercial value. Other examples include the Iridium communication constellation, where the platforms have been designed to have capacity for a secondary payload. As space continues to become a premium commodity, especially in the geostationary and low Earth orbit, companies, such as UrtheCast, will start to 'piggyback' on existing large space assets.

Real-time data

Greater demand in near real-time applications, especially from the commercial and defence markets, has led to the development of geostationary data relay

[1] https://www.nasa.gov/offices/oct/home/roadmaps/index.html
[2] http://invest-space.eu/wp-content/uploads/2016/03/ESA-Technology-roadmap-2013-presentation.pdf

satellites, such as ESA's European Data Relay Satellite System (EDRS), the first of which was launched in 2016.

Such satellites will enable EO satellites in low Earth orbits to have almost continual communication with ground control stations. This will facilitate near real-time data transfer from satellite to ground.

Video from space

Several companies already offer this capability, such as Planet and UrtheCast, and UK company Earth-i will complete its constellation in 2019. Currently, offerings are limited and very expensive, but this type of technology and offering will continue to become more prolific. Video from space will allow true situational awareness over a farming site. It will provide insight about fleet management, real-time generation of terrain models, change detection and feature extraction.

Better technical specifications

As the industry continues to carry out advances in the miniaturisation of electronics, better optics systems, power capture and storage and communications systems, EO satellites continue to improve their technical specifications. These advancements are concentrated in five key areas:

- Spatial resolution
- Temporal resolution
- Radiometric resolution
- Real-time data access
- Greater capacity

These advances also facilitate the development of cheaper satellites, which enables individual companies and institutions to buy their own dedicated spaceborne assets

On-board processing

Satellites produce ever-increasing amounts of data. Sentinel 1 alone generates 1.6TB/day, which needs to be downlinked to a ground station. This puts a huge strain on the downlink in the service chain, especially when the end user might only use a fraction of this data to extract the desired useful information. The move from edge computing where the intelligence (analytics) is undertaken in the cloud to fog computing where the intelligence takes place at the end of the network (at the sensors) will reduce data exchange and increase system responsiveness.

SatComs and GNSS

Satellite IoT systems that are able to support lower data rates in real time will become pervasive, enabled by the development of new, smaller, low-power, less expensive sensor devices and the integration with 5G networks within the next three years. An increased reliability of communications signals will be enabled by the development of integrated hybrid receiver devices able to connect to satellite, cellular, Wi-Fi and eventually high-altitude platforms within a three-year time frame.

Ongoing developments in multi-sensor integration, particularly between hybrid GNSS and vision-based systems, will enable ubiquity in positioning both over and underground in the 3–5-year time frame. Both Europe's Galileo and China's Beidou Constellations are scheduled to become fully operational in 2020. Multi-Constellation/Frequency GNSS receivers are already in development and will become pervasive by 2020. Evolutions in GNSS constellations and receivers will provide faster time to first acquisition of a signal and sub-10cm position accuracy over ground using only GNSS. Integration of 5G with SatComs systems offering more resilient service will be operational by 2020.

Landsat 8 Earth observation satellite
Image credit: NASA

Opportunities for further development

As outlined in this review, satellites enable and enhance precision farming applications in many different ways, from providing positioning information, facilitating communication, to delivering wide-scale observation on a regular basis. Looking into the future, the space sector is set to play a critical role in the creation of 'smarter' and impactful agricultural solutions driven by the increasing availability of powerful EO imagery, as well as growing data and information expected from connected sensors. This will generate many novel research questions and, ultimately, innovative commercial products and services. The push to be 'smarter' and to develop solutions that sustainably increase food production is creating requirements right across the supply chain, as highlighted in Figure 15.

Figure 15. Example of requirements from across the agricultural supply chain – where satellites can help to increase food production
Graphic: Agri-Tech East

Glossary

Term	Definition
AIS	Automated Identification System
ARD	Analysis Ready Data. Standardised, processed EOS data suitable for analysis
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer (Terra sensor)
AVHRR	Advanced Very High Resolution Radiometer
Catapult	Satellite Applications Catapult
EDRS	European Data Relay Satellite System
EM	Electromagnetic
EO	Earth Observation
EOS	Earth Observation Satellites
ESA	European Space Agency
ETM+	Enhanced Thematic Mapper (Landsat-7 sensor)
EVI	Enhanced Vegetation Index
fPAR	Fraction of Photosynthetically Active Radiation
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GRD	Ground Range Detected Processing Level
HAPS	High Altitude Pseudo-Satellite
IoT	Internet of Things
JRC	Joint Research Council
LAI	Leaf Area Index
LiDAR	Light Detection and Ranging
LoRaWAN	Long Range Wide Area Network
MODIS	Moderate Resolution Imaging Spectroradiometer (Terra/Aqua sensor)
MSI	Multi-spectral Instrument
NASA	National Aeronautics and Space Administration (USA)
NDVI	Normalised Difference Vegetation Index
NIR	Near-infrared
NOAA	National Oceanic and Atmospheric Administration (USA)
NOPSEMA	National Offshore Petroleum Safety and Environmental Authority
OSR	Oilseed Rape
Radar	Radio Detection and Ranging. By usage: data from radar systems
SAR	Synthetic Aperture Radar
Satcom	Satellite Communication Systems
SLC	Single Look Complex Processing Level
SLMS	Satellite Land Monitoring System
SWIR	Shortwave Infrared
TIR	Thermal Infrared Sensor
UAV	Unmanned Aerial Vehicle
UK	United Kingdom of Great Britain and Northern Ireland
USGS	United States Geological Survey
VNIR	Visible Near-infrared

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