



CubeSat constellations: New era for precision agriculture?

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ABSTRACT

Precision Agriculture (PA) has undergone a remarkable transformation in recent decades due to the rapid evolution of technologies to optimize farming practices. CubeSats (CS), specifically PlanetScope (PS) Constellations, are playing a crucial role in revolutionizing remote sensing in the agricultural sector. These small and cost-effective satellites are equipped with advanced sensors, such as cameras and multispectral imaging devices, which enable high-resolution data capture of crop conditions and land parameters. By providing frequent and regular monitoring capabilities, they empower stakeholders with daily near real-time information essential for decision-making. Integrating this satellite data with other information resulting from heterogeneous sources enhances precision farming applications, allowing them to make informed choices regarding crop management, disease detection, irrigation strategies, and yield predictions. This review introduces the concept of CS in PA, highlighting their state-of-the-art and recent advances. It explores the role of CS, mainly Planet Labs Products, in the field of PA, discussing the evolution of PS, its recent developments, and the monitoring capabilities it offers for crops. Additionally, this review aims to assess the potential of PS alone and in combination with other existing data products. Finally, it discusses the limitations and challenges associated with CS in general and PS in particular and suggests areas for improvement in this new era of technology.

1. Introduction

Rapid population growth is raising serious concerns about food security worldwide. The United Nations projects the global population to be around 8.5 billion by 2030, 9.7 billion by 2050 and 10.4 billion by 2100 (United Nations Department of Economic and Social Affairs, 2022). Agriculture, constrained by limited resources such as land, water, and fertilizers, must become more efficient to meet this growing demand. Precision agriculture (PA) offers a potential solution by adopting a system approach aimed at low-input, high-efficiency, and sustainable farming (Shibusawa, 1998). Remote sensing (RS) technologies based on high-resolution imagery have been gaining popularity in the last two decades to monitor crops and assist in agricultural management. Satellite data are distributed globally by Earth Observation (EO) systems, such as Copernicus, NASA, NOAA, etc., allowing access to and exploitation (Kansakar & Hossain, 2016). They have been reviewed from multiple angles, including specific applications, methods, sensors, platforms, and specific locations. They are disseminated worldwide through information technology infrastructures by means of Graphical

User Interfaces (GUI) or Application Programming Interfaces (API). The advancements of RS technologies allow farmers to access digital agricultural systems by acquiring data from various sources. Various platforms are being used to implement PA (i.e., Sentinel-2 and uncrewed aerial systems, UASs). Sentinel-2 (S2) is a widely used RS platform in PA, offering free open-source data with enhanced temporal, spatial, and spectral resolution. It is useful for monitoring abiotic and biotic stress, managing agricultural practices. However, cloud cover can cause data gaps and affect phenological studies, especially when estimating the Start of Season (SOS) and Peak of Season (POS). Additionally, the absence of thermal bands limits the estimation of evapotranspiration and water stress. Spatial resolution (10 m, 20 m, and 60 m) constraints also pose challenges for detailed agricultural applications. While S2 provides information on larger fields, it has spatial limitations, especially for smaller fields. As the number of clean pixels is lower, the pixel loss percentage is higher (Misra et al., 2020; Richter et al., 2012; Segarra et al., 2020; Vajsová et al., 2020). UASs have sharply increased applications since the second decade of the 2000 s (Khanal et al., 2020; Sishodia et al., 2020; Yao et al., 2019) and are used for several

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applications like crop vigor mapping, yield prediction, and many others (Badagliacca et al., 2023; Messina et al., 2020, 2021; Messina & Modica, 2020; Modica et al., 2020). UASs offer ultra-high spatial resolution and flexibility, making them ideal for localized, detailed studies, such as agricultural monitoring and radiometric correction of multi-flight imagery (Jiang et al., 2022). However, their limited coverage area and susceptibility to weather conditions, alongside regulatory constraints, pose significant challenges (Yao et al., 2019). S2 systematic acquisition capabilities offer a cost-effective alternative to UASs (Pádua et al., 2020) (Alvarez-Vanhard et al., 2021), but they also have shortcomings (Yao et al., 2019). Farmers can optimize yields and contribute to environmental sustainability, profitability, and overall agricultural quality (Khanal et al., 2020; Lanucara et al., 2018; Sishodia et al., 2020) by making informed decisions at different stages of crop production. The adoption of PA depends on factors such as farm size, knowledge sharing, and financial assistance, highlighting the need for cost-effective, user-friendly technologies, collaborative efforts, affordable technology, education, support, and policy reforms specifically tailored for small farms (Mizik, 2023). Looking ahead to the future vision of 2050, these developments are expected to revolutionize agricultural practices, resulting in increased industry efficiency, sustainability, and productivity (Y. Huang & Brown, 2018). Critically, the availability of cost-effective and user-friendly technologies (i.e., S2) is unsuitable for small farms. This gap has led to the introduction of CubeSats (CS) in the realm of PA. Nanosatellites (NS), or so-called CS, are by definition SmallSats i.e., small spacecraft with a mass of less than 180 kg (Laufer & Pelton, 2020); they are paving the way to their popularization in PA since 2013. Additionally, it assists in forest monitoring (Cui et al., 2022; Keay et al., 2023; Lima et al., 2019; Shimizu et al., 2020), contributing to effective forest management and preservation efforts. It is considered a novel approach and an opportunity for PA applications to provide global daily coverage (McCabe et al., 2016). PlanetScope (PS) satellites, one of Planet Labs' products, provide daily global coverage and high spatial resolution. Planet CS are smaller compared to the traditional modular satellites, typically $10 \times 10 \times 30$ cm in size weighing 5.8 kg (Earth Online, 2022), and can be launched more quickly and at a lower cost (McCabe et al., 2017a). They are designed to be cheaper and more cost-efficient than traditional, larger satellites and can be launched in larger numbers to provide more comprehensive coverage of the Earth's surface, a step forward in the implementation of the Digital Earth concept (Annoni et al., 2023). As CS, they fill a critical niche in providing frequent imagery updates for environmental monitoring. They demonstrated great potential to monitor agricultural systems and can subsidize, on forthcoming research, the local and regional monitoring of agricultural areas and contribute to better management regarding strategic planning of governmental and corporate decision-making over technical issues (Guilherme Teixeira Crusiol et al., 2021). The comparison between UASs, PS, and S2 platforms in EO reveals distinct advantages and limitations that cater to diverse application needs, as highlighted in recent scientific literature (Messina et al., 2020).

Other CS has been introduced in PA, such as: a) a constellation of SWEET-like CS would extend the coverage to the whole Planet, delivering daily data to ensure reliable access to clean water for millions of people worldwide (Antonini et al., 2017); b) the CaNOP CS mission tests multispectral imaging monitors rainforest changes, utilizes AI for target identification, and observes urban night lighting due to LED streetlights (Santangelo & Crosby, 2020); c) the mission employs a 3U CS camera system and communicates through LinkStar radios, collecting valuable data for scientific analysis and community sharing (Nanosats Database, 2023).

In our review paper, we investigate whether NS represent a new era in precision agriculture. The focus is primarily on PS constellations, which have been extensively studied and are more widely examined in research compared to other nanosatellites. This emphasis may be attributed to the availability of a complementary program for researchers offered by the industry, known as the "Education and Research

Program". To the best of our knowledge, there is no comprehensive assessment, written in English, of the progress and challenges in CS Technology studies with a key focus on PA. In this work, we tackle this issue by reviewing state-of-the-art vegetation monitoring since the availability of CS data in 2003. Also, this study reviews the progress, opportunities, and challenges of CS in PA. This paper is structured into five main sections: (1) an introduction to PA and CS, (2) a discussion on the choice of PS constellations and their widespread applications, (3) an exploration of their capabilities in PA studies and other fields, alone and/or integrated with other product sources, (4) a review of all their limitations and challenges, and (5) future research directions and outlooks for CS technology, focusing on crop management and monitoring, as well as exploring other aspects like water, pest, and weed management in PA.

2. Material & methods

The literature search for this paper was conducted from December 2023 to January 2024 using the Scopus and Web of Science databases, involved querying these search terms: ("precision agriculture" OR "precision farming" OR "smart agriculture") AND (cubesat OR PlanetScope OR "Planet Labs" OR "Planet Dove" OR "SuperDove"). Only peer-reviewed publications in English were considered, resulting in 620 sources. Duplicates were removed using the package 'bibliometrix' in R environment (Aria and Cuccurullo, 2017; The R Foundation, 2018). Moreover, after a manual screening process, certain studies were excluded as they didn't serve the purpose of the study. Additional relevant studies were identified by examining the references of the initially retrieved sources (i.e., the snowballing method). Given the broad applicability of CS technology, only studies focused on precision agriculture, particularly vegetation monitoring, were included in the review, bringing the total number of sources used in this study to 110. The collected literature encompassed various formats, including short surveys, notes, editorials, articles, reviews, book chapters, and conference papers.

3. Why PlanetScope Constellations?

3.1. Synopsis of Planet Labs

Planet Labs is an aerospace commercial company, founded in 2010 by three NASA scientists, that designs, builds, operates, and holds the world's largest constellation of NS known as 'Doves,' providing consumers with multispectral imagery since 2016. Until 2013, CS was launched by universities and research institutes worldwide, most of which were 1U or 2U. 1U, 2U, and 3U refer to the standard sizes of CubeSats, with 'U' denoting a unit cube of approximately 10 cm on each side (Swartwout, 2013). Adding more units allows for modular scalability in satellite design and offers expanded capabilities for scientific and commercial missions (Bomani, 2021; Swartwout, 2013). However, Planet Labs Inc. (Labs, 2023) and Spire Global Inc. (Spire Global Inc, 2023) launched the first 3U CS in 2013. That signaled the beginning of the CS revolution in EO. These NS are low-cost constellations and offer high spatial resolution imagery with a geometrical resolution resampled up to 3 m. They can revisit any location on Earth daily (Planet Labs, 2015). Planet Labs provides global data dissemination through its web platform, allowing users to download and process data via its GUI or API. The Planet Labs API is the gateway to access the Planet database and has comprehensive documentation, as well as making the process of automatization of data acquisition and processing smoother. Planet offers multiple APIs for discovering, ordering, and managing imagery and analytics. Planet's API is a Representational State Transfer (RESTful) interface for managing their complete imagery catalog; guides and tutorials are available through Planet School (Planet Labs Inc., 2023). Two data types are available as part of the Planet policy, which can be characterized as 'Archival' and 'Tasked'. Archival data are imagery

collected in the past either through regular satellite operations or through directed tasking requests. The archival data set is irregular and dictated by previous tasking activities. The tasked data are acquired in response to users' specific requests. In this case, a request was submitted in advance, defining the area of interest and temporal frequency of desired imagery collection (McGrath et al., 2023; Planet Labs Inc., 2023).

The PS satellite constellations consist of multiple launches (flocks) of Dove satellites. On-orbit capacity is constantly improving in capability and quantity, with technological improvements deployed at a rapid pace. The PS sensors are inexpensive, with no onboard calibration devices, and their orbits are not maintained. Different sensor generations reflect evolving technology. Since its first launch in 2014, Planet Labs has released three PS instruments that have been developed, and their data are available for purchase at low-cost. PS imagery is increasingly used for science and environmental applications, including PA. More details about the different PS-released instrument types are described in Table 1. The Doves are characterized as 3U CubeSats. The old Generation Dove-Classic (PS2) scenes were captured in broadbands: red, green, and blue (RGB) wavelength bands with a variable view, sun illumination geometries, and a ground sampling distance (GSD) of approximately 3.7 m. Dove-R (PS2.SD) scenes were also captured in broadbands of RGB, adding a Near Infrared band (NIR). Most recently, the availability of 8 bands daily PS imagery called SuperDove (PSB.SD). It has created new opportunities for monitoring the Earth at high spatial resolution. SuperDove scenes are captured in four more additional bands: Coastal

Blue, RedEdge, Green 1 and Yellow (Kim et al., 2021). Despite slight differences in bandwidths and placements, SuperDove and Dove-R remain compatible (Frazier & Hemingway, 2021).

3.2. Harmonization with Sentinel-2, atmospheric & geometric corrections, and calibration

Planet Labs operates three generations of Dove satellites—Dove Classics, Dove-R, and SuperDove—each featuring distinct spectral responses. A harmonization process is employed to facilitate the interchangeable use of imagery from these satellites (Planet Labs Inc., 2023). This process standardizes the spectral responses of the images to closely match that of the S2 sensor, which is mainly designed for agriculture and land cover monitoring. The harmonization tool focuses on aligning the Red, Green, Blue, and NIR bands across all Dove variants with the S2 sensor, ensuring uniformity and compatibility of data for time series and historical analysis (See Fig. 1). This standardization is crucial for maintaining consistency in scene-to-scene observations and for accurately calculating metrics and Vegetation Indices (VIs) such as Normalized Difference Vegetation Index (NDVI) and Normalized Difference Red Edge Index (NDRE). It's important to note that the RedEdge band, often crucial for detailed vegetation analysis, is not included in the harmonization process between PS and S2 imagery. This detail, clarified in the New-Generation PS FAQs (Planet Labs Inc., 2023), indicates a focus on the primary RGB and NIR bands for harmonization, excluding the RedEdge band. This exclusion is crucial for researchers and practitioners aiming to use S2 bands (Red, Blue, Green, and NIR) as proxies for PS bands to conduct time series analysis extending back to 2018 and interpolating actual PS bands from 2022 to the present as the harmonization of bands started in January 2022. The methodology behind this harmonization, as discussed by Kington and Alan (2022) along with further insights by Scheffler et al. (2020) underscores the importance of this process in bridging the gap between the spectral characteristics of Dove-C, Dove-R/SuperDove imagery, and S2 imagery, enabling seamless integration of these datasets for practical applications.

The Atmospheric correction is an essential step in utilizing imagery from various sources. This correction is particularly crucial when integrating image data with other geographic information. The Dark Spectrum Fitting (DSF) method for atmospheric correction, adapted explicitly for PS and RapidEye systems, effectively retrieves surface reflectance values, especially in the visible bands (Vanhellemont, 2023). Furthermore, using physics-based inversion techniques, employing surface reflectance products from PS imagery, allows for retrieving bathymetry and water quality information (Niroumand-Jadidi et al., 2020). The constellation ensures consistent geometric accuracy (Roy et al., 2021). However, it is worth noting that PS images may exhibit geometric artifacts, such as scene-to-scene misregistration and inconsistent geolocation accuracy between spectral bands (Aati et al., 2022). These factors can pose challenges and introduce inaccuracies in quantitative ground displacement analysis. The calibrated PS imagery plays a crucial role in providing high-resolution data for modeling and event extraction, ultimately contributing to the advancement of PA. In a recent technical report of Planet, the relative spectral responses (RSRs) between S2 and Dove-R/SuperDove are very similar (Collison & Bourne, 2022), allowing crossover scenes from anywhere worldwide to be collected for on-orbit calibration. The RSR similarity means that the calibration of Dove-R and SuperDove does not need to be limited to only calibration sites. This is significant because it allows collecting enough crossovers for each satellite, even given their small footprints. Therefore, the crossover comparisons for Dove-Rs and SuperDoves can be conducted globally without needing specific, well-characterized calibration sites, making the calibration process more flexible and efficient. A calibration update was conducted for the SuperDove satellites using data collected from January 1 to June 30, 2021, and involves analyzing approximately 1.5 million crossover pairs between the SuperDove satellites and the S2 satellite. The crossover pairs were used to compare and

Table 1 PlanetScope product types (Mead & States, 2022).

Instrument Id	PS2	PS2.SD	PSB.SD
Size	10 x 10 x 30 cm		
Instrument Name	Dove-C	Dove-R	SuperDove
Sensor Name	PSScene3Band	PSScene4Band	PSScene8Band
N° Satellites	~24	~150	~180
Radiometric Resolution	16 bits		
Bands Type & Wavelength	Red: 590–670 nm Green: 500–590 nm Blue: 455–515 nm	Blue: 464–517 nm Green: 547–585 nm Red: 650–682 nm NIR: 846–888 nm	Coastal Blue 431–452 nm Blue: 465–515 nm Green I: 513–549 nm Green: 547–583 nm Yellow: 600–620 nm Red: 650–680 nm Red Edge: 697–713 nm NIR: 845–885 nm
Frame Size	25.0 km x 11.5 km	25.0 km x 23.0 km	32.5 km x 19.6 km
Ground Sample Distance (at nadir)	3.0 m-4.1 m	3.0 m-4.1 m	3.7 m
Accuracy	<10 m RMSE		
Orbit Height	450–580 km (~98° inclination)		475–525 km
Orbit Type	Sun-synchronous Orbit		
Swath Width	25 km		
Revisit time	Daily at nadir		
Relative Spectral Responses (RSRs)	Different from Sentinel-2		Similar to Sentinel-2
Temporal coverage	July 2014 to April 2022	March 2019 to April 2022	March 2022 to present
PlanetScope Ortho Scene product	*PlanetScope Visual Ortho Scene product	*PlanetScope Surface Reflectance product *PlanetScope Analytic Ortho Scene Surface Reflectance product	*PlanetScope Surface Reflectance product *PlanetScope Analytic Ortho Scene Surface Reflectance product

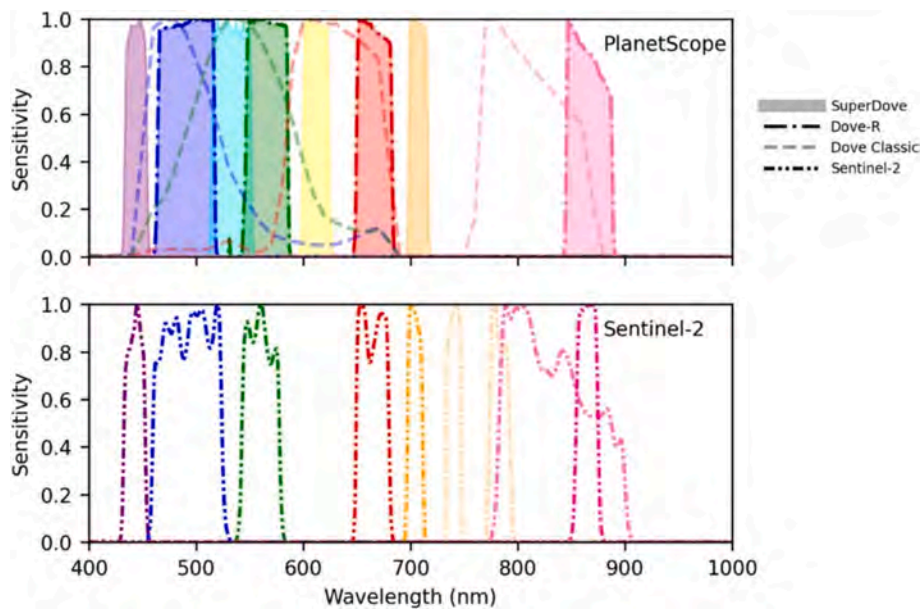


Fig. 1. The spectral response of Sentinel-2 and PlanetScope in the wavelength range (Mead & States, 2022).

calibrate the data collected by the SuperDove satellites, ensuring accuracy and consistency in the calibration process for a comprehensive assessment and adjustment of the calibration parameters for the SuperDove satellites.

3.3. Spatial and temporal evolution of PlanetScope products

The PS constellations, consisting of over 200 Dove and SuperDove satellites, can capture images of almost all of Earth’s land daily, covering a total area of 200 million km²/day. These constellations are revolutionizing RS with its unique coverage, frequency, and resolution combination. As previously mentioned, the first PS product was launched in 2013, with data becoming available in July 2014. To illustrate the evolution of PS products, we have decided to simplify the analysis by dividing it into spatial and temporal evolution, allowing for a better understanding of the overall trend.

Several studies have been conducted using different PS products, such as Dove-C, Dove-R, and SuperDove. Fig. 2 summarizes a decade of scholarly engagement with PS satellite imagery from 2013 to 2023. The data used for Fig. 2 were collected and organized from the Scopus database. The number of studies was counted based on the country’s location in the study area. The map focuses on specific keywords related to PS instruments and missions and is based on a color gradient representing the volume of studies conducted in each country, allowing for a

visual assessment of international research patterns. The keywords used include ‘PlanetScope,’ ‘Planet Dove,’ ‘SuperDove,’ ‘Dove-C,’ ‘Dove-R,’ ‘Dove Classic,’ ‘PlanetScope-0,’ ‘PlanetScope-1,’ and ‘Planet Labs’. A custom Python script was developed to process the raw data, using the Plotly library to create the visualization map. The map reveals clusters of research intensity in specific geographical areas, prompting further investigation into the factors driving these concentrations. Possible areas of inquiry include the distribution of funding resources, the presence and strength of collaborative academic networks, and the effectiveness of satellite data in addressing local or regional environmental challenges. The distribution of research depicted in this map has implications for our understanding of the environment and the policies that may arise from it. The map highlights the importance of critically evaluating whether underrepresented areas are simply under-researched or systemic barriers prevent their inclusion in the scientific discourse.

Fig. 3 summarizes the development of the PS Constellations, providing a detailed timeline of satellite development by Planet Labs from 2010 to 2024. It highlights key milestones in improving their Earth observation capabilities. The associated spectral response charts visually demonstrate the wavelengths that each satellite type can detect. The shaded regions in the figure indicate the time frames when different types of satellite imagery were available, with a note indicating the end of service in April 2022 for Both Dove Classic and Dove-R.

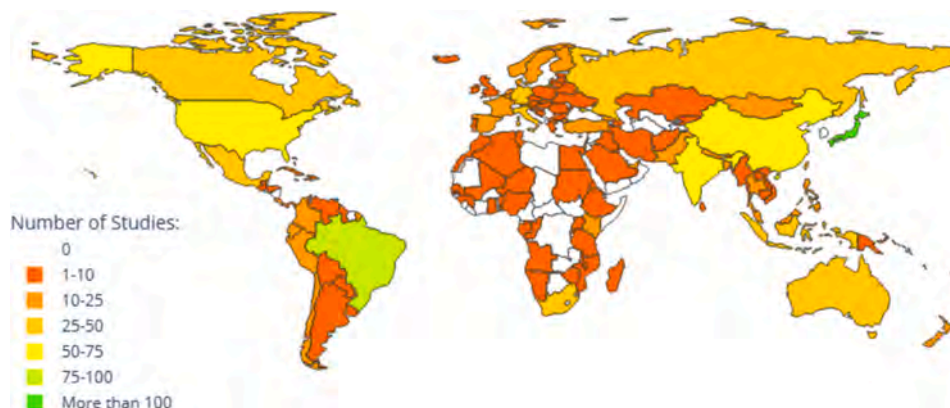


Fig. 2. Spatial evolution map of the world distribution of Number of studies using PlanetScope data in all research fields (January 2024).

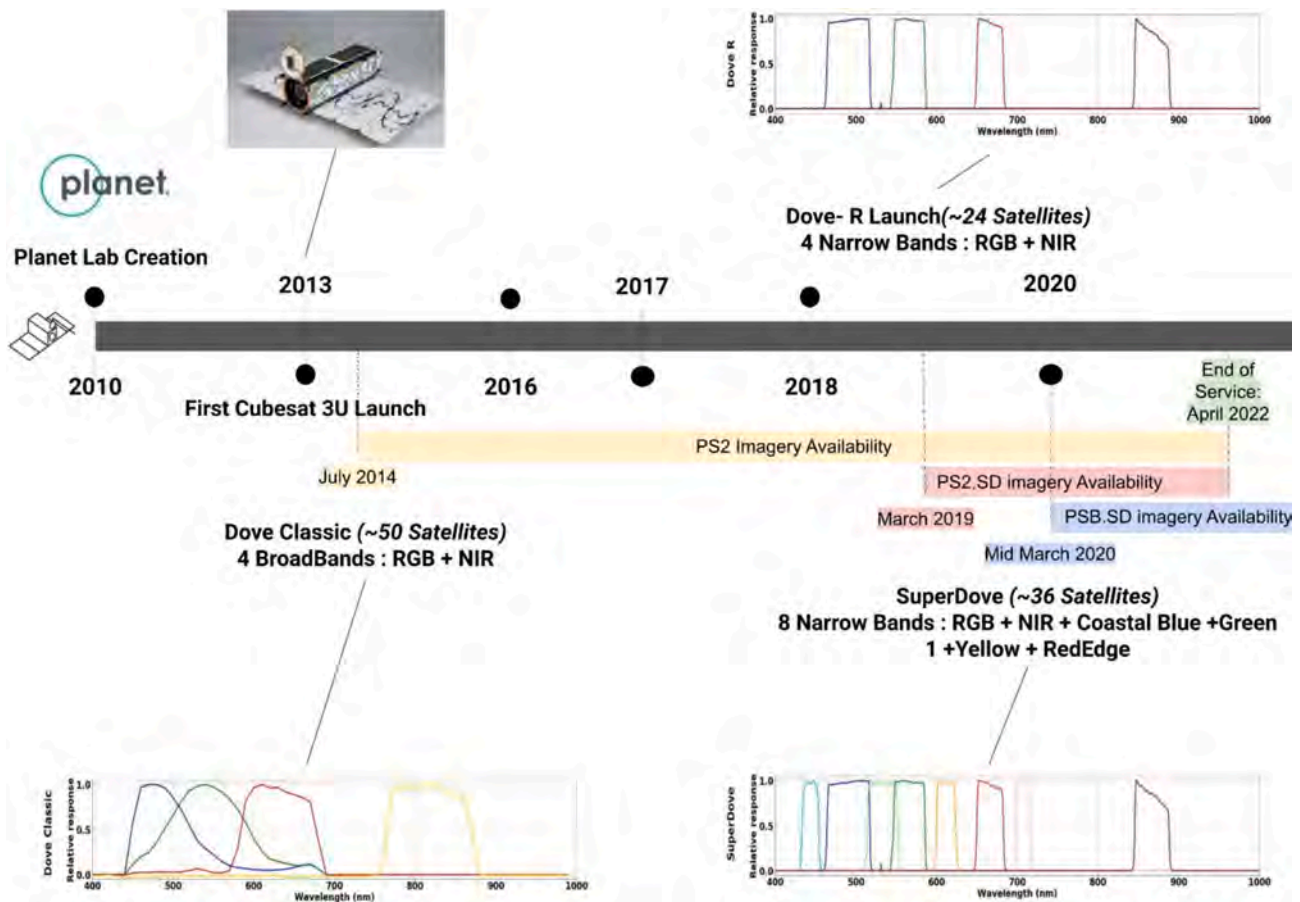


Fig. 3. PlanetScope Constellations development Timeline by Planet Labs from 2010 up to date. *RGB: Red-Blue-Green; NIR: Near Infra-Red. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

In their work, [Houborg and McCabe, \(2016\)](#) discuss how Planet Labs utilizes their PS satellites to obtain daily and global Earth images by translating them into a vegetation index. Since RGB alone may not be sufficient for vegetation monitoring, the near-infrared (NIR) region is crucial due to its high sensitivity to changes in vegetation density (Asner, 1998). By leveraging the high radiometric quality and near-infrared imaging capabilities of Landsat-8 (L8), the authors aim to optimize Planet’s broadband RGB time-series imagery for agricultural applications ([Houborg and McCabe, 2016](#)). Integrating the NIR band to PS allowed for calculating the NDVI without needing data from other sources. This technological evolution continued with the release of the four narrowband Dove-R products, which improved compatibility with the S2 satellite, and later, the introduction of the SuperDove in 2020, featuring eight narrow bands. Six of these narrow bands mimic those of S2, allowing for the computation of various vegetation indices, thereby significantly enhancing the capability to monitor and analyze vegetation health and density.

PS data can be utilized to monitor sowing dates, which ultimately impacts crop yields; comparing successive satellite images to detect changes, allowing for identifying alterations in the field surface color throughout their growth cycle, that occur when no-tillage seeding is performed ([Sadeh et al., 2019](#)).

4. PlanetScope Constellations: Applications & opportunities

The PS role in PA is multi-faceted, impacting various key areas ([Table 2](#)). Regarding crop monitoring ([Abou Ali et al., 2020](#); [Cai et al., 2019](#); [Cohen et al., 2019](#); [Garg et al., 2022](#); [Messina et al., 2020](#); [Sadeh et al., 2021](#); [Shevyrnogov et al., 2019](#)), this technology enables farmers

Table 2

PlanetScope (PS) applications in various precision agriculture (PA) sub-fields.

Specific Agricultural Applications	References
Land use and zoning	(Lanucara et al., 2024 ; Rösch et al., 2022 ; Rufin et al., 2022 ; Sano et al., 2023)
Yield Prediction	(Abou Ali et al., 2020 ; Amankulova et al., 2023 ; Farmonov et al., 2023 ; Lacerda et al., 2022 ; C. Li et al., 2022 ; Manivasagam et al., 2021 ; Sadeh et al., 2021 ; Sagan et al., 2021 ; Shevyrnogov et al., 2021 ; Skakun et al., 2021 ; Wei et al., 2023)
Soil Management	(Du et al., 2022 ; Tan et al., 2023)
Nitrogen Management	(Cai et al., 2019 ; Pereira et al., 2022)
Water Management	(Aragon et al., 2018, 2021 ; Cohen et al., 2019 ; Mansaray et al., 2021 ; McCabe et al., 2017b)
Pest, disease, and anomaly detection	(Castillo-Villamor et al., 2021 ; Lanucara & Modica, 2021)
Weed Detection & Management	(Mudereri et al., 2019)

to closely observe their fields, offering insights into crop health, growth, and potential issues. Furthermore, PS aids in yield estimation ([Abou Ali et al., 2020](#); [Amankulova et al., 2023](#); [Farmonov et al., 2023](#); [Garg et al., 2022](#); [Martello et al., 2022](#); [Mirvakhobova et al., 2018](#); [Shevyrnogov et al., 2021](#)), helping farmers predict their agricultural output more accurately. It also plays a role in soil management, supporting soil quality maintenance ([Du et al., 2022](#); [Tan et al., 2023](#)). Finally, PS contributes to the water management ([Aragon et al., 2018, 2021](#); [Cohen et al., 2019](#); [Mansaray et al., 2021](#); [McCabe et al., 2017b](#)), emphasizing its importance in preserving and effectively utilizing this vital resource,

enhancing food and water security efforts, and enabling rapid agricultural decision-making. Notably, PS offers a cost-effective and efficient approach to monitoring crop nitrogen status (Cai et al., 2019; Pereira et al., 2022), empowering farmers to make informed nitrogen management decisions. Beyond crop-related applications, PS plays a pivotal role in identifying anomalies in the vegetative vigor of fields (Castillo-Villamor et al., 2021; Lanucara & Modica, 2021). These researchers demonstrate the potential of utilizing PS high-resolution satellite imagery in various agricultural monitoring and management aspects. These researchers highlight the value of combining different data sources, such as S2 and UAS imagery, to improve crop assessment.

Integrating PS imagery with existing RS technologies is crucial for monitoring vegetation and leaf phenology. Researchers have explored the utility of PS, along with other data sources, such as L8, S2, and UASs, in different areas of PA. In orchard management, CS data from PS aids in estimating vegetation parameters, contributing to balanced crop development (Shimizu et al., 2020). Additionally, PS is beneficial for assessing land surface phenology and predicting the leaf area index (LAI) when combined with light detection and ranging (LiDAR) metrics (Andreatta et al., 2022; Lima et al., 2019). Combining textural features with topographic data yields optimal results in mapping mountain pine stands, with PS showing comparable outcomes to S2 (Acharki, 2022; Rösach et al., 2022). The satellite's role extends to land surface phenology assessment and predicting LAI, especially when combined with LiDAR metrics and machine learning algorithms (Hirigoyen et al., 2022; Moon et al., 2021). Notably, PS displays a higher density of cloud-free observations than S2, resulting in more consistent spatial patterns and fewer distortions in phenology retrievals (Cheng et al., 2020). Collectively, these studies emphasize the versatility and utility of PS data in various RS applications. They presented a wide range of applications for satellite imagery, explicitly focusing on PS data and its role in various fields. Jiang et al. (2022) found that achieving spectral consistency between sensors relies heavily on radiometric calibration accuracy. They also observed that the difference in spatial scale between UAS and satellite imagery could present challenges during co-registration. However, they noted that misregistration had a lesser effect on the spectral consistency between UAS data and satellites with larger spatial scale differences. Despite its limitations, such as radiometric inconsistency and additional calibration (Zhao et al., 2023). The Planet Fusion methodology integrates the CubeSat-Enabled Spatio-Temporal Enhancement Method (CESTEM), harmonizing SuperDove reflectance data with L8 and S2 data. This integration enables a more comprehensive and integrated approach to satellite data analysis (Tu et al., 2022). Furthermore, integrating with the harmonized Landsat S2 (HLS) data (Zhao et al., 2023) has been instrumental in monitoring the leaf phenology of individual trees using multi-satellite time series data. Table 3 summarizes the characteristics of comparison between PS, S2, and UASs.

In addition to these scientific applications, PS imagery has been integrated into various platforms for broader accessibility and use, including Esri ArcGIS, Google Earth Engine, and QGIS (Planet Labs, 2023). This integration facilitates a wide range of applications in environmental monitoring and agricultural management, demonstrating the versatility and importance of PS imagery in contemporary RS and geospatial analysis.

The potential of the additional bands of SuperDove is still being explored, but there have been some promising studies. Tan et al. (2023) underscored the potential of SuperDove data for precise, fine-scale monitoring and mapping of soil salinity in arid regions. Moreover, Farmonov et al. (2023) emphasize that integrating environmental data (i.e., climate and topography) with PS data resulted in the highest accuracy for improved wheat yield estimation at the field scale. In addition, Amankulova et al. (2023) the precision of soybean yield prediction was evaluated using RS data from different satellites, including PS, S2, and L8; the study concluded that the high spatial resolution satellite data from PS provided the most accurate soybean yield estimation. Du et al.

Table 3

Characteristics comparison between PlanetScope, Sentinel-2 and UASs.

Feature/ Aspect	UASs	PS SuperDove	Sentinel-2
Spatial Resolution	Very high (up to centimeter-level)	High (~3m)	Moderate (10 m, 20 m, 60 m)
Temporal Resolution	Very high (Tasked)	Daily	5 days (equator, with two satellites)
Spectral Resolution	Variable, depends on the sensor	8 spectral bands	13 spectral bands across visible, NIR, SWIR
Coverage	Limited by flight duration and regulations	Global	Global
Radiometric Resolution	High, depends on the sensor	12-bit	10-bit or 12-bit (depending on the band)
Data Accessibility	Restricted by operator, often not openly available	Openly available with subscription options	Free and open access
Near-Real-Time Applications	Possible but limited by data processing and regulations	Excellent due to daily revisit and rapid data processing	Good, limited by 5-day revisit time and data processing delays
Cloud Penetration Applications	No Need	Not possible (optical)	Not possible (optical)
Opportunities	Precision agriculture, detailed mapping, infrastructure inspection – High flexibility and maneuverability – Customizable payloads – Immediate deployment	Precision agriculture, disaster response, environmental monitoring – Daily global coverage – Rapid revisit rate for change detection – Consistent data quality	Precision agriculture, land cover mapping, environmental monitoring – Free and open data policy – Wide-area monitoring – High spectral resolution for detailed analysis – Affected by cloud cover
Limitations	– Limited coverage area – Weather dependent – Regulatory restrictions	– Lower spatial resolution than UASs – Limited spectral bands compared to Sentinel-2 – Data cost for high-volume usage	– Less frequent revisits than PlanetScope – revisiting time ranging between 3 to 5 days (in European regions) and 10 days in some regions like Australia

(2022) developed a new method for mapping meter-scale soil moisture conditions globally and with high-temporal repeat using Soil Moisture Active Passive (SMAP) and SuperDove technologies that provide a powerful tool for mapping soil moisture at a local scale, with potential applications in agriculture, hydrology, and climate research. Adding to these findings, Zhou et al. (2022) focused on the grain-filling process of winter wheat using PS imagery. They developed growth models based on vegetation indices, finding a high correlation with winter wheat maturity, emphasizing the platform's potential for non-destructive crop monitoring. Seong et al. (2024) introduced the SFC-DenseNet-AM model, which leverages multitemporal PS images for cultivated crop area extraction in South Korea. This model accurately classified onion and garlic crop areas, a critical step in forecasting crop yields. Jiang et al. (2022) conducted a multi-scale and multi-sensor assessment, comparing UAS-based multispectral data with PS, S2, and L8 data. Their study focused on the spectral consistency between these datasets, providing insights into the challenges and potential of integrating different RS technologies. In the context of PA, using PS data presents several opportunities and potentialities, as detailed in the following subsections.

4.1. New possible vegetation indices and bands combinations

Several studies have leveraged PS data, primarily utilizing Dove-C and then Dove-R satellites, to calculate only the NDVI (Rouse et al., 1973), a widely spread index in precision agriculture (Botvich et al., 2021; Houborg & McCabe, 2016, 2018; Shevyrnogov et al., 2021). Introducing SuperDove satellites, equipped with four additional spectral bands—Coastal Blue, Green I, Yellow, and RedEdge—marks a significant advancement in remote sensing capabilities. These enhancements not only facilitate the calculation of established VIs such as NDVI and Green NDVI (GNDVI)(Gitelson et al., 1996) but also open avenues for employing more complex indices like the Enhanced Vegetation Index (EVI)(A. Huete et al., 2002), Green Difference Vegetation Index (GDVI) (Sripada et al., 2005), Soil-Adjusted Vegetation Index (SAVI)(A. R. Huete, 1988), Weighted Difference Vegetation Index (WDVI)(Clevers, 1991), Meris Terrestrial Chlorophyll Index (MTCI)(Dash & Curran, 2004), and Modified Triangular Vegetation Index 2 (MTVI2)(Raymond Hunt et al., 2011). However, the computation of some of these indices may still require the broader spectral range offered by other platforms, such as S2 or L8, to capture the nuances of vegetation health and stress fully (Farmonov et al., 2023). Despite the potential, research exploring the capabilities of the PS SuperDove satellites and their additional bands for calculating VIs (Amankulova et al., 2023; Farmonov et al., 2023; Seong et al., 2024), a wider array of VIs remains limited due to the absence of the SWIR and thermal bands. The expanded spectral range of SuperDove not only enhances the calculation of existing indices but also paves the way for developing new indices tailored to the nuanced requirements of precision agriculture, such as Yellow Salinity Indices (YRNSI and YRNDVI) (Tan et al., 2023). All mentioned indices can be calculated using S2 data, although SuperDove gives additional flexibility (i.e., daily revisit time) and higher spatial resolution than S2 (3 m). This evolution signifies a leap forward in our ability to monitor, analyze, and manage agricultural resources more effectively, offering insights into crop health, soil conditions, and environmental stress with unprecedented detail. Table 4 summarizes essential VIs calculated for PA with the SuperDove sensor only.

4.2. Cost analysis of PlanetScope and its competitors/ data cost and accessibility

The cost analysis of PS and its competitors reveals an increasingly competitive and diverse market, with options available for a wide range of applications and budgets. As the satellite imagery market continues to evolve, the focus on affordability, accessibility, and technological innovation will be key to meeting the growing demand for timely and accurate earth observation data. PS has positioned itself as a more affordable alternative in the satellite imagery market, offering competitive pricing compared to its rivals such as WorldView-3 and SPOT6/7. Table 5 compares the pricing costs between the later and PS. The acquisition of Synergize by Planet Labs has been a game-changer regarding of data accessibility and subscription models. This strategic move has allowed Planet to integrate Synergizes’ advanced processing

Table 4
Important vegetation indices calculated using only PlanetScope SuperDove in Precision Agriculture.

VIs	Data Used	Formulas	Purpose	References
reNDVI/ NDRE	*	$\rho_{NIR} - \rho_{RedEdge}$ $\rho_{NIR} + \rho_{RedEdge}$	Refined NDVI for potentially better discrimination of vegetation characteristics	(Farmonov et al., 2023)
MTCI	** ***	$\rho_{NIR} - \rho_{RedEdge}$ $\rho_{RedEdge} + \rho_{Red}$	Chlorophyll concentration assessment, indicative of nitrogen content	(Farmonov et al., 2023)
MTVI2	** ***	$1.2 * [1.2 (\rho_{RedEdge} - \rho_{Green}) - 2.5 (\rho_{Red} - \rho_{Green})]$	Improved estimation of vegetation cover and chlorophyll content	(Amankulova et al., 2023; Farmonov et al., 2023)

* PS SuperDove alone.
** with S2 data.
*** with Landsat-8 data.

Table 5
PlanetScope products compared to SPOT6-7, and WorldView-3.

Feature	PlanetScope	SPOT6-7	WorldView-3
Spatial Resolution	3 m (multispectral)	1.5 m (panchromatic), 6 m (multispectral)	31 cm (panchromatic), 1.24 m (multispectral), 3.7 m (SWIR)
Temporal Resolution	Daily revisits	1 to 3 days (varies with latitude)	<1 day at 1 m GSD
Radiometric Resolution	4-band (pre-2019), 8-band (post-2019)	4-band multispectral (green, red, NIR)	11-bits (pan & multispectral), 14-bits (SWIR)
Available Bands	4 or 8 multispectral bands	Panchromatic, 3-band multispectral	Panchromatic, 8-band multispectral, 8-band SWIR, 12-band CAVIS
Price per Sq Km	\$1.80	\$4.75	Starts at \$22.50 for 30 cm resolution
Minimum Order Size	250 km ²	100 km ²	100 km ²

capabilities with its extensive satellite imagery archive, resulting in enhanced data products and services. The new subscription models introduced post-acquisition and are available through the Sentinel Hub platform offer monthly or annual plans that cater to a wide range of needs, from basic monitoring to advanced analytical applications. These plans are designed to be flexible, including various options for data access, processing units, and the number of requests, making it easier for users to select a package that best fits their requirements. The integration of Synergizes technology has not only improved the quality and accessibility of PS data but also introduced new capabilities that greatly expand the flexibility, speed, and computing capabilities available to users. Access to data through APIs has been a significant advancement, enabling automated data retrieval and integration into custom applications, thereby streamlining workflows, and reducing the time and effort required to obtain and process satellite imagery.

4.3. A new era of high-frequency satellite imagery (constellations)

One notable characteristic of PS constellations is daily revisit time. This combination was previously unavailable at an affordable price with other products. The daily revisit time offers substantial potential for analysts. Limited studies have tried to use a time series of five cloud-free images (Zhou et al., 2022). However, to our best knowledge, no study has fully exploited this unique functionality of PS. Roy et al. (2021) specify that cloud analysis shows high probabilities of cloud-free observations in most global land points, with lower probabilities in equatorial regions and high latitudes. This characteristic allows flexibility for selecting the desired data date, as Sarkar et al. (2023) demonstrated, where the authors could choose a five-day interval. While frequent revisits provide up-to-date information, they can also lead to data overload, posing challenges for effective data storage, management, processing, and interpretation. Nevertheless, this challenge can be managed by implementing time-series analysis and machine-learning algorithms. These strategies can aid in extracting relevant information

from the daily data and reducing noise in the dataset. This characteristic of PS can be advantageous for high-frequency time series analysis. This is even feasible in the cloudiest forest regions, where constructing cloud-free composites from optical imagery with shorter return intervals is challenging. The ability to capture annual variations within a year can be more important for classifying cropland than spectral depth. PS records can be used for 3D photogrammetric reconstruction and for creating global-scale digital surface models (DSMs) (D. Huang et al., 2022).

5. PlanetScope Constellations: Limitations & challenges

Despite the PA progress, challenges remain in developing tools and frameworks for near real-time applications of RS data in PA. Several issues are involved in the difficulties in developing tools and frameworks for real-time applications of RS data in PA. The most important of these is the requirement for extensive technical knowledge and expertise when processing satellite data for practical, real-world applications. PA necessitates data with high geographical, spectral, and temporal resolution, which may only sometimes be satisfied by publicly available satellite data. Several studies have identified various PS limitations, particularly with the prior two PS Products (PS2.SD and PSB.SD). The key limitations that keep coming up are detailed in the following subsections.

5.1. Cloud cover

Cloud cover and changing irradiance are challenging, affecting satellite images' quality and utility for environmental applications, especially in agricultural management. Cloud cover is a problem that generally concerns the use of data acquired with a passive sensor rather than specifically PS. The latter's images are provided as *ortho*-rectified and converted to surface reflectance. However, there are residual errors from inter-sensor differences and the radiometric normalization process (Houborg & McCabe, 2018), variations in the orientation of scene footprints, as well as the high frequency of cloud cover over some regions (Roy et al., 2021, Roy et al., 2024) that are not fully captured by the provided cloud masks and the need for rigorous quality control, underscoring the need for careful interpretation and validation against other satellite data. These findings indicate that while cloud cover detection in PS imagery is effective, it faces challenges related to resolution, specific environmental conditions, and the need for advanced detection algorithms. To address this issue, users can implement cloud masking algorithms to filter out cloud-covered areas or utilize other satellite data sources with less cloud interference for cloudy periods. Different studies (Dagobert et al., 2019; Drouyer, 2022; Wang et al., 2021, Wang et al., 2022) demonstrate the ongoing efforts to enhance cloud cover detection in PS imagery by introducing approaches to fill the gap of missing pixels in PS time series data. The improvements seen in the latest versions of Planet's Usable Data Mask (UDM), such as UDM2.1, are part of these efforts. By refining the classification of haze and cloud, UDM2.1 aims to provide more accurate and usable EO data, thereby improving the efficiency and effectiveness of research and commercial applications that rely on PS imagery (Planet Labs Inc., 2023). The improvements in UDM2.1, such as the refined classification of haze and cloud, are steps towards addressing these challenges, enhancing the usability and accuracy of EO data.

5.2. Radiometric, geometric and calibration issues

Another key issue is the inconsistency in radiometric quality and degradation level among the satellites in its constellation. This variation can impact the consistency and stability of radiometric data. Additionally, achieving perfect geometric image alignment when integrating data from different sensors is challenging (Aati & Avouac, 2020; Noh & Howat, 2023), often requiring advanced techniques for sub-pixel

geometric harmonization. There are also uncertainties in utilizing the extra bands from the SuperDove surface reflectance data, primarily due to difficulties in developing specific relationships to accurately correct and verify this data. These challenges highlight the need for further studies and advancements to enhance the reliability and applicability of PS data in various RS applications (Tu et al., 2022). Additionally, limitations may include the need for careful consideration of temporal differences between satellite and reference data, and the potential impact of varying surface units on the accuracy of the data. Further studies may be needed to address these challenges and limitations (Tu et al., 2022). Frazier and Hemingway (2021) state that the geometric and radiometric quality of PS imagery does not match the quality expected by the community as it is not ready to be used for analysis directly. In fact, PS Images need additional processing beyond the baseline done by Planet to be integrated into the analytical processing pipelines. The temporal differences between satellite and reference data, along with the potential impact of varying surface units, also affect the accuracy of the data. Dobrinic (2018) stated that PS orthorectified images have better accuracy and precision than RapidEye images. Moreover, addressing the uncertainty caused by the Bidirectional Reflectance Distribution Function (BRDF) effects is essential for SuperDove data to achieve a robust reflectance retrieval workflow. However, Planet Labs has continuously upgraded sensor instrumentation over generations, indicating radiometric inconsistency and geometric incompatibility, making precise spectral analyses difficult (Frazier & Hemingway, 2021).

Regarding calibration, the images from S2 are considered superior to those from PS (Z. Li et al., 2020). A thorough characterization of a satellite's sensor is necessary to achieve effective calibration. Each PS's satellite generation has its unique sensor design and relative spectral response. While sensors within the same generation are similar, the original Dove Classic design features four broad, overlapping bands in the blue, green, red, and near-infrared. On the other hand, the subsequent generation Dove-R satellites have four narrow, non-overlapping spectral bands that closely match the corresponding bands of S2. The latest Planet payload, SuperDove, has eight narrow, well-defined spectral bands, with four aligning with Dove-R's VNIR (Visible Near InfraRed) bands. Six of the SuperDove bands are shared with S2 (Collison & Bourne, 2022).

5.3. SWIR and thermal bands Unavailability

Another limitation is the missing bands in the SuperDove data compared to S2 (i.e., SWIR and thermal), which complicates the development of transferable relationships for data analysis. Challenges include the absence of SWIR bands, variable solar geometry impacting image quality, and the necessity for extensive training data to ensure reliable classification (Martins et al., 2022). Unfortunately, no official data has been provided regarding PS's development of other sensors, particularly those related to the thermal and/or SWIR bands. Discussing with the Planet research team to understand why SWIR and thermal bands are not available until now, stating that the unique reason researchers deal with is the difficulty of integrating them in CS (Hansen & Malchow, 2008; Thimsen et al., 2017), primarily due to the constraints of CS design, including limited space, power, and cooling capabilities. SWIR and thermal sensors necessitate advanced thermal management to maintain sensor sensitivity and accuracy, a requirement that is difficult to meet within the compact and resource-limited confines of CS (Hansen & Malchow, 2008; Thimsen et al., 2017). These sensors are not only power-intensive but also demand sophisticated data processing algorithms, further straining the limited computational resources available on CS, making the integration of SWIR and thermal bands a complex engineering problem that necessitates innovative solutions and advancements in miniaturized sensor technology to overcome (Hansen & Malchow, 2008; Thimsen et al., 2017).

6. Future directions and Outlooks

As with all satellites, PS is designed to suit a domain more accurately than another. To offer advantages to some fields of research and not all of them. PS, operated by Planet Labs, is a network of Earth-imaging satellites that provides high-resolution and regularly updated satellite imagery. This technology is valuable for PA because it enables daily monitoring of crops, ranging from leaf harvesting to detecting nitrogen variation in agricultural parcels. Moreover, the daily global coverage provided by PS presents favorable opportunities for obtaining high-resolution images for time series analysis. However, certain limitations and alternatives become apparent compared to other RS technologies. The spatial resolution of PS data typically hovers around 3 m, which may not be sufficient for specific PA applications requiring higher detail levels, particularly for small-scale farming operations. To address this limitation, PS data can be combined with higher-resolution satellite imagery or UAS data to obtain more detailed information for specific tasks within PA. It is important to note that the orbits of the PS sensor are not maintained, and different overpass times are scheduled to accommodate the large number of sensors in the constellation. Due to its daily revisit time, PS is flexible in choosing free cloud data to work with and avoiding cloudy scenes.

The choice to utilize PS should be based on the specific requirements of the PA application, considering factors such as spatial-temporal resolution needs, work spectrum, flexibility, the type of data analysis required, and the cost. As with any technology, PS is part of a broader toolkit, each component of which possesses unique strengths and applications within the realm of PA. RS in PA is facing the trade-off between spatio-temporal, radiometric resolution, and cost. However, the introduction of SuperDove satellite systems has partially addressed some of these limitations. It offers daily 3 m resolution and 8 bands of data encompassing the visible and infrared spectrum with the lowest cost in the market. This advancement presents a significant opportunity for developing cost-effective tools for monitoring and evaluating vegetation systems. Introducing the SuperDove constellation allows researchers to utilize its data without integrating with other products. This fills research gaps in many PA fields where band deficiency is a concern, although some fields may still require the fusion of PS data with other product data to address missing bands like SWIR and thermal. This is particularly important for domains such as soil moisture and irrigation management.

The SuperDove, with its global coverage data of an approximate 3-m spatial resolution and near-daily temporal resolution, opens unique opportunities to capture diverse plant phenological development. It greatly enhances geospatial data collection for various applications. Further research is warranted to fully harness the advantages and capabilities of PS while also addressing its limitations, particularly in the context of PA. Additionally, efforts should be made to promote widespread adoption of this technology in research, given its accessibility through API, cost-effectiveness, availability in 8 bands, 3 m spatial resolution, and daily temporal resolution. The unique combination of coverage, frequency, resolution, and affordable prices offered by PS positions it as a valuable tool in PA. By incorporating additional spectral bands, the accuracy of radiative transfer models improves significantly, thus reducing uncertainties. While PS SuperDove holds immense potential, it remains underexplored and is yet to be fully unlocked soon. Specific areas where further exploration can be highlighted:

- Maximizing the benefits of the daily revisit time.
- Investigating the potential of the additional four bands: Coastal Blue, Green1, Yellow, and RedEdge.
- Harnessing the power of novel combinations of vegetation indices to enhance existing models or develop new ones.

Further research is recommended to explore the potential benefits of utilizing the information provided by the different overpass times (Roy

et al., 2021). If realized in the near future, introducing a thermal band to the PS satellite constellation could represent a significant advancement in remote sensing capabilities. This enhancement, combined with the constellation's daily temporal resolution, would markedly improve soil moisture content monitoring. This development could lead to a substantial leap forward in our ability to monitor and manage natural resources and agricultural practices, offering more timely and accurate data for decision-making processes. Integrating thermal data with the existing high-resolution optical imagery could unlock new possibilities in irrigation management, weed management, and evapotranspiration estimation.

CRedit authorship contribution statement

Lamia Rahali: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Data curation, Conceptualization. **Salvatore Praticò:** Writing – review & editing, Project administration, Methodology, Funding acquisition. **Simone Lanucara:** Writing – review & editing, Resources, Investigation. **Giuseppe Modica:** Writing – review & editing, Methodology, Investigation, Funding acquisition, Supervision, Project administration, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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