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Monitoring the environmental benefits of *Canavalia ensiformis* green manure in Thai rice cultivation using PlanetScope satellite data

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ABSTRACT. We investigate the potential of *Canavalia ensiformis* green manure in enhancing soil fertility, rice growth, and environmental sustainability in Thai rice cultivation. The research integrates field measurements with high-resolution PlanetScope satellite data to monitor the environmental changes induced by green manure application. Fourteen vegetation indices (VIs) were derived from satellite data to assess the impact of green manure on rice growth and development. The results demonstrate short-term improvements in soil organic matter, nitrogen, phosphorus, and potassium levels in the green manure-amended plots, with strong correlations observed between VIs and field-measured parameters. The visible atmospherically resistant index showed the strongest correlations with soil moisture across various depths ($r = 0.621$ to 0.935, $p < 0.01$), and the yellow normalized difference vegetation index demonstrated the highest correlation with available phosphorus ($r = 0.812$, $p < 0.05$). For rice growth parameters, the carotenoid reflectance indices (CRI Green550) exhibited the strongest correlation with plant height ($r = 0.878$), and the chlorophyll content estimation indices (Chl Green550) with chlorophyll content ($r = 0.642$). The normalized difference vegetation index showed the highest correlation with rice yield ($r = 0.885$). The study highlights the effectiveness of these indices in monitoring soil and plant parameters in response to green manure application. However, the benefits of green manure diminished over time, emphasizing the need for regular application and complementary soil conservation practices. The findings contribute to developing sustainable rice cultivation practices and underscore the potential of integrating green manure with remote sensing technologies to enhance soil health, crop productivity, and environmental sustainability in Thai rice farming systems.

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1 Introduction

Agriculture faces the dual challenge of meeting the world's growing food demands while minimizing environmental impact, particularly in countries such as Thailand, where rice cultivation plays a central role in the economy and culture. The use of green manures, such as *Canavalia*

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ensiformis (Jack bean [*C. ensiformis*]), has emerged as a sustainable agricultural practice with numerous environmental benefits. *Canavalia ensiformis* is known for its ability to fix atmospheric nitrogen, enrich soil fertility and improve soil structure. These are critical factors in rice farming for maintaining crop yield and overall productivity.[1] Previous studies have investigated the use of green manures in rice cultivation and their impact on soil properties and crop performance. For example, Pame et al.[2] explored the use of biofertilizers in combination with best management practices. They found that the application of plant growth led to increased nitrogen-use efficiency (57% higher than farmer practices) in rice cultivation. Moreover, Valizadeh et al.[3] used an integrated and extended version of the theory of planned behavior to predict and encourage the adoption of green manure technology in Iran. Their findings revealed that moral norms, attitudes, perceived behavioral control, and trialability of green manure have significant positive effects on farmers' intentions to use green manure. These insights provide valuable guidance for policy-makers, planners, and practitioners in developing strategies to encourage the adoption of green manure technology.

Remote sensing technology has been increasingly applied to monitor agricultural practices and environmental changes in rice cultivation.[4,5] Satellite data enables the observation and analysis of land use changes, soil conditions, and crop health over extensive areas, providing valuable insights for informed decision-making.[6,7]

Remote sensing indices have emerged as powerful tools for assessing vegetation and soil properties in agricultural settings. These indices, derived from mathematical combinations of spectral reflectance values across different wavelength bands, are designed to highlight specific features while minimizing the influence of confounding factors such as atmospheric conditions or background noise.[8] In the context of soil and crop analysis, these indices offer valuable insights into critical properties such as soil organic matter (OM), nutrient content, and crop characteristics.

The estimation of soil OM using remote sensing has been a focus of numerous studies. For instance, Gholizadeh et al.[9] demonstrated the potential of using Sentinel-2 data to estimate soil organic carbon, a key component of OM. They utilized 11 wavebands to compute 18 different indices, developing predictive models that showed satisfactory results compared with laboratory observations. Estimation of soil nutrients, including nitrogen, phosphorus, and potassium, using remote sensing remains challenging but promising. While direct estimation of these nutrients from spectral data is complex, indirect methods have shown potential. For instance, vegetation indices (VIs) sensitive to plant chlorophyll content, such as the modified chlorophyll absorption ratio index, can provide insights into plant nitrogen status, which is related to soil nitrogen availability.[10] However, accurate estimation of soil nitrogen, phosphorus, and potassium often requires the integration of spectral data with field measurements and other environmental factors. Moreover, in phosphorus (P) and potassium (K) estimation, researchers have explored the use of multiple spectral bands and indices. While direct estimation of these nutrients remains challenging, studies have shown correlations between certain VIs and P and K content. For example, Kaur et al.[11] used various machine learning techniques to predict soil nutrient contents, including P and K, in the western region of India.

Crop yield estimation using remote sensing has been achieved through various VIs. Hatfield and Prueger[12] found that different VIs were effective for quantifying crop characteristics at various growth stages, which can be indicative of potential yield. For instance, they noted that the normalized difference vegetation index (NDVI) showed a strong positive correlation with crop yield ($r = 0.885$), demonstrating its potential as a yield predictor. In addition, Gitelson et al.[13,14] developed and applied chlorophyll-related indices, such as the green chlorophyll index (Chl Green550) and the red-edge chlorophyll index (Chl RedEdge700), which showed strong relationships with crop biophysical parameters closely linked to yield potential. These studies highlight the value of VIs in providing non-destructive, large-scale estimates of crop yield throughout the growing season. Furthermore, crop height estimation has been explored using various remote sensing techniques, including the use of VIs and more advanced methods such as LiDAR. While specific indices for height estimation are less common, the relationship between crop vigor (as indicated by indices such as NDVI) and crop height has been utilized in some studies.[15]

The application of these remote sensing techniques in agriculture continues to evolve, offering increasingly accurate and comprehensive assessments of soil and crop conditions. As technology advances, these methods promise to play a crucial role in precision agriculture and sustainable land management practices. In particular, the use of PlanetScope satellite data has emerged as a promising approach for monitoring the environmental benefits of green manure application in rice cultivation. PlanetScope satellites offer high-resolution, frequent revisit times, and a broad spatial coverage.[16] However, there is limited research on the specific application of high-resolution satellite data. By integrating PlanetScope satellite data with field-level observations, researchers can gain a comprehensive understanding of the environmental and agronomic implications of adopting *C. ensiformis* as green manure in Thai rice production systems.

This study aims to address this gap by utilizing PlanetScope satellite data to derive VIs and monitor the temporal changes in soil properties and crop performance in response to *C. ensiformis* green manure application in Thai rice plots. The high spatial resolution and frequent revisit time of PlanetScope data provide a unique opportunity to capture the dynamic impacts of green manure on rice cultivation. The specific objectives of this study are to (1) assess the changes in key soil properties, such as OM, nitrogen, phosphorus, and potassium, including rice yield in response to *C. ensiformis* green manure application; (2) evaluate the temporal variations in VIs derived from PlanetScope data and their relationship with field-measured parameters; and (3) discuss the potential and limitations of using PlanetScope data for monitoring the environmental benefits of green manure in rice cultivation.

The findings of this study are expected to contribute to the development of sustainable rice cultivation practices that enhance soil health and crop productivity while minimizing environmental impacts. By leveraging the capabilities of high-resolution satellite data, this research aims to provide valuable insights into the effective monitoring and management of green manure application in Thai rice farming systems, ultimately supporting the transition toward more sustainable and resilient agricultural practices.

2 Materials and Methods

2.1 Study Area and Experimental Plot

The rice experimental plot is located in Tan Sum (15.36401876, 105.09333070), Ubon Ratchathani Province, a region in northeastern Thailand known for its agrarian economy (Fig. 1). The area experiences a tropical savanna climate, with a distinct dry season and a wet season, aligning with the monsoon rains typical of Southeast Asia. Geologically, the area is characterized by its fertile loamy soils, which are well-suited for agriculture, particularly rice cultivation, the main crop in this region.[17]

The experimental plot was designed to compare the effect of *C. ensiformis* green manure on main plant nutrients (N, P, and K), OM, and rice yield. The study was conducted from March 2021 to October 2023. The experiment was set up as a factorial in a completely randomized design with two treatments: soil with green manure (*C. ensiformis*) (WG) and soil without green manure (WOG). The plot sizes were 703.12 and 837.54 m^2 for WG and WOG, respectively.

Seeds of *C. ensiformis* (Jack bean) were obtained from the Ubon Ratchathani Land Development Station, Thailand. The green manure was incorporated into the soil in the WG plot, whereas the WOG plot served as a control. All other agricultural practices, such as irrigation, pest management, and fertilization, were kept consistent between the two plots to ensure that the observed differences could be attributed to the presence or absence of green manure. The rice variety used in both plots was *Oryza sativa* L., cultivar (RD 10), a popular high-yielding variety in the region.

The experimental design allowed for a comprehensive assessment of the impact of *C. ensiformis* green manure on soil properties and rice productivity over multiple growing seasons. By comparing the WG and WOG plots, the study aimed to provide valuable insights into the potential benefits of incorporating green manure into rice cultivation practices in the region.

2.2 Data Collection

2.2.1 *Field measurements*

Field measurements were conducted to assess the impact of *C. ensiformis* green manure on soil properties and rice growth parameters. Samples were collected before and after planting Jack beans (March to early June period) and rice (July to October).

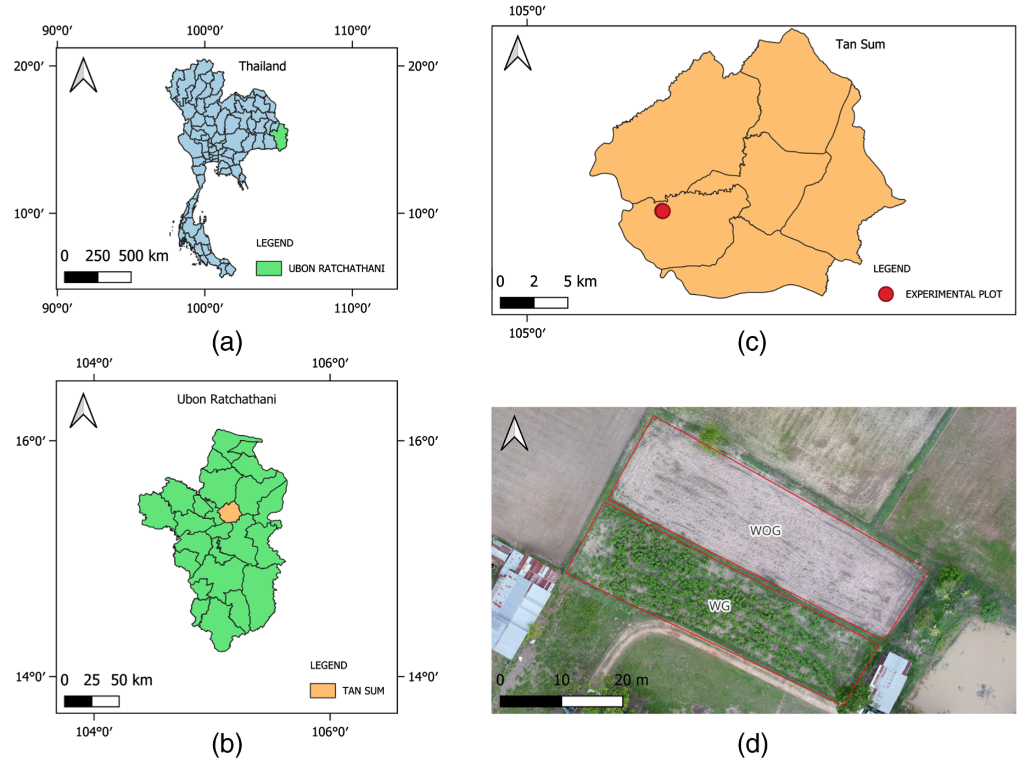

Fig. 1 Location of the rice experimental plot in Tan Sum, Ubon Ratchathani Province, Thailand. The study area is situated in the northeastern region of the country, known for its fertile loamy soils and agrarian economy. The experimental plot was designed to compare the effects of *C. ensiformis* green manure on soil properties, rice growth, and yield between March 2021 and October 2023. The plot was divided into two treatments: WG and WOG, to assess the impact of green manure application on the rice cropping system. (a) Map of Thailand highlighting Ubon Ratchathani Province. (b) Ubon Ratchathani Province with Tan Sum district highlighted. (c) Map of Tan Sum showing the experimental plot location. (d) Aerial view of the plot with WG and WOG treatments.

Soil samples were collected from both WG and WOG plots at depths of 0 to 100 cm using a soil auger. The samples were analyzed for various soil properties, including (1) soil moisture content—measured using a PR2 soil moisture probe at depths of 10, 20, 30, 40, 60, and 100 cm, and (2) chemical properties—OM (%), total nitrogen (N, %), available phosphorus (Avai.P, mg/kg), and available potassium (Avai.K, mg/kg), as shown in Fig. 2.

Rice growth and yield parameters were measured at different growth stages, including (1) plant height (cm), measured using a measuring tape from the base of the plant to the tip of the highest leaf; (2) chlorophyll content: measured using a SPAD meter, which estimates the

Fig. 2 (a) Transplanted part of the *C. ensiformis* in the rice field. (b) Staked out 0.36 sqm measurement quadrant grid of rice field. (c) Soil moisture is measured at depths of 0–100 cm from the surface using a PR2 soil moisture probe.

relative amount of chlorophyll present in the leaves; and (3) yield (kg/ha), determined by harvesting the rice from a designated area within each plot, drying, and weighing the grains.

2.2.2 *Satellite data: PlanetScope SuperDove instrument*

This study utilized the PlanetScope SuperDove (PSB.SD) instrument, a part of Planet Labs' Dove satellite constellation, for remote sensing of the study area between March 2020 and November 2023. The PlanetScope constellation consists of ∼120 satellites, each in a 3U CubeSat form factor ($10 \times 10 \times 30$ cm).[18]

The PSB.SD instrument is known for its high-resolution capabilities, providing a spatial resolution of ∼3 m. The high resolution allows for precise measurement and analysis of experimental results, making PlanetScope an appropriate choice for our studies conducted on small agricultural plots. Each satellite is equipped with a telescope and a frame CCD camera with a Bayer-mask filter, enabling the capture of data across multiple spectral bands.[19] These bands include coastal blue, 431 to 452 nm; blue, 465 to 515 nm; green I, 513 to 549 nm; green II, 547 to 583 nm; yellow, 600 to 620 nm; red, 650 to 680 nm; red-edge, 697 to 713 nm; and NIR, 845 to 885 nm.[20] The diverse spectral bands offered by the PSB.SD instruments are particularly valuable for detailed agricultural monitoring, as they allow for the analysis of various vegetation properties and health indicators.[21] The PlanetScope constellation's daily revisit rate is another key advantage, providing an unprecedented opportunity to observe and analyze short-term changes in land use and vegetation dynamics.[19]

In this study, the high spatial resolution and multi-spectral capabilities of the PlanetScope PSB.SD instruments were leveraged to derive various VIs and monitor the environmental changes in the rice plots with and without *C. ensiformis* green manure. The frequent temporal coverage allowed for the assessment of the dynamic impacts of green manure application on soil properties and crop performance throughout the study period.

2.3 Vegetation Indices in Environmental Monitoring

VIs derived from remote sensing data are essential tools for monitoring environmental changes in agricultural systems, such as rice cultivation. These indices provide valuable information about vegetation health, growth, and productivity by analyzing the spectral reflectance properties of the canopy.[7] In this study, we utilized 14 VIs derived from PlanetScope satellite data to assess the impact of *C. ensiformis* green manure on rice growth and development (Table 1).

The selected VIs can be categorized into seven main groups based on their focus and the spectral bands used in their calculation.

1. *General vegetation vigor and health indices*. The NDVI and the red-edge normalized difference vegetation index (RENDVI) are widely used to assess overall vegetation vigor and health. These indices provide information about the green biomass and photosynthetic activity of the canopy.
2. *Chlorophyll content estimation indices*. The green chlorophyll index (Chl Green550) and the red-edge chlorophyll index (Chl RedEdge700) are designed to estimate leaf chlorophyll content, which is an indicator of plant nutrient status and photosynthetic capacity.[23]
3. *Pigment indices*. The carotenoid reflectance indices (CRI Green550 and CRI RedEdge700) and the anthocyanin reflectance index (ARI) are used to estimate the presence of accessory pigments, such as carotenoids and anthocyanins, which can be indicative of plant stress or senescence.[23]
4. *Moisture content index*. The normalized difference water index (NDWI) is sensitive to changes in plant water content and can be used to monitor plant water status and soil moisture dynamics.[24]
5. *Soil adjusted index*. The modified soil-adjusted vegetation index 2 (MSAVI2) is designed to minimize the influence of soil background on vegetation signal, improving the accuracy of vegetation cover and biomass estimates in partially vegetated areas.[25]
6. *Visible range indices*. The visible atmospherically resistant index (VARI), the triangular greenness index (TGI), and the modified triangular vegetation index 2 (MTVI2) are

Table 1 Summary of the fourteen VIs used in this analysis.

Index	Description	Formula	Source
NDVI	Measures vegetation vigor by comparing red and near-infrared reflectance	$\frac{(\text{NIR}-\text{Red})}{(\text{NIR}+\text{Red})}$	Ref. 22
Chl Green550	Estimates chlorophyll content using green band reflectance	$\left(\frac{\text{NIR}}{\text{GreenII}}\right)-1$	Ref. 23
Chl rededge700	Chlorophyll estimation using red-edge band reflectance	$\left(\frac{\text{NIR}}{\text{Red}-\text{edge}}\right)-1$	Ref. 23
CRI green550	Carotenoid reflectance index using green band	$\left(\frac{1}{\text{GreenI}}-\frac{1}{\text{GreenII}}\right)*\text{NIR}$	Ref. 23
CRI rededge700	Carotenoid index using red-edge reflectance	$\left(\frac{1}{\text{GreenI}}-\frac{1}{\text{Red}-\text{edge}}\right)*\text{NI}$	Ref. 23
ARI	Anthocyanin reflectance index	$\left(\frac{1}{\text{GreenI}}-\frac{1}{\text{Red}-\text{edge}}\right)*\text{NIR}$	Ref. 23
NDWI	Normalized difference water index, indicates moisture	$\frac{(\text{GreenII}-\text{NIR})}{(\text{GreenII}+\text{NIR})}$	Ref. 24
MSAVI2	Modified soil-adjusted vegetation index, minimizes soil background influence	$\frac{\left(2*\text{NIR}+1\sqrt{(2*\text{NIR}+1)^2-8*(\text{NIR}-\text{Red})}\right)}{2}$	Ref. 25
VARI	Visible atmospherically resistant index, for green vegetation from RGB data	$\frac{(\text{GreenII}-\text{Red})}{(\text{GreenII}+\text{Red}-\text{Blue})}$	Ref. 26
TGI	Triangular greenness index, indicates plant greenness	$\text{GreenII}-(0.39*\text{Red})-(0.61*\text{Blue})$	Ref. 27
MTVI2	Modified triangular vegetation index, for enhanced vegetation monitoring	$\frac{1.5\times(1.2\times(\text{NIR}-\text{GreenII})-2.5\times(\text{Red}-\text{Green}))}{\sqrt{(2\times\text{NIR}+1)^2-\left(6\times\text{NIR}-5\times\sqrt{\text{Red}}\right)-0.5}}$	Ref. 28
RENDVI	Red-edge normalized difference vegetation index	$\frac{(\text{NIR}-\text{Red}-\text{edge})}{(\text{NIR}+\text{Red}-\text{edge})}$	Ref. 29
YNDVI	Yellow normalized difference vegetation index	$\frac{(\text{NIR}-\text{Yellow})}{(\text{NIR}+\text{Yellow})}$	Ref. 30
GNDVI	Green normalized difference vegetation index	$\frac{(\text{NIR}-\text{GreenII})}{(\text{NIR}+\text{GreenII})}$	Ref. 31

enhanced vegetation indices that incorporate the reflectance in the green, red, and near-infrared bands to improve the sensitivity to vegetation characteristics, focus on the visible portion of the electromagnetic spectrum to assess green vegetation and plant greenness, respectively.[26]

7. *Other normalized difference indices*. The yellow normalized difference vegetation index (YNDVI) and the green normalized difference vegetation index (GNDVI) use specific color bands (yellow and green, respectively) in combination with the near-infrared band to assess vegetation properties.

Using these diverse indices, the study can capture various aspects of the plant-soil system response to green manure application. The general vegetation vigor and health indices (NDVI and RENDVI) can help monitor changes in vegetation cover and biomass, whereas the chlorophyll content estimation indices (Chl Green550 and Chl RedEdge700) can provide insights into the nitrogen status of the rice plants. The carotenoid and anthocyanin content estimation indices (CRI Green550, CRI RedEdge700, and ARI) can help assess plant stress and senescence, and the moisture content index (NDWI) can be used to monitor plant water status and soil moisture dynamics.

The soil-adjusted index (MSAVI2) is particularly useful in the early stages of crop growth when the canopy is not fully developed, as it minimizes the influence of soil background on the vegetation signal. The visible range indices (VARI, TGI, and MTVI2) can provide complementary information about the overall greenness and physiological characteristics of the rice crop.

In summary, the selected VIs offer a comprehensive approach to monitoring the environmental changes induced by *C. ensiformis* green manure application in rice cultivation. By leveraging the strengths of different index groups, this study aims to provide a holistic understanding of the impact of green manure on plant health, growth, and productivity, as well as its influence on soil properties and moisture dynamics.

2.4 Correlation Analysis

To gain a deeper understanding of the relationships between remote sensing data, field measurements, soil properties, and rice yield, a comprehensive correlation analysis was conducted using a large dataset spanning 3 years. This analysis aimed to explore the potential of using remote sensing indices as a tool for monitoring soil health and predicting crop productivity in the context of sustainable rice cultivation with *C. ensiformis* green manure.

To perform the correlation analysis, the underlying values of the 14 indices were extracted for each field sampling point, ensuring a direct correspondence between the remote sensing data and the field measurements. The field data included soil properties, such as OM content, nutrient availability, and moisture levels, as well as rice growth parameters and yield.

The Spearman correlation coefficient (r) was chosen as the measure of association between the remote sensing indices and the field data.[32] The large dataset spanning 3 years added robustness to the correlation analysis, capturing the temporal variability in the relationships between remote sensing indices and field measurements. This multi-year approach ensured that the observed correlations were not merely a result of short-term fluctuations but rather reflected the underlying ecological processes and the long-term impact of green manure application on soil health and rice productivity.

3 Results

3.1 Impact of *C. ensiformis* on Soil Properties

The incorporation of *C. ensiformis* as a green manure (WG) had a significant impact on key soil properties compared with the control plots WOG. The study assessed changes in soil OM, total nitrogen, available phosphorus, and available potassium over 3 years (2021 to 2023) to evaluate the effectiveness of green manure application in improving soil fertility.

Soil OM [Fig. 3(a)] and total nitrogen [Fig. 3(b)] content showed similar trends, with higher values in the WG plots compared to the pre-planting levels in years 1 (2021) and 2 (2022). However, a decrease was observed in year 3 (2023), suggesting that the benefits of green manure may diminish over time without continued application. Interestingly, the WOG plots also exhibited increased OM and nitrogen levels compared with the pre-planting soil, albeit to a lesser extent than the WG plots.

Available phosphorus [Fig. 3(c)] and potassium [Fig. 3(d)] levels followed a similar pattern, with the WG plots showing higher values than the pre-planting soil in years 1 and 2. The exceptionally high phosphorus content in year 2 (2022) could be attributed to farmers' fertilizer management practices. As with OM and nitrogen, a decrease in phosphorus and potassium was observed in year 3.

These results demonstrate that the application of *C. ensiformis* green manure can lead to short-term improvements in soil fertility, as evidenced by the increased levels of OM, nitrogen, phosphorus, and potassium in the WG plots during the first 2 years of the study. The enhanced soil nutrient status can be attributed to the ability of *C. ensiformis* to fix atmospheric nitrogen and its contribution to soil OM through biomass decomposition.[1,33]

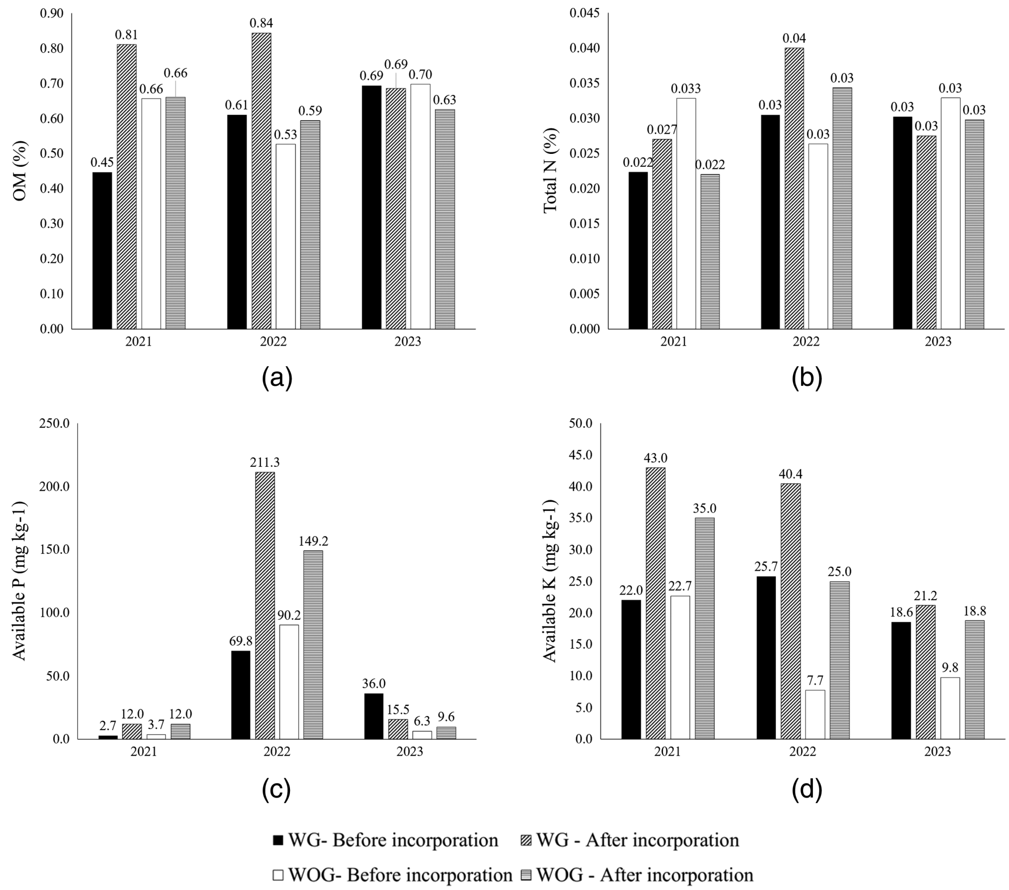

Fig. 3 Changes in key soil properties in the experimental plots during 2021 to 2023. (a) Soil OM (%), (b) total nitrogen (%), (c) available phosphorus (mg/kg), and (d) available potassium (mg/kg) were measured in the green manure-amended plots (WG) and control plots WOG before and after incorporation.

However, the decline in soil properties observed in year 3 suggests that the benefits of green manure may not be sustained over longer periods without regular application. This finding highlights the need for a more comprehensive soil management strategy that includes the continuous incorporation of green manure alongside other sustainable agricultural practices.[34]

Furthermore, the variations in soil properties observed in the WOG plots underscore the importance of considering the broader context of soil management in the region. Factors such as farmers' fertilizer use and other agricultural practices may influence soil fertility, even in the absence of green manure application.[3]

In summary, the results demonstrate the potential of *C. ensiformis* green manure to enhance soil fertility in the short term. However, the long-term sustainability of these benefits requires further investigation and the development of integrated soil management strategies that address the complex interplay of green manure application, farmers' practices, and regional soil dynamics.

3.2 Temporal Dynamics of Vegetation Indices Derived from PlanetScope Data

The temporal variations of the 14 VIs derived from PlanetScope satellite data were analyzed to assess the impact of *C. ensiformis* green manure on rice growth and development. The results are presented according to the seven main groups of indices identified in the previous section, with reference to Figs. 4 and 5.

1. *General vegetation vigor and health indices*. The NDVI and RENDVI consistently showed higher values in the green manure-amended plots (WG) compared with the control plots (WOG) during the early vegetative stage [Figs. 4(a) and 5(d)]. NDVI values in WG

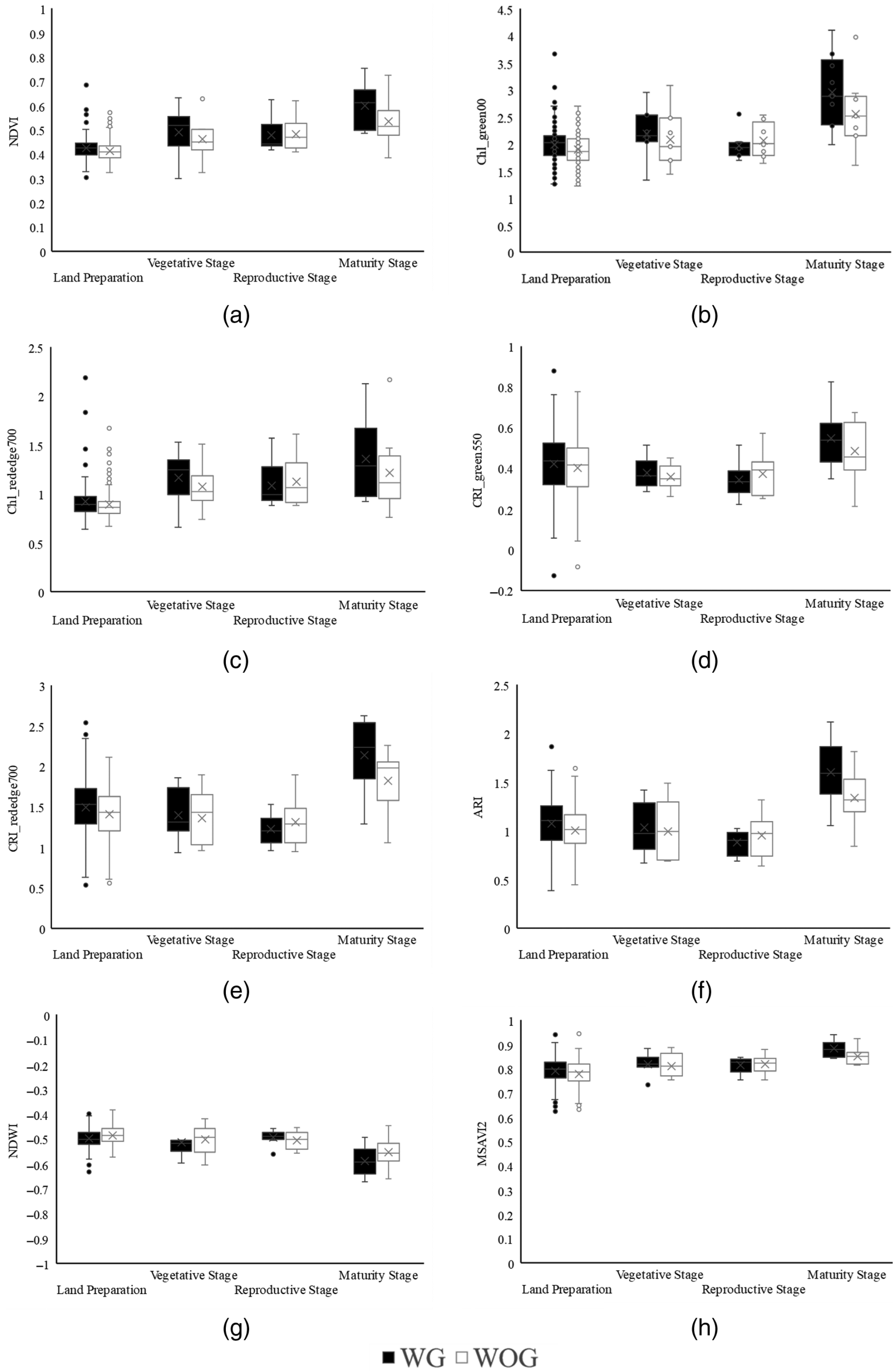

Fig. 4 VIs at the vegetative stage of rice with *C. ensiformis* green manure (WG) and soil WOG. These VIs included NDVI (a), Chl Green550 (b), Chl redrededge700 (c), CRI green550 (d), CRI rededge700 (e), ARI (f), NDWI (g), and MSAVI2 (h).

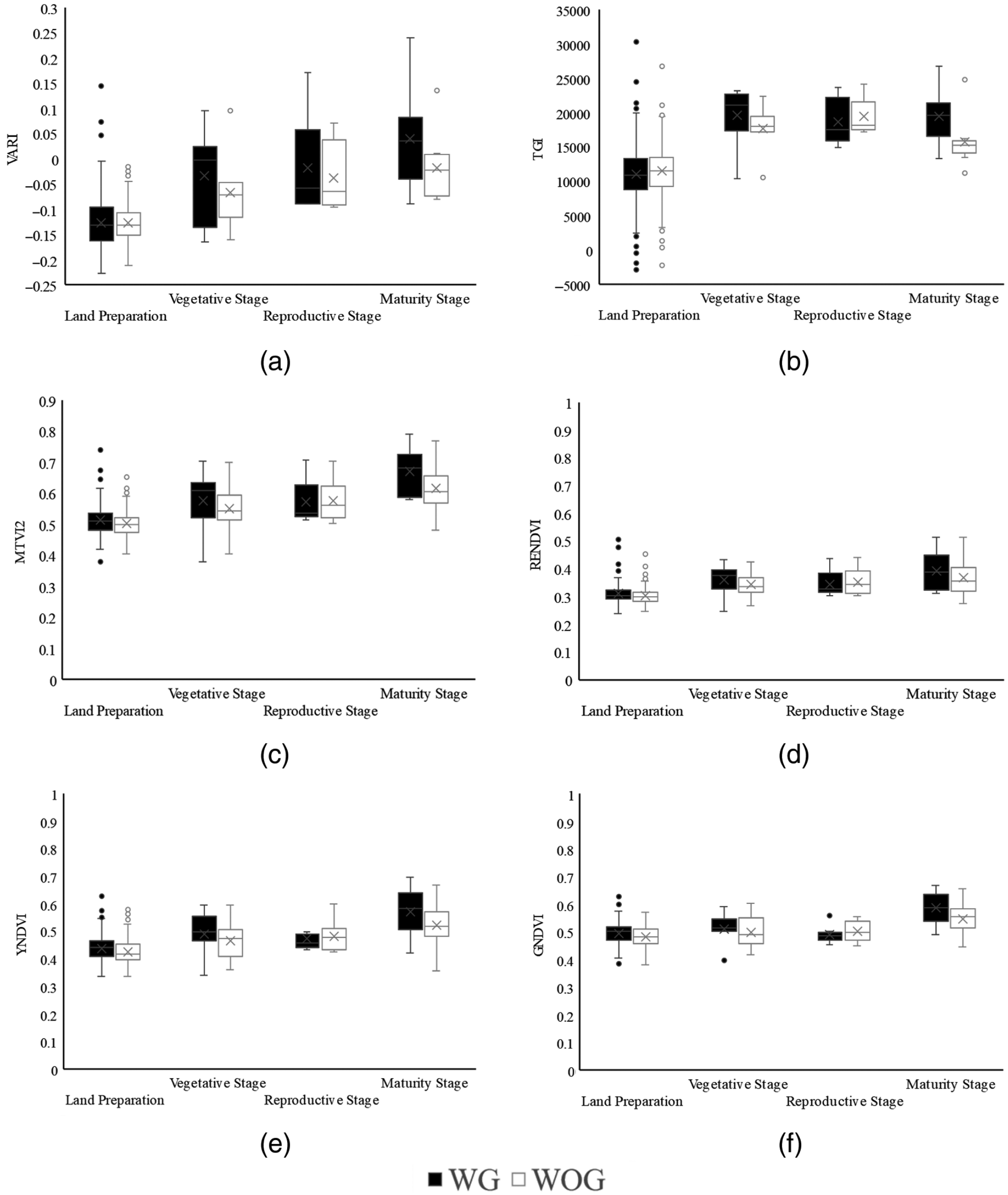

Fig. 5 VIs at the vegetative stage of rice with *C. ensiformis* green manure (WG) and soil without green manure (WOG). These VIs included VARI (a), TGI (b), MTVI2 (c), RENDVI (d), YNDVI (e), and GNDVI (f).

plots were noticeably higher than in WOG plots, particularly in the first 40 days after planting, whereas RENDVI showed a similar trend with a more pronounced difference throughout the vegetative stage.

2. *Chlorophyll content estimation indices.* The green chlorophyll index (Chl Green550) and red-edge chlorophyll index (Chl RedEdge700) exhibited consistently higher values in the WG plots throughout the vegetative stage [Figs. 4(b) and 4(c)]. This pattern suggests improved leaf chlorophyll content and, by extension, better plant nutrient status in the green manure-amended plots.
3. *Pigment indices*. Interestingly, the carotenoid reflectance indices (CRI Green550 and CRI RedEdge700) and the ARI showed lower values in the WG plots compared with the WOG plots [Figs. 4(d)–4(f)]. This trend was particularly evident in the later stages of the vegetative period, indicating potentially reduced plant stress and delayed senescence in the green manure-amended plots.

4. *Moisture content index*. The NDWI values were higher in the WG plots during the early vegetative stage [Fig. 4(g)], suggesting improved plant water content and soil moisture availability. However, this difference diminished as the growing season progressed, with values converging around day 60.
5. *Soil-adjusted index*. The MSAVI2 showed higher values in the WG plots compared with the WOG plots, particularly during the early growth stages [Fig. 4(h)]. This indicates better vegetation cover and reduced soil background influence in the green manure-amended plots.
6. *Visible range indices*. The VARI demonstrated consistently higher values in the WG plots throughout the vegetative stage [Fig. 5(a)]. The TGI and MTVI2 showed similar trends [Figs. 5(b) and 5(c)], further supporting enhanced green vegetation and plant greenness in the green manure-amended plots.
7. *Other normalized difference indices*. The YNDVI and GNDVI both showed higher values in the WG plots [Figs. 5(e) and 5(f)], indicating improved overall vegetation properties in the green manure-amended plots. The difference was particularly pronounced in the early stages of growth.

In summary, the temporal analysis of VIs derived from PlanetScope data, as illustrated in Figs. 4 and 5, consistently demonstrated enhanced vegetation vigor, improved chlorophyll content, reduced plant stress, and better water status in the green manure-amended plots compared to the control plots. These results provide strong evidence for the positive impact of *C. ensiformis* green manure on rice growth and development, particularly during the early vegetative stage. However, it is noteworthy that for most indices, the differences between WG and WOG plots tended to diminish as the growing season progressed, suggesting that the benefits of green manure application may be most pronounced in the early stages of rice growth.

3.3 Correlation Between Field Measurements and Vegetation Indices

To assess the relationships between the VIs derived from PlanetScope satellite data and field-measured parameters, a correlation analysis was conducted using Pearson's correlation coefficient (r). The results provide insights into the effectiveness of the VIs in capturing the variations in soil properties and rice growth characteristics as shown in Table 2.

Among soil properties, soil moisture showed the most consistent and strong correlations with VIs. Strong positive correlations were observed between soil moisture at various depths (30 to 100 cm) and most VIs. VARI demonstrated the strongest correlations with soil moisture across all depths ($r = 0.621$ to 0.935, $p < 0.01$), indicating its potential as a reliable indicator of soil water content. NDVI, Chl Green550, and Chl RedEdge700 also exhibited strong positive correlations with soil moisture, particularly at 30 cm depth ($r = 0.846$, 0.788, and 0.774, respectively, $p < 0.01$). Interestingly, NDWI showed a negative correlation with soil moisture, which was significant at 100 cm depth ($r = -0.683$, $p < 0.01$), suggesting a complex relationship between this index and deeper soil moisture.

Regarding soil nutrients, available phosphorus (P) showed strong positive correlations with YNDVI ($r = 0.812$, $p < 0.05$) and moderate positive correlations with several other indices including NDVI, Chl Green550, and Chl RedEdge700 ($r = 0.68$ to 0.692). This suggests that these indices, particularly YNDVI, may be useful for assessing soil phosphorus status. Available potassium (K) and OM showed weak to moderate positive correlations with most indices, but these correlations were not statistically significant. Total nitrogen (N) showed weak correlations with most indices, with the exception of a strong negative correlation with NDWI ($r = -0.749$, not statistically significant).

For rice growth parameters, plant height showed the strongest positive correlation with CRI Green550 ($r = 0.878$, not statistically significant), whereas other indices showed weak to moderate correlations. Measured chlorophyll content correlated most strongly with Chl Green550 ($r = 0.642$, not statistically significant), followed by moderate positive correlations with ARI and Chl RedEdge700 ($r = 0.586$ and 0.514, respectively). These relationships suggest the potential of these indices for non-destructive estimation of plant chlorophyll content.

Rice yield demonstrated the strongest positive correlation with NDVI ($r = 0.885$, not statistically significant), highlighting the potential of this widely used index for yield estimation.

Table 2 Pearson's correlation analysis between field measurements and VIs.

Parameters	NDVI	Chl green550	Chl rededge700	CRI green550	CRI rededge700	ARI	NDWI	MSAVI2	VARI	TGI	MTVI2	RENDVI	YNDVI	GNDVI
Soil nutrients														
OM (%)	0.284	0.225	0.158	−0.105	0.06	0.058	−0.313	−0.008	0.172	0.408	0.183	0.152	0.361	0.261
Total N (%)	0.134	0.173	0.336	−0.084	0.047	0.043	−0.749	−0.312	−0.374	−0.419	0.146	0.292	0.362	0.168
Avai.P (mg/kg)	0.68	0.683	0.692	−0.049	0.436	0.507	−0.829*	0.025	0.04	−0.087	0.669	0.646	0.812*	0.682
Avai.K (mg/kg)	0.603	0.592	0.48	−0.434	0.175	0.348	−0.474	0.421	0.228	0.315	0.493	0.485	0.67	0.619
Soil moisture (VMC, m^3/m^3)														
10 cm	−0.961	−0.963	−0.997*	−0.999*	−0.863	−0.162	−0.394	−0.86	−0.695	−0.996	−0.929	−0.998*	−0.97	−0.945
20 cm	0.752	0.672	0.622	−0.348	0.64	0.752	−0.738	0.398	0.943*	−0.319	0.817	0.709	0.757	0.72
30 cm	0.846**	0.788**	0.774**	−0.003	0.612**	0.735**	−0.505*	0.621**	0.935**	0.607**	0.836**	0.804**	0.797**	0.781**
40 cm	0.712**	0.609**	0.615**	0.045	0.43	0.549*	−0.328	0.480*	0.878**	0.654**	0.717**	0.651**	0.637**	0.613**
60 cm	0.735**	0.626**	0.573*	−0.058	0.522*	0.667**	−0.45	0.565*	0.846**	0.494*	0.744**	0.643**	0.668**	0.664**
100 cm	0.774**	0.608**	0.521*	−0.103	0.530*	0.675**	−0.683**	0.571*	0.621**	0.307	0.764**	0.628**	0.684**	0.687**
Rice														
Hight (cm)	0.485	0.01	0.206	0.878	0.071	−0.054	−0.481	−0.302	0.528	0.48	0.55	0.257	0.355	−0.003
Chlorophyll (SPAD)	0.207	0.642	0.514	−0.31	0.541	0.586	−0.329	0.805	−0.066	0.261	0.107	0.442	0.313	0.606
Yield (kg/ha)	0.885	−0.857	−0.996	−0.561	−0.721	−0.305	−0.984	−0.722	−0.684	−0.828	−0.826	−0.982	−0.892	−0.824

*The correlation coefficient for each parameter with a significant difference at *p*-value 0.05.
**The correlation coefficient for each parameter with a significant difference at *p*-value 0.01 level.

Conversely, Chl RedEdge700 and NDWI showed strong negative correlations with yield ($r = -0.996$ and -0.984, respectively, not statistically significant), a finding that warrants further investigation.

It is important to note that while many correlations were strong, not all were statistically significant, possibly due to the limited sample size. The results highlight the potential of VIs, particularly VARI, NDVI, and chlorophyll-related indices, in estimating soil moisture content across various depths and assessing other soil and plant parameters.

4 Discussion

4.1 Impact of *C. ensiformis* Green Manure on Soil Properties and Rice Growth

The incorporation of *C. ensiformis* as a green manure (WG) demonstrated significant benefits for soil fertility and rice growth compared with the control plots WOG. The study showed that WG plots had higher levels of soil OM, nitrogen, phosphorus, and potassium during the first 2 years, indicating the potential of green manure to improve soil health in the short term. These findings align with previous research on the use of legume-based green manures in rice systems.[3,35]

The enhanced soil nutrient status in WG plots can be attributed to the ability of *C. ensiformis* to fix atmospheric nitrogen and its contribution to soil OM through biomass decomposition.[1] Improved soil fertility, in turn, supports better rice growth and development, as evidenced by the higher values of VIs in the WG plots during the early vegetative stage.

However, the study also revealed that the benefits of green manure diminished over time, with a decline in soil properties observed in the third year. This finding emphasizes the need for regular green manure application and complementary soil conservation practices to maintain the long-term improvement of soil health in rice cultivation systems.

4.2 Effectiveness of Vegetation Indices in Monitoring Green Manure Effects

The use of VIs derived from PlanetScope satellite data proved effective in monitoring the environmental changes induced by *C. ensiformis* green manure application. The analysis of these indices allowed for a non-destructive and spatially comprehensive assessment of soil and plant parameters throughout the growing season.

4.2.1 *Indices for soil property assessment*

Among the VIs, VARI showed the strongest correlations with soil moisture across all depths ($r = 0.621$ to 0.935, $p < 0.01$), making it the most reliable indicator for soil water content. NDVI, Chl Green550, and Chl RedEdge700 also exhibited strong positive correlations with soil moisture, particularly at 30 cm depth ($r = 0.846$, 0.788, and 0.774, respectively, $p < 0.01$).

For soil nutrient assessment, YNDVI demonstrated the strongest correlation with available phosphorus ($r = 0.812$, $p < 0.05$), suggesting its potential use in monitoring soil phosphorus status. NDVI, Chl Green550, and Chl RedEdge700 also showed moderate positive correlations with available phosphorus ($r = 0.68$ to 0.692).

4.2.2 *Indices for rice growth and yield assessment*

In terms of rice growth parameters, CRI Green550 (carotenoid reflectance index) showed the strongest correlation with plant height ($r = 0.878$, not statistically significant), whereas Chl Green550 exhibited the strongest correlation with measured chlorophyll content ($r = 0.642$, not statistically significant).

For yield estimation, NDVI demonstrated the strongest positive correlation ($r = 0.885$, not statistically significant), highlighting its potential as a yield predictor. Conversely, Chl RedEdge700 and NDWI showed strong negative correlations with yield ($r = -0.996$ and -0.984, respectively, not statistically significant), a finding that warrants further investigation.

4.3 Implications and Future Directions

The findings of this study have important implications for the development of sustainable rice cultivation practices. The integration of *C. ensiformis* green manure with advanced remote sensing technologies offers a promising approach to enhance soil health, crop productivity, and environmental sustainability.

Future research should focus on long-term field experiments to assess the cumulative effects of green manure application on soil health and crop performance. Integration of multi-source remote sensing data, such as SAR and thermal imagery, could improve the monitoring of soil moisture dynamics and plant water status. The development of predictive models combining remote sensing data, field measurements, and machine learning techniques for yield estimation and resource management optimization is another promising avenue. In addition, socio-economic and policy research is crucial to identify barriers and incentives for the adoption of green manure and other sustainable agricultural practices by smallholder farmers.

By addressing these research gaps and promoting the integration of green manure applications with advanced remote sensing technologies, we can significantly enhance the sustainability and resilience of rice cultivation systems in Thailand and beyond.

5 Conclusion

This study demonstrates the potential of integrating *C. ensiformis* green manure with high-resolution remote sensing to enhance sustainable rice cultivation in Thailand. Our findings reveal the short-term benefits of green manure on soil fertility and rice growth while highlighting challenges in maintaining these benefits long-term. A key contribution is the successful use of PlanetScope satellite data to monitor small agricultural plots, demonstrating the applicability of remote sensing for precision agriculture in small-holder farming systems. This research represents one of the first comprehensive studies using satellite data to monitor various factors affecting *C. ensiformis* cultivation, establishing a novel, non-invasive approach to assess green manure impacts on rice production. The application of *C. ensiformis* resulted in measurable improvements in soil OM, nitrogen, phosphorus, and potassium levels during the initial years, translating to improved rice growth parameters. However, the decline in soil properties by the third year underscores the need for consistent green manure application and complementary soil conservation practices.

VIs derived from PlanetScope data showed strong correlations with soil moisture, nutrient status, and rice growth parameters, offering a non-destructive and spatially comprehensive approach to assessing the effects of sustainable agricultural practices. This research contributes to the growing body of evidence supporting the integration of sustainable agricultural practices with advanced monitoring technologies. By combining green manure application with remote sensing-based monitoring, farmers and agricultural managers can make more informed decisions about soil and crop management, potentially leading to improved yields and reduced environmental impacts.

Disclosures

No potential conflict of interest was reported by the authors.

Code and Data Availability

The data supporting this study's findings are available from the corresponding author upon reasonable request. PlanetScope images used in this research are accessible under a basic license from the Education and Research Program of Planet Labs Inc. via PlanetExplorer (https://www.planet.com/). Access to raw satellite imagery may be subject to Planet Labs Inc.'s terms of service and licensing agreements.

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