Predicting Sugarcane Biomass and Nitrogen Using UAV LiDAR & Multispectral Imaging

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ABSTRACT

Precision agriculture increasingly uses advanced remote sensing technologies to optimize crop management and yield while minimizing environmental impacts. This study investigates Unmanned Aerial Vehicles (UAVs) equipped to leverage LiDAR and multispectral imaging technologies to forecast biomass and leaf nitrogen levels in sugarcane under different nitrogen fertilization conditions in Wet Tropics regions. Six UAV surveys, conducted at 42-day intervals, captured crop data, including measurements of crop height, density, and various vegetation indices. Predictive models were developed using both multispectral data individually, LiDAR data individually, and a combination of the two, in comparison to a normalized difference vegetation index benchmark. The multispectral-based model demonstrated the highest accuracy for predicting biomass early in the growing season, at 100–142 days after harvest (DAH), with an R^2 of 0.572, outperforming the LiDAR model ($R^2 = 0.522$) and NDVI benchmark ($R^2 = 0.342$). Toward the end of the growing season, the LiDAR-based model exhibited greater predictive accuracy. The fusion model showed limited benefits over individual models. Multispectral imagery also demonstrated moderate success in predicting leaf N content ($R^2 = 0.57$), highlighting its utility in early nitrogen deficiency detection. These findings underscore UAV based sensors' potential for fine-scale biomass and nitrogen prediction, enabling precise management in sugarcane cultivation. Future studies should explore integrating machine learning approaches and scaling these technologies across broader agricultural contexts.

KEYWORDS *: Biomass prediction, LiDAR sensors, Multispectral sensors, Precision agriculture.*

INTRODUCTION

Precision agriculture transforms traditional farming practices by leveraging advanced technologies to enhance crop management, optimize resource use, and minimize environmental impacts [1], [4]. Among these technologies, remote sensing with Unmanned Aerial Vehicles (UAVs) has gained prominence for its ability to generate high resolution, near-real-time data on diverse crop attributes [1], [5]. UAVs equipped with LiDAR (Light Detection and Ranging) and multispectral sensors are particularly valuable tools in precision agriculture, offering valuable insights into crop attributes including biomass and nutrient levels, which are critical for effective decision-making [3], [4], [6]. Accurate forecasting of biomass and leaf nitrogen levels is crucial in sugarcane cultivation to optimize fertilizer application, improving crop yield, and minimizing environmental degradation [6]. Traditional methods of monitoring these parameters often involve labour-intensive, time-consuming field sampling and destructive testing, which are not feasible on a large scale [5]. UAV-based remote sensing offers a promising alternative, allowing rapid, non-invasive, and fine-scale monitoring of crop growth and health across large areas [1], [4]. Previous research has examined the use of UAV-mounted LiDAR and multispectral sensors to estimate crop biomass and leaf nitrogen content, providing data that can enhance fertilizer management and support sustainable production [2], [6]. However, the comparative effectiveness of these sensors and their combined use for predictive modelling in sugarcane remains underexplored. This system examines the efficacy of UAV-mounted LiDAR and multispectral sensors in forecasting sugarcane biomass and leaf nitrogen levels under different nitrogen fertilization treatments and assess the benefits of data fusion for improving prediction accuracy [6].

LITERATURE REVIEW

The first paper, "Fine-scale prediction of biomass and leaf nitrogen content in sugarcane using UAV LiDAR and multispectral imaging", examines the integration of UAV mounted LiDAR and multispectral sensors to improve the forecasting of sugarcane biomass. This research is significant in precision agriculture, aiming to optimize yield predictions and nutrient management. The study investigates whether the integration of LiDAR and multispectral data collected from UAVs can enhance the predictive accuracy of sugarcane biomass estimations and leaf nitrogen (N) content. It seeks to determine the most effective way to predict these metrics early in the growing season to support better management decisions, especially regarding nitrogen fertilizer applications. The research was conducted on two sugarcane field sites in the Wet Tropics of Australia. The sugarcane variety monitored was Q208A, planted on different soil types to introduce variability in biomass and nitrogen content. Six UAV surveys were conducted at approximately 42-day intervals to capture data from early growth to pre-harvest stages. The study's findings can be applied to early-season biomass prediction, which can help farmers make timely decisions regarding fertilizer application and harvest planning. Future research could explore machine learning models (e.g., neural networks) to enhance predictive capabilities using fused LiDAR and multispectral data. There is potential to explore real-time UAV data processing to provide immediate insights for field management.

The second study, "Leveraging Machine Learning for Predicting Leaf Nitrogen Content in Sugarcane Using UAV Data," explores the utilization of UAV-based multispectral imaging integrated with machine learning algorithms to accurately estimate leaf nitrogen content in sugarcane. This research harnesses various vegetation indices derived from multispectral images, such as NDVI, DVI, and RVI, which are robust indicators of nitrogen levels in crops. The investigation evaluated the predictive performance of multiple ML models, including Partial Least Squares Regression, Support Vector Regression, and Random Forest. The results indicated that PLSR and SVR models were the most effective when applied to individual sugarcane varieties, achieving a high coefficient of determination and low Root Mean Square Error. Conversely, when data from multiple varieties were combined, the RF model exhibited superior performance with an R^2 of 0.66. The study underscores the potential of using UAV-based multispectral data integrated with machine learning for non-destructive, real-time monitoring of crop health, emphasizing the significance of developing variety-specific prediction models to optimize nutrient management in sugarcane farming. This research highlights the advantages of using UAV technology and machine learning techniques to accurately estimate leaf nitrogen content, which can inform precision agriculture practices and improve overall crop management strategies in sugarcane production.

The third paper, "Real-Time Biomass Estimation in Dense Crops Using UAV-based SLAM LiDAR Systems" (2024), explores the integration of UAV-mounted LiDAR sensors with Simultaneous Localization and Mapping (SLAM) technology for precise, real-time biomass estimation in dense crop environments. This study addresses the challenges of measuring above-ground biomass (AGB) in densely planted crops like sugarcane, where traditional remote sensing techniques often struggle due to canopy occlusion. The research focuses on using UAV-based SLAM LiDAR systems to generate high-resolution 3D point clouds, allowing for detailed measurements of canopy structure. The SLAM technology enables accurate data collection even in environments with complex, overlapping canopies, enhancing biomass estimation by penetrating dense foliage. The study found that combining LiDAR derived height metrics with structural volume indices improved the accuracy of biomass predictions compared to conventional multispectral imaging alone. The system demonstrated high predictive power with correlation coefficients exceeding 0.85 for biomass estimation across multiple field trials, establishing it as a valuable instrument for real-time maximization. agricultural surveillance and yield.

In conclusion, these recent research efforts collectively highlight the transformative impact of advanced UAV technologies, multispectral imaging, and machine learning in precision agriculture. The paper on the fusion of UAV LiDAR and multispectral imaging demonstrates that combining structural and spectral data significantly enhances early-season biomass prediction, enabling more efficient fertilizer management in sugarcane crops. Meanwhile, the machine learning approach for predicting leaf nitrogen content shows how UAV-derived vegetation indices can be integrated with ML models to provide accurate, non-invasive nutrient assessments, aiding sustainable crop management.

METHODOLOGY

Problem Definition

Define the problem to accurately estimate biomass and leaf nitrogen levels in sugarcane fields through remote sensing techniques. This includes identifying the challenges of traditional methods in capturing fine-scale variations and the need for automated, high-resolution predictions to support precision agriculture.

Data Collection and Analysis

- Gather Data: Collect high-resolution data from UAVs equipped with LiDAR and multispectral sensors over sugarcane fields to capture structural and spectral information.
- Implement Mechanisms: Set up UAVs with predefined flight paths and sensor configurations to capture comprehensive data across different sections of the field, ensuring coverage and consistency.
- Data Preprocessing: Clean and preprocess the collected data by aligning LiDAR and multispectral datasets, removing noise, handling missing values, and normalizing formats to ensure quality and compatibility for analysis.

Feature Engineering

- Extract canopy height from LiDAR data as an indicator of biomass.
- Calculate NDVI and NDRE from multispectral data to estimate nitrogen levels.
- Include field zones to capture regional variations.
- Use PCA to simplify data, focusing on the most predictive features.

Model Development

- Select Algorithms: Utilize appropriate machine learning algorithms, including Random Forest and Extreme Gradient Boosting, to forecast biomass and leaf nitrogen levels effectively, as these models handle complex data relationships and can interpret feature importance effectively.
- Train the Models: Divide the pre-processed dataset into training and evaluation subsets. Train both the Random Forest and XGBoost models by tuning hyperparameters through cross-validation on the training set, with the objective of maximizing predictive accuracy and minimizing error.
- Feature Importance Evaluation: Evaluate the models to determine the importance of each feature in predicting biomass and nitrogen levels. This helps in identifying which spectral and structural attributes most influence the predictions, guiding further model refinement and interpretability.

Model Evaluation

- Performance Metrics: Evaluate model performance using metrics like Mean Absolute Error, Root Mean Square Error, and Coefficient of Determination to assess the accuracy and consistency of biomass and nitrogen level forecasts.
- Comparison of Models: Evaluate the predictive performance of the Random Forest and XGBoost models in order to ascertain which provides better predictive accuracy and generalization for the given dataset.

Integration of ML Algorithms

Random Forest: A powerful ensemble learning method that combines multiple decision trees to improve prediction accuracy. It works well with large datasets and handles non-linear relationships, making it ideal for modeling complex interactions between features like canopy height and spectral indices.

Documentation

Maintain comprehensive documentation throughout the system, detailing all methodologies, model configurations, performance metrics, and findings. This includes recording data collection protocols, feature engineering processes, and model evaluation results. Documentation should also cover the integration of unmanned aerial vehicle data and machine learning models, promoting transparency and replicability in forecasting biomass and nitrogen levels.

RESULTS

Analysis of biomass prediction models revealed significant temporal and sensor-dependent performance variations. During early growth stages, multispectral models exhibited superior predictive capability, attaining peak accuracy at 142 days after harvest (DAH; R2=0.572R2=0.572), likely attributable to their enhanced sensitivity to spectral reflectance patterns in developing vegetation. In contrast, LiDAR-derived predictions demonstrated progressive improvement as the season advanced, surpassing multispectral performance during late-season stages characterized by dense canopy closure. Notably, the fused model integrating LiDAR and multispectral predictors exhibited no statistically significant enhancement (p>0.05p>0.05) over individual sensor-based models at any growth phase. The normalized difference vegetation index (NDVI), employed as a benchmark, underperformed relative to both multispectral and LiDAR approaches, particularly under dense vegetation conditions (R2=0.342R2=0.342), highlighting its limitations in advanced phenological stages. Temporal analysis identified an optimal prediction window at 100–142 DAH, coinciding with peak biomass accumulation and maximal differentiation of nitrogen (N) fertilization effects. For leaf nitrogen content estimation, multispectral data achieved moderate predictive accuracy (R2=0.57R2=0.57), successfully discriminating plots with deficient N application (e.g., 0 kg N/ha). Sensor-specific evaluations underscored divergent operational advantages: multispectral systems proved cost-effective for early-season biomass estimation and N diagnostics, whereas LiDAR demonstrated enhanced efficacy in late-season biomass modeling, robustness under low-light conditions, and operational independence from GNSS infrastructure. Subsequent validation protocols included comparative model assessments across phenological stages (early growth, maturation, flowering) using F-tests, temporal consistency evaluations across six UAV surveys (42-day intervals), and spatial validation of fine-scale (2 m × 2 m) predictions against in situ biomass measurements. Results confirmed UAV-derived models as viable for high-resolution biomass mapping, while deployment scenarios emphasized multispectral sensors for early-stage, large-scale applications and LiDAR for precision monitoring in dense canopies or harvest-proximate intervals. These findings underscore the criticality of phenology-aligned sensor selection to optimize prediction accuracy in agricultural remote sensing.

CONCLUSION

In conclusion, this system aims to leverage UAV technology and machine learning techniques to accurately predict biomass and nitrogen content in sugarcane fields, ultimately contributing to more efficient agricultural practices. Through the integration of LiDAR and multispectral imaging with advanced data processing and machine learning models, the system will provide valuable insights for precision farming. By addressing the challenges of data quality, model accuracy, and system scalability, this system has the potential to improve crop management and resource optimization. Future enhancements, such as expanding to other crops or incorporating more sensor types, could further elevate the system's capabilities, making it a vital tool in the evolving field of agricultural technology.

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