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Non-destructive detection of herbicide damage in curly lettuce using spectral data and machine learning algorithms

Franciele Morlin Carneiro[1*], Tiago Vidigal Maciel[1], Gabriel Albuquerque Araujo[1], Henrique de Oliveira Cavalheiro[1], Bárbara Carolline Matwijou[1], Marco Antônio da Silva[1], José Dimas Rodrigues Oliveira[1], Armando Lopes de Brito Filho[2], Maura Gabriela da Silva Brochado[1]

[1]Federal Technological University of Paraná (UTFPR), Santa Helena *campus*, Paraná State, Brazil.
[2]Western Paraná State University (UNIOESTE), Cascavel *campus*, Paraná State, Brazil.
*email: fmcarneiro@utfpr.edu.br

Abstract.

Curly lettuce (Lactuca sativa var. crispa) is a prominent horticultural crop due to its high demand for both production and human consumption. It plays a vital role in creating healthier, more balanced diets. However, the application of phytosanitary products, such as herbicides, whether applied by air or land, can lead to chemical drift into adjacent areas, negatively impacting sensitive crops. This drift can cause phytotoxicity and, in severe cases, result in total crop loss, depending on factors such as the method of application, environmental conditions, and the intensity of the drift. In this context, this study proposes the innovative use of sustainable geotechnologies, particularly remote sensing, in conjunction with data analysis using artificial intelligence (AI). These tools aim to monitor and estimate damage to crops. The study's objectives are: (i) to assess the damage caused to curly lettuce crops by the herbicides 2,4-D and glyphosate using proximal remote sensing (PRS) integrated with machine learning algorithms; and (ii) to compare the effectiveness of different algorithms in detecting and quantifying the level of damage. The research was conducted at the Federal Technological University of Paraná (UTFPR), specifically at the Santa Helena campus in the state of Paraná, Brazil. The experiment took place in a greenhouse situated at the geodetic coordinates of 24°50'48.41" S and 54°20'42.18" W, at an altitude of 234 meters. The dataset included various input variables, such as the vegetation indices NDVI (Normalized Difference Vegetation Index) and NDRE (Normalized Difference Red Edge Index), leaf area percentage, and dry mass, with the injury score serving as the output variable. Initially, the dataset comprised 288 samples, covering all evaluated time periods: 3, 7, 14, and 21 days after emergence. For predictive modeling, the data were divided into 80% for training the model and 20% for validation. The machine learning algorithms assessed in the study were Random Forest, CatBoost, K-Nearest Neighbors (KNN), and XGBoost. The performance of these models was evaluated using the coefficient of determination (R^2) and the root mean square error (RMSE). The best validated performances were achieved with the following algorithms: Random Forest (R^2 = 78.99%; RMSE = 16.14%), CatBoost (R^2 = 78.96%; RMSE = 16.14%), KNN (R^2 = 78.06%; RMSE = 15.93%), and XGBoost (R^2 = 77.50%; RMSE = 16.62%). The study concludes that integrating spectral reflectance properties (SRP) with artificial intelligence (AI) offers an effective approach for estimating injuries in lettuce crops. This method is sustainable, non-destructive, and provides rapid responses, demonstrating high potential for supporting decision-making in agricultural management systems while helping to reduce both productive and environmental risks.

Keywords.

Digital Agriculture, Precision Agriculture, Precision Horticulture, Machine learning.

Introduction

Pesticide drift poses a significant challenge for agricultural production systems, especially for sensitive crops such as lettuce. It can cause physiological damage and yield losses (REBESQUINI et al., 2024). In this context, advances in Precision Agriculture (PA), associated with Remote Sensing (RS) and Artificial Intelligence (AI), expand the possibilities for monitoring and analyzing crops quickly and non-destructively (MOLIN et al., 2015). The hypothesis was that integrating these technologies enables high-precision detection and quantification of injuries caused by herbicide drift in lettuce crops (FURUYA et al., 2024). Therefore, this study aimed to estimate the damage caused by the herbicides 2,4-D and glyphosate in curly lettuce using Proximal Remote Sensing (PRS) combined with machine learning (ML) algorithms. It also aimed to compare the models' performance in detecting and quantifying phytotoxicity levels.

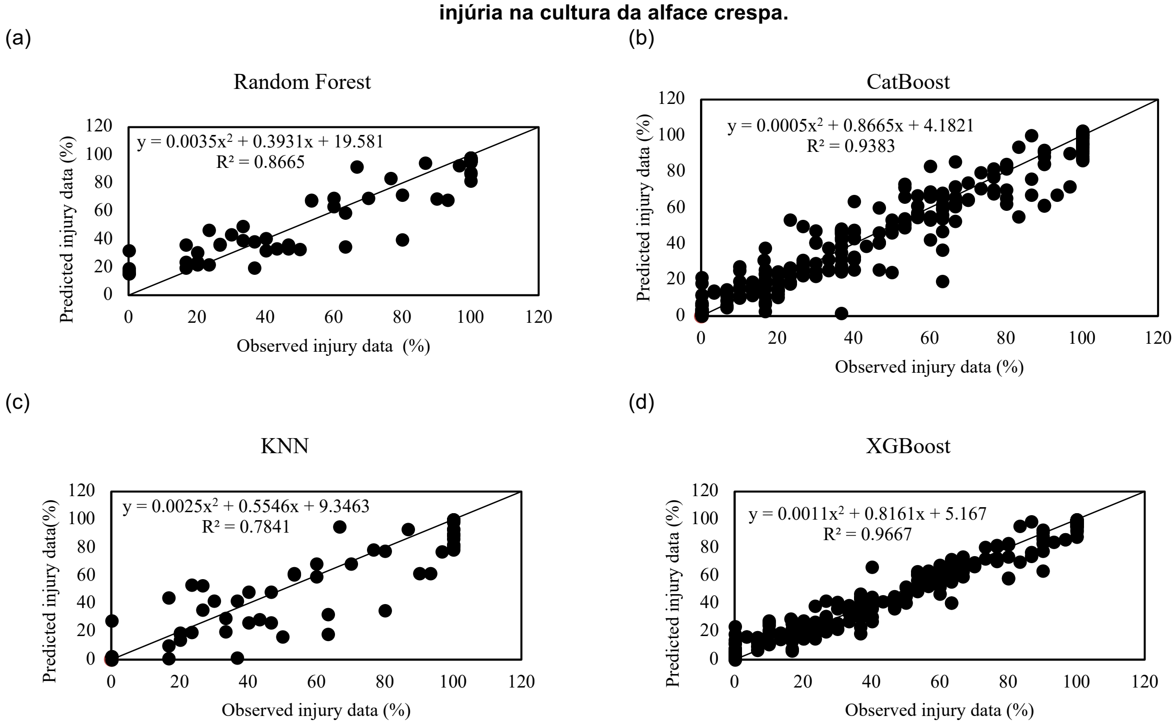
Material and Methods

The study was conducted in a greenhouse and at the Herbology and Herbicides Laboratory (Herb$^+$) of the Federal Technological University of Paraná (UTFPR), Santa Helena *campus*, Paraná, Brazil. To monitor injuries caused by simulated drift of glyphosate and 2,4-D herbicides in curly lettuce crops, evaluations were conducted at 3, 7, 14, and 21 days after treatment. The database included NDVI and NDRE vegetation indices, canopy cover estimated by the Canopeo application, and plant dry mass, while the output variable was injury intensity, determined by visual assessment performed by three independent evaluators using a percentage scale from 0 to 100% (EWRC, 1964; WELLS et al., 2019). Spectral indices were obtained through proximal remote sensing with the RapidScan CS-45 sensor, and the final dataset comprised 288 samples, split 80% for training and 20% for model validation. After data organization and preprocessing, analyses were performed in the Google Colaboratory (Google Colab) environment using Python. Subsequently, the Random Forest Regressor (RF), Categorical Boosting (CatBoost), K-Nearest Neighbors (KNN), and Extreme Gradient Boosting (XGBoost) algorithms were evaluated and compared using the coefficient of determination (R^2), Mean Absolute Error (MAE), and Root Mean Square Error (RMSE).

Results and Discussion

The XGBoost algorithm stood out as the most consistent, achieving R^2 = 96.67%, demonstrating excellent explanatory power and high predictive accuracy (Fig 1d). The distribution of points along the 1:1 line indicated low dispersion of residuals, suggesting that the model was able to adequately capture the non-linear relationships between the explanatory variables and plant injury, even at higher levels of damage, a condition that is often challenging in agricultural systems. The results of this study highlighted the high potential of integrating SRP and ML algorithms to detect and quantify injuries from herbicide drift in lettuce crops (SPIRALSKI et al., 2025).

Fig 1. Desempenho dos modelos preditivos na validação entre valores observados e preditos para a estimativa de injúria na cultura da alface crespa.



Conclusions

It was concluded that integrating PRS and ML algorithms is a robust, accurate, and non-destructive approach for detecting and quantifying herbicide drift damage in curly lettuce crops. Among ensemble and boosting methods, XGBoost and CatBoost showed superior performance, with high coefficients of determination and lower residual dispersion. These algorithms better captured non-linear relationships and intrinsic variability in the agricultural system, outperforming simpler approaches such as KNN and RF, which had limitations in generalization and predictive stability.

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