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MONITORING DIFFERENT GRASS VARIETIES USING MULTISPECTRAL IMAGERY BASED ON DIFFERENT IRRIGATION REGIMES

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Abstract

This study analyses the physiological response and visual quality of several grass varieties grown on four experimental lots, using multispectral imaging for monitoring. The control lot did not receive irrigation, while the other three experimental lots were subjected to distinct irrigation regimes: rotors (lot 1), sprays (lot 2), and underground drip irrigation (lot 3). Multispectral data allowed the assessment of vegetative parameters, to analyse the differences in vegetative state and water stress levels between the lots and grass varieties. The results showed significant variations between the experimental lots, depending on both the type of irrigation and the grass variety, highlighting the efficiency of different irrigation systems in both water conservation and maintaining an optimal vegetative state. The study offers valuable insights for optimizing irrigation practices and selecting grass varieties suited to both specific site conditions and the implementation of sustainable maintenance strategies.

Key words: *monitoring, multispectral imagery, remote sensing.*

INTRODUCTION

Parks represent an important resource in the sustainable and lasting development of cities and municipalities. The grass within these areas serves numerous roles, besides its aesthetic function, it also contributes to maintaining adequate air quality (Chiesura, 2004). Maintaining green spaces with lawns presents a challenge in terms of irrigation while also ensuring efficient water management (Schebella et al., 2014). The management of water resources, particularly in the context of climate change and the rapid expansion of large cities at the expense of diminishing water supplies, remains a constant concern for specialists (Kenna & Horst, 1993). The use of multispectral imaging to assess the efficiency of irrigation systems and optimize turfgrass mixtures to reduce water consumption is an important focus in the current context of climate change and urban development (Krum et al., 2010). Building on previous studies (Kerry et al., 2024), our research differs by implementing a field experiment differently as other studies (Orta et al., 2023) with four test lots, each subjected to three different irrigation treatments, along with a control lot that received no irrigation. The irrigation treatments delivered the same amount of water to the grass in each respective lot. Additionally, all test lots contained 12 different turfgrass mixtures, allowing us to evaluate their behaviour using multispectral imaging. The study was conducted during autumn, just before the dormancy period, to highlight the resilience of turfgrass based on the accumulated vegetative growth over the season. Furthermore, the research aimed to emphasize the importance of fertilizer application in maintaining turfgrass performance and adaptability.

MATERIALS AND METHODS

This study investigates the influence of different irrigation types on various vegetation indices across multiple lawn mix types. The vegetation indices analysed include the Green Normalized Difference Vegetation Index (GNDVI; Gitelson et al., 1996), Leaf Chlorophyll Index (LCI; Sousa-Souto et al., 2018), Modified Chlorophyll Absorption Ratio Index (MCARI; Daughtry et al., 2000), Normalized Difference Red Edge Index (NDRE; Gitelson et al., 1996), Normalized Difference Vegetation Index (NDVI; Tucker, 1979), and Structure Insensitive Pigment Index (SIPI_2; Peñuelas et al., 1995). The study aims to determine the most effective irrigation method for maintaining optimal plant health and nutrient absorption.

A series of field trials were conducted on multiple lawn mix types under different irrigation treatments. The experimental design of the field and office works are presented (Sestras et al., 2019) in Figure 1.

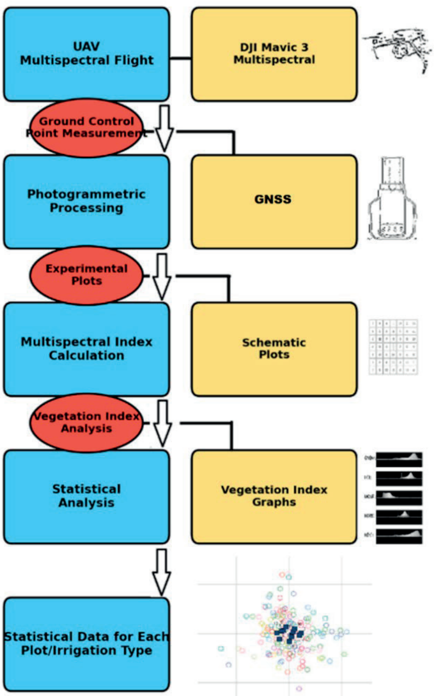

Figure 1. Experimental design

Measurements were taken using remote sensing techniques, and statistical analysis was performed to identify trends among irrigation types and lawn mix performance. For this study, a DJI Mavic 3 Multispectral (3M) drone was utilized, equipped with two advanced cameras that enable high-precision scanning and analysis of various crops. The photogrammetric processing was conducted in Agisoft Photoscan and the Ground Control Points (GCPs) served just as verification points, as the drone was equipped with RTK Module. All the indices were computed in Agisoft metashape, using raster calculator, then exported as raster images. This type of equipment is widely used in agriculture and forestry applications, providing valuable insights into vegetation health and land management. The analyses were preformed using ArGis (Popescu et al., 2024; Bilaşco et al., 2016; Sestras et al., 2018), and IBM SPSS Statistics (SPSS).

The main characteristics of the equipment are presented in Table 1. Because we were able to fly at low altitudes, we obtained a spatial resolution under 1 cm/pixel.

Table 1. Multispectral drone specifications

Component	Specification
Multispectral Camera - Spectral Bands	Green (560 ± 16 nm), Red (650 ± 16 nm), Red Edge (730 ± 16 nm), Near-Infrared (860 ± 26 nm)

These spectral bands offer valuable insights for assessing plant health, identifying stress factors, and enhancing precision agriculture practices. By integrating both RGB and multispectral imaging capabilities, the DJI Mavic 3M drone proves to be a versatile instrument for remote sensing in agriculture, forestry, and environmental monitoring.

In this study, experimental plots featuring twelve distinct lawn types were analyzed, arranged as shown in Figure 2.

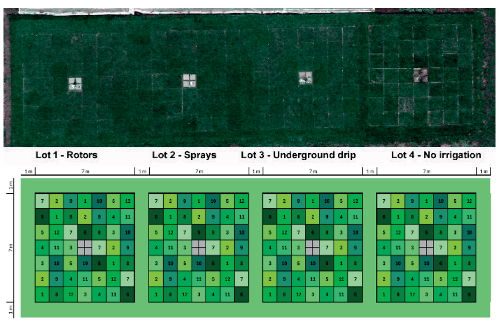

Figure 2. Experimental lots

The twelve lawn mix types are described in the Table 2, with all the mixt numbering correlated with the lots and all the components and the percentage of each lawn used (Hitter et al., 2021). As shown in the experimental design, we conducted a multispectral image acquisition and then applied diverse spectral vegetation indices are presented in Table 3.

The desired quantity of water used for irrigation is presented in Table 4.

Table 2. Lawn Mixes and composition

No.	Mix Name	Composition
1	**BRB Bar Power RPR**	*Lolium perenne* 40%, *L. perenne* 20%, *Festuca rubra commutata* 20%, *F. rubra rubra* 10%, *Poa pratensis* 10%
2	**BRB Rapid**	*Lolium perenne* 30%, *L. perenne* 25%, *L. perenne* 20%, *Festuca rubra* 15%, *Poa pratensis* 10%
3	**BRB Shadow**	*Festuca rubra* 60%, *Lolium perenne* 20%, *Poa pratensis* 20%
4	**BRB SOS - Super Over Seeding**	*Lolium perenne* 50%, *L. perenne* 50%
5	**BRB Speedy Green**	*Lolium perenne* 34%, *L. p.* BARRAGE 31%, *L. perenne* 31%, *L. perenne* 4%
6	**BRB WaterSaver**	*Lolium perenne* 10%, *Festuca arundinacea* 20%, *F. around.* 20%, *F. around.* 40%, *Poa pratensis* 10%
7	**DLF TURFLINE Eco Lawn**	*Lolium perenne* 30%, *Festuca rubra* 40%, *F. rubra litoralis* 20%, *Poa pratensis* 5%, *Trifolium repens* 5%
8	**DLF TURFLINE Sport**	*Lolium perenne* 30%, *Festuca rubra commutata* 30%, *F. rubra litoralis* 15%, *F. ovina* 5%, *Poa pratensis* 20%
9	**DLF TURFLINE Waterless**	*Lolium perenne* 10%, *Festuca arundinacea* 80%, *Poa pratensis* 10%
10	**ICL Landscaper Pro Performance**	*Lolium perenne* 80%, *Festuca rubra rubra* 20%
11	**ICL Landscaper Pro Rapid**	*Lolium perenne* 75%, *Festuca rubra rubra* 15%, *Poa pratensis* 10%
12	**ICL ProSelect Regenerator Plus**	*Lolium perenne* 75%, *Poa pratensis* 25%

Table 3. Spectral Vegetation Indices used

Index	Description	Calculation Formula	Author
NDVI (Normalized Difference Vegetation Index)	Assesses vegetation health and vigour.	(NIR - Red) / (NIR + Red)	Tucker, 1979
GNDVI (Green Normalized Difference Vegetation Index)	Evaluates chlorophyll levels and plant health.	(NIR - Green) / (NIR + Green)	Gitelson, 1996
NDRE (Normalized Difference Red Edge Index)	Measures nitrogen uptake and chlorophyll concentration.	(NIR - RedEdge) / (NIR + RedEdge)	Haboudane, 2004
LCI (Leaf Chlorophyll Index)	Estimates chlorophyll concentration in leaves.	(NIR - RedEdge) / (NIR + RedEdge)	Souto, 2018
MCARI (Modified Chlorophyll Absorption in Reflective Index)	Determines chlorophyll absorption and plant stress levels.	1.2 * (2.5 * (NIR - Red) - 1.3 * (NIR - Green)) / (normalized to reflectance in red, green, and NIR bands)	Daughtry, 2000
SIPI_2 (Structure Insensitive Pigment Index)	Analyses pigment ratios and stress resistance in plants.	(NIR - Blue) / (NIR + Red)	Peñuelas et al., 1995

Table 4. Desired Irrigation quantity

Irrigation Type	**Precipitation Rate (mm/h)**	**Run Time (minutes)**	**Desired depth of water application (mm/sqm**
Spray Irrigation (2)	40	6	4.5
Rotor Irrigation (1)	24	12	4.5
Drip Irrigation (3)	18.37	15	4.5
No Irrigation (0)	0	0	0

RESULTS AND DISCUSSIONS

The photogrammetric survey was made on 7th As shown in the Figure 4 it could be clearly seen that the moisture is decreasing gradually, as there was no irrigation used on this period, having in mind that the lawn was prepared for winter. Also correlating this graph with the weather graph presented in Figure 3 it can be clearly seen that the temperatures were below 0 degrees, so that no irrigation could have been applied.

November 2024, in order to see how the post vegetative stage affects the grass health, and in what percentage the fertilization and the accumulated nutrients help the plants to maintain a healthy aspect. The weather evolution before the photogrammetric survey it is presented Figure 3.

The soil moisture was also recorded on the ground level, at approximately 5cm underground, the main results for soil moisture are presented in Figure 4, as a medium value of three sensors each placed on lot 1, 2 and 3.

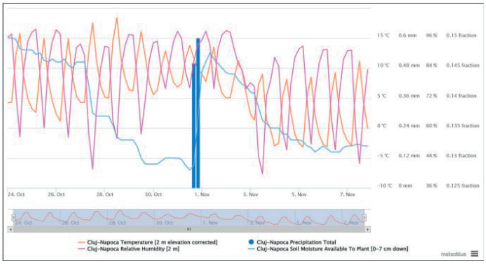

Figure 3. Weather and precipitations before and around the survey (Source Meteoblue)

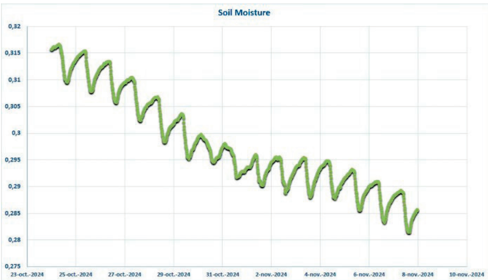

Figure 4. Soil Moisture graph for the period before the survey

The NDVIis a widely used metric for assessing vegetation health and density based on spectral reflectance. It measures the difference between the absorption of red light by chlorophyll and the reflection of near-infrared (NIR) light by plant structures (Herbei& Badaluta-Minda, 2024).

In Figure 5 it can be seen the results obtained for the NDVI index applied on our experimental lots.

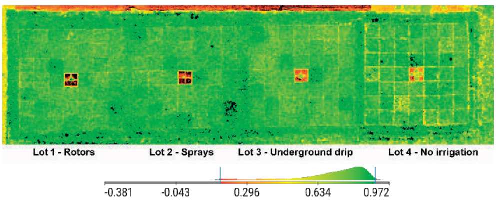

Figure 5. NDVI Index applied on the experimental lot

Range: NDVI values typically vary between -1 and +1, providing insights into vegetation cover and health (Constantinescu et al., 2018).

High NDVI Values (close to +1): represent dense, healthy green vegetation with high chlorophyll content. These areas appear bright green on NDVI maps.

Moderate NDVI Values (around 0): indicate sparse vegetation or grassland areas with lower chlorophyll levels. These zones are often shown in yellow or light green.

Low NDVI Values (close to -1): correspond to barren land, exposed soil, or rock surfaces, where vegetation is absent. Such areas appear in brown or reddish tones.

The Green Normalized Difference Vegetation Index (GNDVI) is a widely used vegetation index that measures the amount of healthy green vegetation within an area. By comparing the reflectance values of specific spectral bands, GNDVI provides a quantitative assessment of vegetation health and vigour. The results for our experimental lots are presented in Figure 6.

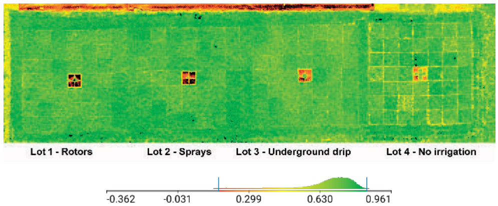

Figure 6. GNDVI Index applied on the experimental lot

GNDVI values range from -1 to +1, with higher values indicating denser and healthier vegetation cover.

High GNDVI values (closer to +1) suggest areas with high chlorophyll content and strong photosynthetic activity, typically associated with lush, healthy vegetation.

Moderate GNDVI values indicate areas with some vegetation, such as grasslands or sparse crops, where plant health varies.

Low GNDVI values (close to 0) are characteristic of bare soil, urban areas, or areas with low vegetation density.

Negative values suggest the presence of water bodies, barren land, or non-vegetated surfaces.

For our studied area, the distribution of GNDVI values shows a peak in the positive range, indicating a predominance of vegetation with healthy chlorophyll levels.

The colour gradient in the legend transitions from grey (-1) to orange (low values), yellow (moderate values), and green (high values), which visually represents the varying density of vegetation.

The histogram peak in the green region suggests that most of the analysed area consists of healthy and dense vegetation, while smaller portions fall in the yellow and orange ranges, indicating areas with moderate or lower vegetation health.

The Normalized Difference Red Edge Index (NDRE) is a vegetation index closely related to NDVI but incorporates Red Edge light instead of the traditional Red band. The Red Edge wavelength penetrates deeper into the leaf structure, allowing for a more accurate assessment of chlorophyll content and plant stress.

The results for our experimental lots are presented in Figure 7.

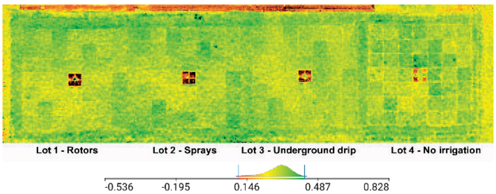

Figure 7. NDRE Index applied on the experimental lot

The representation of NDRE, as shown Figure 7, follows a gradient:

Negative values or values close to zero (grey to dark orange) represent barren land, non-vegetated surfaces, or unhealthy vegetation.

Moderate values (yellow to light green) indicate areas with some vegetation, but with possible stress or lower chlorophyll content.

High values (bright green) are associated with dense, healthy vegetation, indicating strong chlorophyll activity and robust plant health.

The NDRE histogram suggests that most of the measured values are concentrated in the positive range (yellow to green), indicating overall good vegetation health in the analysed area.

A gradual transition from orange to yellow and then to green demonstrates variations in plant vigour, with some areas experiencing stress while others remain healthy.

The use of Red Edge light makes NDRE particularly valuable for detecting subtle variations in vegetation health before visible symptoms appear, making it a powerful tool for precision agriculture and crop monitoring.

The Leaf Chlorophyll Index (LCI) is a vegetation index designed to measure chlorophyll content in leaves, offering valuable insights into plant health and photosynthetic efficiency. LCI utilizes the Near Infrared (NIR) and Red Edge spectral bands, as NIR is sensitive to the internal structure and moisture content of the leaf, while Red Edge strongly correlates with chlorophyll concentration. The results for our experimental lots are presented in Figure 8.

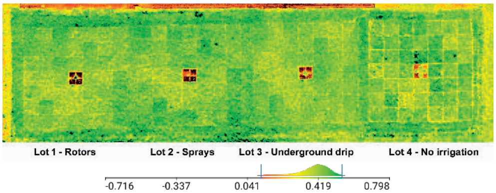

Figure 8. LCI Index applied on the experimental lot

The representation of LCI, as shown in Figure 6 colour scale, follows a gradient:

Low values (grey to dark orange): indicate areas with low chlorophyll content, which could be associated with barren land, non-vegetated surfaces, or vegetation experiencing severe stress.

Moderate values (yellow to light green): represent regions with some vegetation, but with possible deficiencies in chlorophyll due to environmental stress or suboptimal nutrient availability.

High values (bright green): correspond to healthy, thriving vegetation with high chlorophyll concentration, indicating strong photosynthetic activity and robust plant growth.

The LCI histogram suggests that most of the measured values are concentrated in the positive range (yellow to green), indicating overall good vegetation health in the analysed area.

A gradual transition from orange to yellow and then to green illustrates variations in plant vigour, with certain areas experiencing mild to moderate stress while others exhibit optimal growth.

The combination of NIR and Red Edge bands enhances LCI's ability to detect subtle chlorophyll variations, making it particularly useful for monitoring nutrient status, irrigation effectiveness, and early stress detection.

The Modified Chlorophyll Absorption Ratio Index (MCARI) is a vegetation index designed to measure the intensity of chlorophyll absorption in plants. It is highly sensitive to variations in chlorophyll concentration and the Leaf Area Index (LAI), making it a valuable tool for assessing plant health and stress levels. Unlike some other indices, MCARI is less influenced by lighting conditions, soil background reflectance, and non-photosynthetic materials. The results for our experimental lots are presented in Figure 9.

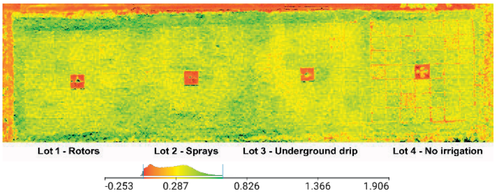

Figure 9. MCARI Index applied on the experimental lot

The MCARI colour scale presented on Figure 9 provides a visual representation of its values:
Low values (dark to light green) indicate a higher chlorophyll content, meaning healthier and more vigorous vegetation.
Moderate values (yellow to orange) represent areas with moderate chlorophyll levels, possibly indicating some plant stress or early signs of nutrient deficiency.
High values (dark orange to red) correspond to regions with low chlorophyll content, which may be associated with plant stress, chlorosis, or reduced photosynthetic activity.
The MCARI histogram shows that most of the analysed area has values in the moderate-to-high range, suggesting a mix of healthy and slightly stressed vegetation.
A strong presence of orange and red areas highlights zones with lower chlorophyll content, possibly indicating stress or poor nutrient absorption.
Since MCARI is primarily used for detecting chlorophyll variations, it is often interpreted in combination with NDVI or LAI to gain a more comprehensive understanding of vegetation health.
The Structure Insensitive Pigment Index (SIPI_2) is a vegetation index that helps assess plant stress and pigment composition, particularly the ratio of carotenoids to chlorophyll. It is widely used to evaluate plant health, stress resilience, and photosynthetic efficiency. Unlike indices that are highly influenced by leaf structure, SIPI_2 minimizes these structural effects, providing a more stable assessment of pigment balance. The results for our experimental lots are presented in Figure 10.

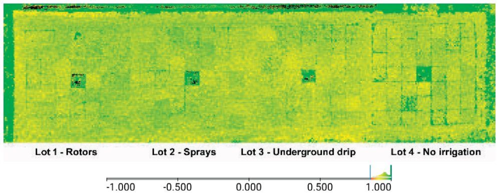

Figure 10. SIPI 2 Index applied on the experimental lot

The SIPI_2 colour scale presented in Figure 10 provides a visual representation of its values:
Low values (dark green to light green) indicate a higher chlorophyll-to-carotenoid ratio, representing healthy, unstressed vegetation with optimal photosynthetic capacity.
Moderate values (yellow to orange) suggest a more balanced ratio, possibly indicating early signs of stress or pigment imbalance.
High values (red to dark orange) correspond to regions with a lower chlorophyll-to-carotenoid ratio, often associated with plant stress, senescence, or nutrient deficiencies. The SIPI_2 histogram shows that most of the analysed area falls within the high-value range (orange to red), suggesting that a significant portion of the vegetation is experiencing some level of stress or chlorophyll degradation.
The limited presence of green areas indicates that only a small portion of the analysed vegetation is in an optimal health state.
A concentration of high SIPI_2 values may be a sign of drought stress, nutrient limitations, or advanced stages of plant aging, which can impact overall biomass production and vigour.
Later, some analyses were conducted on each lot, and we extracted the statistical values for each applied index. The lawn mixes were vectorised, and each one got its own zonal statistic value as a table (Coroian I. et al., 2020). As could be seen in Figure 11, some statistical analyses were conducted later on. In figure 11 the Clustered boxplot on each Lawn mixt type for the GNDVI index could be seen.

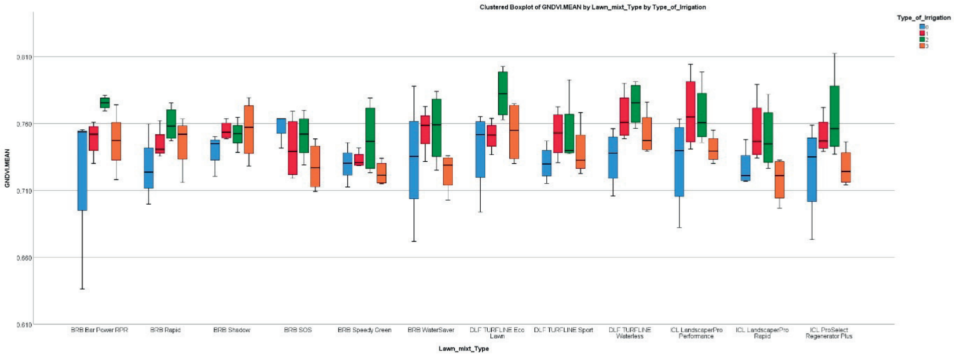

Figure 11. GNDVI index boxplot for each lawn mixt type

This boxplot illustrates the distribution of GNDVI Mean values for various Lawn Mix Types under different irrigation methods. Type 0 (blue) represents No Irrigation, Type 1 (red) represents Rotor Irrigation, Type 2 (green) represents Spray Irrigation, and Type 3 (orange) represents Underground Drip. Since GNDVI (Green Normalized Difference Vegetation Index) reflects plant health, higher values indicate better vegetation quality and water efficiency.

For BRB Bar Power RPR, No Irrigation shows high variability and the lowest median GNDVI, while Spray Irrigation achieves the highest values. BRB Rapid exhibits inconsistent chlorophyll levels under No Irrigation, with Spray performing best. BRB Shadow has a compact distribution across irrigation types, with Rotors and Underground Drip slightly outperforming Spray. BRB SOS performs worst with Underground Drip, while Spray and Rotors yield better results. BRB Speedy Green shows a stable GNDVI distribution, with Spray and Rotors having slightly higher medians. BRB WaterSaver is among the top-performing mixes, with Spray producing the highest chlorophyll content.

DLF TURFLINE Eco Lawn performs better with Rotor and Underground Drip compared to No Irrigation. DLF TURFLINE Sport maintains consistently high GNDVI values, with Spray providing the best results. DLF TURFLINE Waterless shows a large variation across irrigation types, but Spray leads in performance. ICL LandscapePro Performance has a narrow GNDVI spread, with Rotors and Spray performing slightly better than No Irrigation. ICL LandscapePro Rapid achieves high GNDVI values across all irrigation types, with Spray as the top performer. ICL Professional Regeneration Plus exhibits moderate variability, where Spray and Underground Drip perform better than Rotors.

Overall, Spray Irrigation consistently yields the highest GNDVI values, followed by Underground Drip and Rotor, while No Irrigation results in the lowest and most variable GNDVI, indicating water stress.

In Figure 12 the Clustered boxplot on each Lawn mixt type for the LCI index could be seen.

This boxplot illustrates the distribution of LCI Mean (Leaf Chlorophyll Index) values for different Lawn Mix Types under various irrigation methods, including No Irrigation, Rotor Irrigation, Spray Irrigation, and Underground Drip. Since LCI measures chlorophyll content, higher values indicate healthier and more photosynthetically active plants.

For BRB Bar Power RPR, No Irrigation shows high variability and a lower median, indicating inconsistent chlorophyll content and potential water stress. Spray Irrigation and Underground Drip provide more stable distributions and better performance, while Rotor Irrigation performs moderately, with a slightly lower median than Spray and Drip. BRB Rapid has a broad spread and a lower median under No Irrigation, reflecting inconsistent chlorophyll content. Spray Irrigation achieves the highest median, suggesting optimal plant health, while Rotor and Underground Drip show moderate and similar performance. BRB Shadow exhibits similar performance across irrigation types with a moderate spread, with Spray and Underground Drip slightly outperforming No Irrigation.

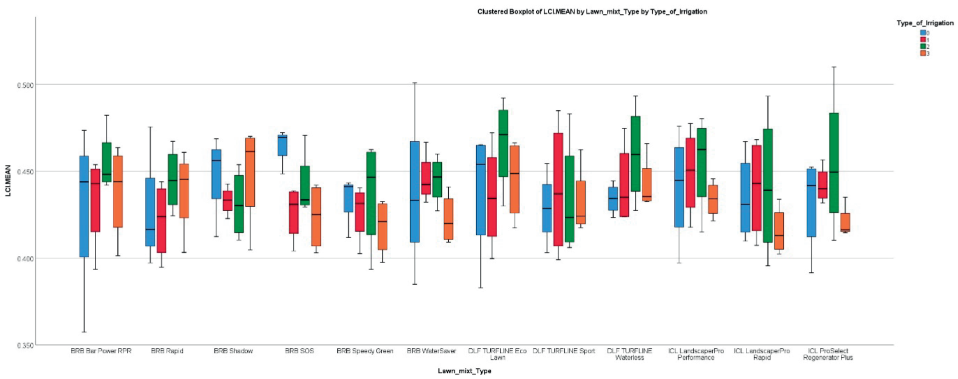

Figure 12. LCI index boxplot for each lawn mixt type

BRB SOS has the lowest median under Underground Drip, suggesting less effectiveness, while No Irrigation, Rotor, and Spray show higher and more stable LCI values. BRB Speedy Green has a compact LCI distribution, indicating consistent performance, with Spray and Rotor Irrigation slightly improving chlorophyll levels. BRB WaterSaver is one of the highest-performing mixes, with Spray Irrigation achieving the highest median, indicating optimal chlorophyll levels, while No Irrigation shows the widest variability and inconsistent performance. DLF TURFLINE Eco Lawn performs slightly better with Rotor and Underground Drip than with No Irrigation, which results in lower LCI values and suggests water stress.

DLF TURFLINE Sport maintains consistently high LCI values across irrigation types, with Spray performing best and No Irrigation showing greater variability and fluctuating chlorophyll levels. DLF TURFLINE Waterless exhibits large variation across irrigation types, with Spray producing the highest median and No Irrigation displaying a widespread, indicating inconsistent plant health. ICL LandscapePro Performance has a narrow LCI spread, reflecting consistent vegetation health, with Rotors and Spray performing slightly better than No Irrigation. ICL LandscapePro Rapid achieves high LCI values across all irrigation types, with Spray producing the highest median and Underground Drip offering stable performance with minimal variation. IL Professional Regeneration Plus shows moderate LCI variability across irrigation types, with Rotor slightly underperforming compared to Spray and Underground Drip.

Overall, Spray Irrigation is the best-performing method, consistently achieving higher LCI values and indicating better chlorophyll levels and plant health. Underground Drip provides stable performance and is often comparable to Rotor Irrigation, though slightly less effective than Spray. Rotor Irrigation shows moderate performance, performing better than No Irrigation but lower than Spray and Drip in most cases. No Irrigation results in moderately variable LCI values, with median levels that are not consistently the lowest across indices - suggesting that while water stress may occur, it does not always lead to the poorest or most inconsistent plant health outcomes

In Figure 13 the Clustered boxplot on each Lawn mixt type for the MCARI index could be seen.

This boxplot illustrates the distribution of MCARI Mean (Modified Chlorophyll Absorption Ratio Index) values for different Lawn Mix Types under various irrigation methods, including No Irrigation, Rotor Irrigation, Spray Irrigation, and Underground Drip. MCARI is an index used to estimate chlorophyll content and stress levels in vegetation, where higher values indicate better chlorophyll retention and lower stress, while lower values may suggest chlorosis, senescence, or water stress.

For BRB Bar Power RPR, No Irrigation shows high variability and the lowest median, suggesting inconsistent chlorophyll content and potential water stress. Spray and Rotor Irrigation have higher median values, indicating better performance, while Underground Drip shows moderate results with a slightly lower median.

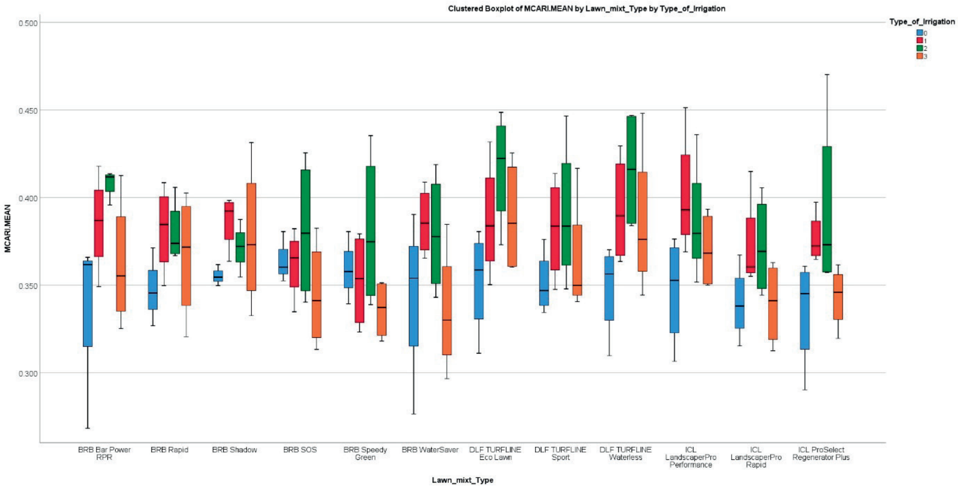

Figure 13. MCARI index boxplot for each lawn mixt type

BRB Rapid has a low median and high variability under No Irrigation, reflecting unstable chlorophyll levels. Spray Irrigation achieves the highest median, suggesting optimal chlorophyll content, while Rotor and Underground Drip demonstrate moderate performance. BRB Shadow exhibits less variability across irrigation types, indicating consistent chlorophyll content, with Spray and Rotor performing slightly better than No Irrigation.

BRB SOS has the lowest median under Underground Drip, suggesting reduced effectiveness, whereas No Irrigation, Rotor, and Spray exhibit higher and more stable MCARI values. BRB Speedy Green maintains a compact MCARI distribution, reflecting consistent chlorophyll levels, with Spray and Rotor achieving higher median values that suggest better chlorophyll retention. BRB WaterSaver is among the highest-performing mixes, with Spray reaching the highest median and indicating optimal chlorophyll content, while No Irrigation presents wide variability and inconsistent plant health. DLF TURFLINE Eco Lawn performs slightly better with Rotor and Underground Drip than with No Irrigation, which results in lower MCARI values and suggests water stress.

DLF TURFLINE Sport consistently maintains high MCARI values across all irrigation types, with Spray performing best, while No Irrigation introduces more variability and fluctuating chlorophyll levels. DLF TURFLINE Waterless exhibits large variations across irrigation types, with Spray achieving the highest median and No Irrigation displaying a widespread, indicating inconsistent plant health. ICL LandscapePro Performance has a narrow MCARI spread, reflecting consistent vegetation health, with Rotors and Spray slightly outperforming No Irrigation. ICL LandscapePro Rapid attains high MCARI values across all irrigation types, with Spray achieving the highest median and Underground Drip providing stable performance with minimal variation. IL Professional Regeneration Plus shows moderate MCARI variability across irrigation types, with Rotor slightly underperforming compared to Spray and Underground Drip.

Overall, Spray Irrigation is the best-performing method, consistently producing higher MCARI values and indicating better chlorophyll retention and lower stress. Underground Drip provides stable performance, often comparable to Rotor Irrigation but slightly less effective than Spray. Rotor Irrigation shows moderate performance, performing better than No Irrigation but lower than Spray and Drip in most cases. No Irrigation produces the lowest and most variable MCARI values, highlighting water stress and inconsistent plant health.

In Figure 14 the Clustered boxplot on each Lawn mixt type for the NDRE index could be seen.

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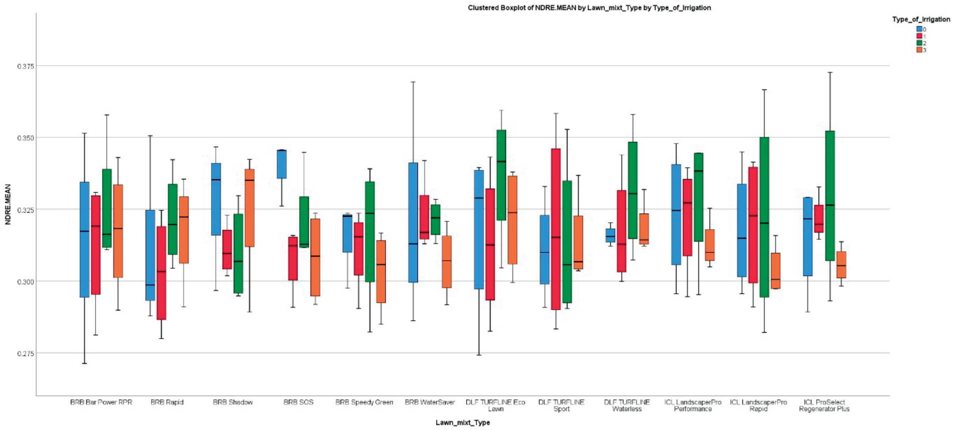

Figure 14. NDRE index boxplot for each lawn mixt type

This boxplot illustrates the distribution of NDRE Mean (Normalized Difference Red Edge Index) values for different Lawn Mix Types under four irrigation types: No Irrigation, Rotor Irrigation, Spray Irrigation, and Underground Drip NDRE is a vegetation index that measures chlorophyll content and nitrogen status in plants. Higher values indicate better plant health, increased nitrogen uptake, and stronger chlorophyll levels, while lower values suggest potential nutrient deficiency or stress.

For BRB Bar Power RPR, No Irrigation presents a moderate spread and a slightly lower median, indicating chlorophyll stress due to water deficiency. Spray Irrigation and Underground Drip show higher medians, suggesting improved nitrogen uptake, while Rotor Irrigation exhibits moderate performance with some variability. BRB Rapid displays a higher spread and lower median under No Irrigation, reflecting unstable chlorophyll levels. Spray Irrigation has the highest median, indicating optimal chlorophyll content, whereas Rotor and Underground Drip demonstrate moderate performance. BRB Shadow maintains similar NDRE values across irrigation types, showing consistent nitrogen uptake, with Spray and Rotor slightly outperforming No Irrigation.

BRB SOS has the lowest median under Underground Drip, suggesting reduced nitrogen uptake efficiency, while Spray, Rotor, and No Irrigation produce higher and more stable NDRE values. BRB Speedy Green shows a compact NDRE distribution, reflecting consistent nitrogen content, with Spray and Rotor achieving higher median values that suggest better nitrogen retention. BRB WaterSaver is among the highest-performing mixes, with Spray reaching the highest median and indicating optimal nitrogen absorption, while No Irrigation presents the widest variability, suggesting inconsistent plant health. DLF TURFLINE Eco Lawn performs slightly better with Rotor and Underground Drip compared to No Irrigation, which results in lower NDRE values and suggests water and nutrient stress.

DLF TURFLINE Sport consistently maintains high NDRE values across all irrigation types, with Spray performing best, while No Irrigation introduces more variability and fluctuating chlorophyll levels. DLF TURFLINE Waterless exhibits large variation across irrigation types, with Spray achieving the highest median and No Irrigation displaying a wide spread, indicating inconsistent plant health. ICL LandscapePro Performance has a narrow NDRE spread, reflecting consistent vegetation health, with Rotors and Spray slightly outperforming No Irrigation. ICL LandscapePro Rapid attains high NDRE values across all irrigation types, with Spray achieving the highest median and Underground Drip providing stable performance with minimal variation. IL Professional Regeneration Plus shows moderate NDRE variability across irrigation types, with Rotor slightly underperforming compared to Spray and Underground Drip.

Overall, Spray Irrigation consistently produces the highest NDRE values, indicating the best nitrogen uptake and plant health. Underground

Drip offers stable performance, often comparable to Rotor Irrigation but slightly less effective than Spray. Rotor Irrigation shows moderate performance, ranking above No Irrigation but below Spray and Underground Drip in most cases. No Irrigation generally shows moderate to high variability in NDRE values, but not consistently the lowest values - indicating that while water and nutrient stress may impact plant health, its effects vary depending on the turfgrass type and conditions.

In Figure 15 the Clustered boxplot on each Lawn mixt type for the NDVI index could be seen.

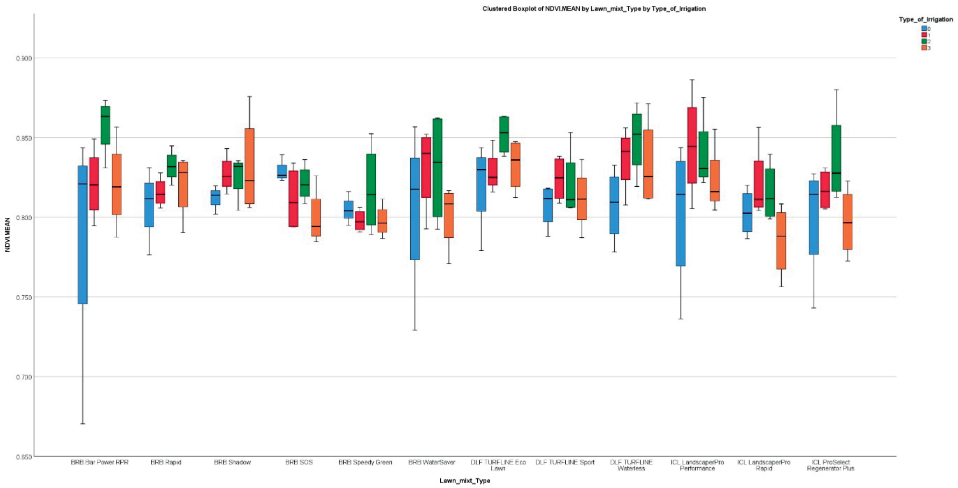

Figure 15. NDVI index boxplot for each lawn mixt type

This boxplot illustrates the distribution of NDVI Mean (Normalized Difference Vegetation Index) values for different Lawn Mix Types under four irrigation methods: No Irrigation, Rotor Irrigation, Spray Irrigation, and Underground Drip. NDVI is a widely used vegetation index that measures plant health, biomass, and chlorophyll levels. Higher NDVI values indicate healthier vegetation with greater chlorophyll content and better water retention, while lower values suggest plant stress due to drought, poor nutrition, or water deficiencies.

For BRB Bar Power RPR, No Irrigation exhibits high variability and the lowest median, indicating inconsistent vegetation health and water stress. Spray and Underground Drip show higher median values, suggesting improved water retention and better plant health, while Rotor Irrigation demonstrates moderate performance with less variability. BRB Rapid has a lower median and high variability under No Irrigation, reflecting fluctuating plant health. Spray Irrigation achieves the highest median, indicating strong chlorophyll levels and water availability, whereas Rotor and Underground Drip display moderate NDVI values. BRB Shadow presents a compact distribution across irrigation types, signifying consistent NDVI performance, with Spray and Rotor achieving slightly higher values than No Irrigation.

BRB SOS has the lowest median under Underground Drip, suggesting less effectiveness in improving NDVI, while Spray, Rotor, and No Irrigation yield higher and more stable values. BRB Speedy Green maintains a compact NDVI distribution, reflecting consistent vegetation health, with Spray and Rotor achieving higher median values, suggesting better chlorophyll retention. BRB WaterSaver is one of the highest-performing mixes, with Spray reaching the highest median and indicating excellent vegetation health, while No Irrigation shows the widest variability, suggesting inconsistent performance. DLF TURFLINE Eco Lawn performs slightly better with Rotor and Underground Drip than with No Irrigation, which results in lower NDVI values and suggests water stress.

DLF TURFLINE Sport consistently maintains high NDVI values across all irrigation types, with Spray achieving the best performance and the highest median, while No Irrigation introduces more variability and fluctuating chlorophyll levels. DLF TURFLINE Waterless exhibits large variation across irrigation types, with Spray showing the highest median, suggesting better water efficiency and plant health, whereas No Irrigation presents a wide spread, indicating inconsistent performance. ICL LandscapePro Performance has a narrow NDVI spread, reflecting consistent plant health, with Rotors and Spray performing slightly better than No Irrigation. ICL LandscapePro Rapid attains higher NDVI values across all irrigation types, with Spray producing the highest median and Underground Drip providing stable performance with minimal variation. IL Professional Regeneration Plus demonstrates moderate NDVI variability across irrigation types, with Rotor slightly underperforming compared to Spray and Underground Drip.

Overall, Spray Irrigation proves to be the most effective method, consistently producing higher NDVI values and indicating better chlorophyll levels and overall plant health. Underground Drip provides stable performance, often comparable to Rotor Irrigation but slightly less effective than Spray. Rotor Irrigation performs moderately well, ranking above No Irrigation but below Spray and Underground Drip in most cases. No Irrigation results in the lowest and most variable NDVI values, highlighting the effects of water stress on plant health. In Figure 16 the Clustered boxplot on each Lawn mixt type for the SIPI_2 index could be seen.

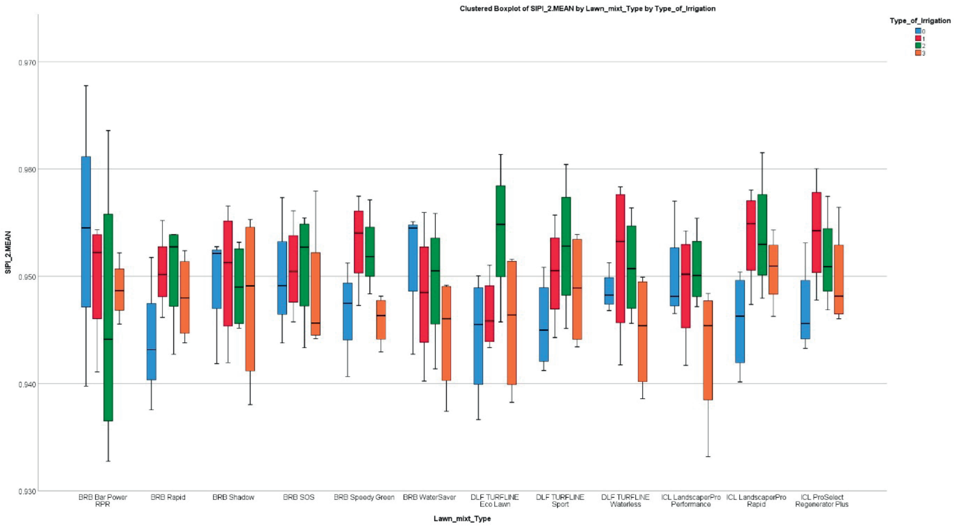

Figure 16. SIPI_2 index boxplot for each lawn mixt type

This boxplot illustrates the distribution of SIPI_2 Mean values across Lawn Mix Types under four irrigation methods: No Irrigation, Rotor, Spray, and Underground Drip. SIPI measures pigment content, where higher values indicate better stress resistance.

Spray consistently achieves the highest SIPI values, reflecting better pigment stability and plant health. Underground Drip provides stable performance, while Rotor performs moderately well. No Irrigation results in the lowest and most variable SIPI values, indicating increased stress and pigment imbalances. Among Lawn Mixes, BRB WaterSaver and DLF TURFLINE Sport show strong pigment retention, while BRB SOS and DLF TURFLINE Waterless exhibit more variability. Efficient irrigation strategies enhance plant resilience and pigment balance.

In order to determine if the multispectral imagery is, or not efficient for lawn monitoring, a canonical discriminant function was applied to the whole data set (Figure 17).

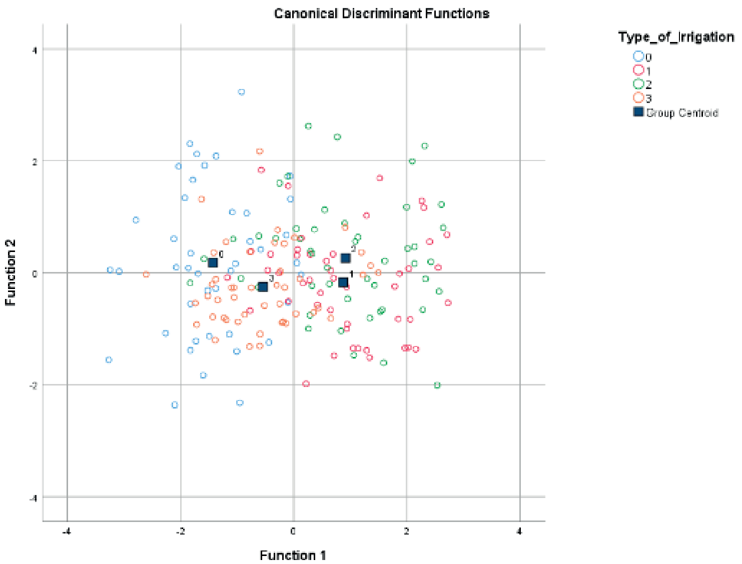

Figure 17. Statistical analysis for the 4 irrigation types – Canonical discriminant function

The Canonical Discriminant Function plot illustrates the distribution of four irrigation types, showing significant overlap, with No Irrigation displaying the greatest separation along Function 1, while Rotor, Spray, and Underground Drip share similar characteristics. However, Underground Drip is closer to No Irrigation due to the lack of applied irrigation and recorded rainfall, which delayed the absorption of granulated fertilizer, further influencing plant response and differentiation.

CONCLUSIONS

The study demonstrates the effectiveness of turf monitoring technology using the multispectral photogrammetric method, highlighting its ability to accurately classify irrigation types and assess their advantages and disadvantages across different lawn mix types.
This study demonstrates that Spray Irrigation (Green) consistently outperforms other irrigation methods across all spectral vegetation indices, making it the most effective for maintaining plant health and optimizing chlorophyll content.
Underground Drip (Orange) provides stable performance, while Rotor Irrigation (Red) is moderately effective. No Irrigation (Blue) results in the lowest values across all indices, indicating significant plant stress and water deficiency.
Best Performing Lawn Mixes: BRB WaterSaver and DLF TURFLINE Sport exhibited the highest resilience and adaptability across multiple irrigation types.
The response to lawn fertilization, in the case of the lot with underground irrigation, had a particularity, most likely due to the fact that, on the one hand, the fertilizer was of the granulated type, with controlled release, and the fact that it did not rain in the period following the fertilizer application prevented the complex of nutrients from reaching the roots.

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