USING MULTISPECTRAL UAV IMAGERY AND GROUND TRUTHING TO ASSESS THE SUCCESS OF VEGETATION REINFORCEMENT IN A COASTAL AREA – THE CASE OF INWADAR NATIONAL PARK, MALTA

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Abstract: Ground-based methods of vegetation survey are slow and expensive, but recent technological developments have made UAVs (Unoccupied Aerial Vehicles or drones) accessible to consumer budgets, facilitating their use in vegetation monitoring. We propose a method for using UAVs to evaluate a vegetation reinforcement programme in a coastal area in Malta and compare its accuracy and cost-effectiveness with that of ground-based methods (including walkthrough-surveys and measurements of chlorophyll-a content). Multi-seasonal imaging of the site was captured using a DJI Phantom 4 drone equipped with sensors sensitive to visible, near infrared (NIR) and red edge (RE) light. These images were used to construct NDVIs of the site from which vegetation characteristics were deduced. Results suggest that UAVs provides a cost-effective way to map, quantify, and detect changes in vegetation cover which can enable assessment of physiological performance once a calibration procedure has been carried out. With an accuracy comparable to ground-based surveys, but quicker and cheaper, drone-based methods provide a viable and economically-attractive alternative to manual surveying methods.

Keywords: UAVs, vegetation monitoring, reinforcement programme, NDVIs, cost-effectiveness

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Introduction

Vegetation reinforcement, in the context of environmental restoration, refers to the process of reintroducing native or adaptive plant species into degraded or disturbed areas to augment existing plant populations, with the consequent aims of restoring ecological function, increasing population viability, improving soil stability, and enhancing habitat quality [4, 9, 13, 23].

The success of any vegetation reinforcement programme can only be evaluated by comparison with two implicit or explicit benchmarks: the pre-reinforcement phytocoenosis (the starting point) and a reference phytocoenosis that would have been, a priori, defined as the 'target' (or end point) of the reinforcement programme. These comparisons imply the necessity of regular surveys of vegetation before, during, and after the implementation of the reinforcement programme. Frequent vegetation surveys over large areas are labour-intensive and are therefore a slow and expensive process [2, 10, 21].

In this regard the recent emergence of UAVs (Unoccupied Aerial Vehicles) accessible to consumer budgets, has facilitated their utilisation for these purposes. The cost of UAVs has decreased substantially, making them affordable for a broader range of users, including individual researchers, small organisations, and conservation groups. Moreover, consumer-grade drones equipped with high-resolution cameras and GPS capabilities can now be purchased at a fraction of the cost of traditional aerial survey equipment [10]. Additionally, improvements in UAV technology, such as enhanced battery life, increased payload capacity, and advanced sensors (including multispectral, thermal, and LiDAR), have expanded the capabilities of these devices, facilitating the creation of various drone-based approaches [19]. These advancements enable detailed and precise data collection, through real-time, high-resolution, and updated imagery, which can be acquired over large and inaccessible areas, making them a practical and cost-effective solution for vegetation surveys [22].

General Aim

In this study, we propose a workflow for using UAVs to evaluate the results of a pilot vegetation reinforcement programme in a coastal area in Malta and compare its accuracy and cost-effectiveness with that of ground-based methods previously used for assessing the same general area, namely manual vegetation-mapping surveys and measurements of chlorophyll-a content of plant leaves in situ, as a general assessment of 'plant health'.

Materials and Methods

The Area of Study

The pilot programme was carried out in Inwadar National Park (INP), a protected area situated along the south-eastern coast of Malta during the period from 5 January 2023 to 31 May 2024. INP, which covers an area of 0.97 km^2, is designated as a Special Area of Conservation (SAC) of National Importance (Malta Government Legal Notice 162, 2019), and is therefore part of Malta's National Ecological Network. Its land cover is predominantly rural, composed of agricultural parcels, many of which are under active cultivation. The land is terraced along a slope leading down to the shoreline, where natural, fragmented phytocoenoses are present. These mainly consist of a coastal scrubland that is superimposed a ruderal flora characteristic of habitat disturbance. Former agricultural areas that are no longer cultivated are undergoing a secondary ecological succession, creating a continuity between the rural landscape and coastal terrains.

The pilot vegetation reinforcement study was carried out in an 'intervention site' within the northwestern sector of the INP. The site was specifically chosen for its coastal maritime garrigue community, typical of the *Crithmo maritimi-Limonietum virgati* phytosociological association [5]. This association mainly consists of low-lying vegetation with a variety of halophytes and chasmophytes. The intervention site also comprises a small segment of a former agriculture field undergoing a second ecological succession ("old-field" succession), dominated by a xerophilous community with less salt-tolerant species. Margins on the south-west aspect of the site were colonised by a high richness of ruderal species, mainly annuals, grasses and geophytes at the time of survey. The intervention site covers an area of 13486 m^2, with the length of the primary and secondary axes measuring 286 m and 105 m respectively. The coordinates of the approximate centre of the site are 35°52'46" N, 14°33'43" E.

General Workflow

The study consisted of the following broad steps:

i. Initial surveying and mapping of the 'Intervention Site' using a UAV.
ii. Ground-based surveying and mapping of vegetation within the Intervention Site.
iii. Ground-based measurement of chlorophyll-a content of leaves from plants in the Intervention Site.
iv. Introduction of plantlets, representing the first stage of the vegetation reinforcement programme.
v. Repeated surveying of the area and assessment of the introduced plants during different seasons using a UAV.
vi. A brief cost-effectiveness analysis comparing the drone-based and ground-based surveys.

Mapping of the Intervention Site Using UAV

Initial Field Surveys

Multispectral imaging of the terrain in the site of study was carried out using a DJI Phantom 4 drone equipped with sensors sensitive to red, blue, green, near infrared (NIR) and red edge (RE) light and flying at an approximate altitude of 30 m above ground level in a series of 27 transects. The area overflown during this study covered 15900 m^2, with a flight path 1886 m in length, comprising 438 waypoints. The image capture had a front overlap ratio of 80 % and side overlap of 60 %. The constituent images that were used to generate the orthomosaic had a resolution of 1.6 cm/px. The flight path was programmed on DJI GS Pro running on an Apple iPad.

UAV Image Processing

The images captured during each flight were used to construct an orthorectified mosaic of the study area using Agisoft MetaShape Pro v.2.0.1 [1]. Each orthomosaic was subsequently transformed into a false-colour raster image showing the Normalised Difference Vegetation Index (NDVI) for each pixel, indicating which parts of the area of study had a reflective signature consistent with that of chlorophyll-a. The presence of chlorophyll-a in these images was assumed to represent active vegetation, an assumption that was later verified empirically through ground-truthing.

The classic NDVI formula [20] was modified to account for high soil reflectivity in the site of study. This correction was modelled on that proposed by [2], and subsequently fine-tuned iteratively until the maximum distinction between 'vegetation' and 'non-vegetation', taken as modified NDVI = 0, was attained. The modified NDVI was calculated as follows:

$$modified\ NDVI = \frac{NIR - Red}{\left(\left((NIR + Red) + 0.9\right) * 1.9\right)}$$

In the equation above 'Red' represents the intensity value of red-light (wavelength range: 650 nm ± 16 nm) and 'NIR' the intensity value of Near-Infrared light (wavelength range: 840 nm ± 26 nm). The modified NDVI formula changes the range to approximately −0.585 to 0.585, narrowing it compared to the standard NDVI range of −1 to 1. This modification makes NDVI values less sensitive to extreme values of reflectance, stabilising the index against noise or measurement errors in the data.

The raster image was subsequently imported into QGIS v.3.36.3 'Maidenhead' [17], converted to a binary image, vectorised, and all polygons representing vegetation cover filtered and identified. The cumulative area of 'vegetation' polygons was calculated, giving an estimate of the proportionate vegetation cover in the area of study.

This process was repeated three times: on 24 February 2023, 13 October 2023, and 5 April 2024, representing the 'wet season', 'late dry season', and 'late wet season' respectively. The boundaries of the orthomosaic images from which the vegetation cover was derived were kept constant across sampling sessions by anchoring the margins of the area of study to permanent, identifiable landmarks. These three vegetation maps were used as the basis of the drone-based surveys.

Ground-Based Surveys

Verification of Drone-based Vegetation Maps

The three vegetation maps obtained from the drone-based surveys were compared with those generated from a ground-based walkthrough vegetation survey using an ordinal scale to represent vegetation cover.

Association with Meteorological Data

The relation between seasonal variation in plant cover and meteorological factors was investigated by comparing proportionate vegetation cover in each of the three seasons with the values of mean maximum temperature, mean incident solar radiation, and total rainfall during a 15-day period prior to each mapping session. Weather data was obtained from a weather station at the University of Malta, providing temperature, solar radiation, and rainfall data at 30-minute intervals.

Reinforcement Programme at INP

The pilot reinforcement programme that took place within the designated 'intervention site' in INP, was part of a related study [6]. During this study, 60 plantlets were cultured in vitro and translocated into five 2 m x 2 m experimental plots within the site, on 5 January 2023 (during the wet season). The species used for targeted reinforcement were *Jacobaea maritima* subsp. *sicula* N.G.Passal., Peruzzi & Pellegrino, *Limbarda crithmoides* (L.) Dumort. and *Suaeda vera* J.F.Gmel., basing this selection on their association with the climax phytocoenosis of the characteristic *sigmetum* of the site. An equal number of species was planted in each plot.

Measurement of Chlorophyll-a Content

Determination of Chlorophyll-a Content of Translocated Plants *in situ*

The state of 'health' of the translocated plantlets was assessed empirically through the measurement of chlorophyll concentration in the leaves and compared with values from 150 leaves of the same species in other parts of INP. This was done using an Opti-Sciences CCM300 Chlorophyll Content Meter. The instrument measures the ratio between the fluorescence of chlorophyll-at 700 nm and 735 nm and converts these into an estimate of chlorophyll concentration in mg/m^2 using the equation proposed by [11].

The chlorophyll-a content of each plant in the experimental plots was estimated by selecting three leaves from each plant: one at the apex, one at the base and another in the central segment. Chlorophyll-a measurements for each leaf were recorded as the median value of five repeated readings. This process was first conducted on 31 January 2023, approximately four weeks post-translocation, and subsequently repeated after six and nine weeks. The process was also repeated at the end of the following dry season (22 November 2023) and at the end of the succeeding wet season of 2024 (5 April 2024).

Determination of 'Background' Chlorophyll-a Concentrations

Additionally, the chlorophyll-a content of 150 randomly selected leaves from each of the three target species (*J. maritima*, *L. crithmoides*, and *S. vera*) was measured to provide a comparative estimate of chlorophyll-a concentration in plants that had germinated and developed in situ. These 'comparison' leaves were sourced from plants within a radius of 100 m of the experimental plots to minimise the influence of any confounding factors arising from environmental heterogeneity. These measurements were conducted on 3 February 2023.

Relative Cost of Drone-based and Ground-based Monitoring Methods

The effectiveness of a monitoring programme to evaluate the longer-term effects of vegetation reinforcement is quantifiable in terms of its cost and of the quality of data obtained. The quality of the data of a direct, ground-based survey would always be expected to reflect the 'real' situation more accurately than a remote survey. However, if the quality of the remotely acquired data approximates (if not emulates) that of direct, ground-based methods within an accepted margin of tolerance, then the trade-off would be referred to the relative cost of the methods. The relative cost of a drone-based vegetation monitoring method compared to ground-based walkthrough surveys was estimated by breaking down both workflows ('drone' and 'manual') into a series of steps, based on the authors' direct experience of the process over several years. The steps selected were the following:

i. Purchase of equipment and software (UAV including a sufficient number of battery packs, chlorophyll meter, software licenses).
ii. Cost (in man-hours) of first survey and data processing. For the drone-based method, the first survey would incorporate the drone flight, post-processing of data, and a ground-based survey for the purposes of ground-truthing. For the manual method, this would comprise the time required for the vegetation survey and processing of its data.
iii. Cost (in man-hours) of second and subsequent surveys. For the drone-based method, this would include the drone flight and post-processing whilst for the manual method it would comprise the vegetation survey and data processing.

The cost of the whole process for a realistic monitoring programme was estimated based on four multi-seasonal surveys per year for a period of five years. The area to be monitored was conservatively estimated to be ten times larger in area than that of the intervention site (0.135 km^2; approximately 14 % of the whole area of the INP). Since the cost of equipment was estimated in currency units, this necessitated the conversion of 'man-hours' into currency, a conversion factor that varies considerably across territories. For the purposes of this study a standard man-hour rate of 40 € was utilised, consistent with the expected cost of this expertise in the Maltese job-market. The cumulative cost of the drone-based and ground-based methods was expressed as a cost-effectiveness ratio.

Results

Seasonal Change in Vegetation Coverage

The three false colour orthomosaic images representing the modified-NDVI values in the Intervention Site in three different seasons, are shown in Figure 1. Each image illustrates the vegetation cover and relative intensities of chlorophyll-a (a priori taken to be a proxy for photosynthetic activity). Whilst much of the coastal fringe was characterised by bare rock, plants typical of the coastal community in INP occurred in isolated pockets of soil. The plant assemblages had varying levels of photosynthetic activity (as indicated by the modified-NDVI value), with the confluence of vegetation cover and photosynthetic rates increasing further away from the shoreline. The photosynthetic activity of shallow-water marine algae colonising the lower coralline limestone platform along the shore is also evident.

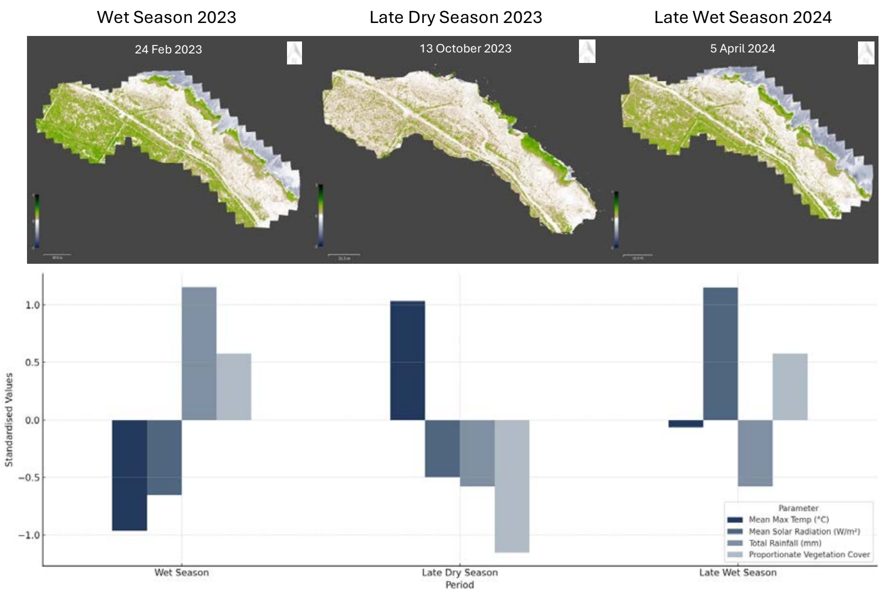

Figure 1 – Variation in vegetation cover in the INP 'intervention site' across the duration of the study. These are false-colour images representing the value of the modified-NDVI index in the area of study. The column graphs show the standardised mean maximum temperature, mean incoming solar radiation, total rainfall and proportionate vegetation cover during the 15-day period preceding each mapping date.

Across the different seasons, the change in vegetation cover is noticeable, as can be observed graphically in Figure 1. The fluctuation in vegetation cover was broadly (and predictably) associated with seasonal variation in rainfall, temperature, and incoming solar radiation, all of which are important determinants of rates of photosynthesis. No quantitative measures of association or correlation have been calculated, as the sample size was too small to permit this. Visual inspection of the results based on walkthrough assessments suggested that the outcomes were broadly comparable and certainly within the acceptable margins of error for large-scale vegetation surveys.

Temporal Variation in Chlorophyll-a Content

An overview of the "performance" of the translocated plants in terms of chlorophyll-a content throughout the monitoring programme, for each target species, is shown in Figure 2.

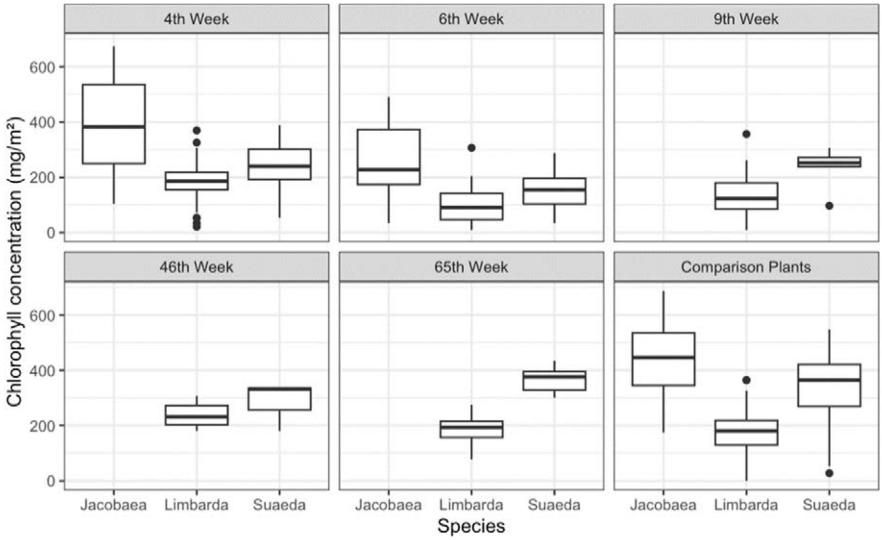

Figure 2 – Chlorophyll concentration (mg/m^2) in the leaves of each of the target species at 4, 6, 9, 46, and 65 weeks post-translocation, and the chlorophyll concentration (mg/m^2) in the leaves of the "Comparison plants" growing in situ. On the x-axis, 'Jacobaea' refers to *Jacobaea maritima* subsp. *sicula*, 'Limbarda' to *Limbarda crithmoides*, and 'Suaeda' to *Suaeda vera*.

A decline in chlorophyll-a content can be noted between the fourth and sixth weeks following translocation, followed by relative stability, where the chlorophyll concentration of the introduced plants was comparable to that of the comparison plants. The relevance of these results to this study are related to their detectability in UAV imagery. The chlorophyll-a concentration of the surviving plants in the reinforcement programme is approximately equivalent to that of the comparison plants after one year following translocation. Following a suitable calibration procedure relating chlorophyll a content to specific NDVI patterns (which was not the scope of the present study), the multispectral imagery would potentially provide information that is not limited to the extent of vegetation cover, but also the broad physiological performance of the introduced plants.

Relative Cost-effectiveness of Methods

The cumulative cost of drone-based and ground-based methods evaluation of the results of the reinforcement programme, based on a 40 € man-hour rate and a five-year multi-seasonal monitoring programme on an area ten times that of the intervention site, are shown in Figure 3A. These estimates suggest that after four sessions (one calendar year), the cumulative cost of both methods is approximately equal. By the end of the five-year monitoring programme, the total cost of the drone survey is approximately 53 % that of the ground-based manual surveys. Even if wide margins of error are allowed for, these results suggest that the drone-based method is far quicker, and therefore much less expensive, than the ground-based method. The ongoing cost difference between the drone-based and ground-based methods is summarised in Figure 3B.

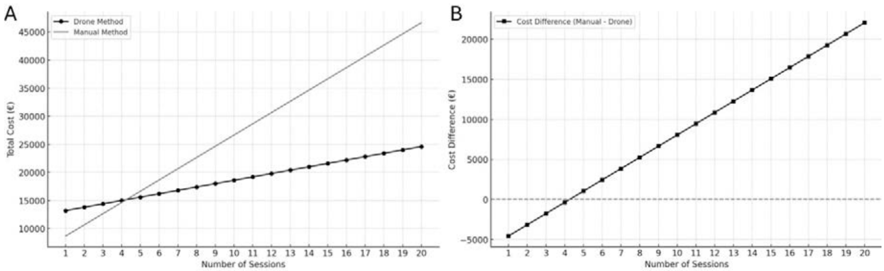

Figure 3 – Comparison of the cumulative cost of drone-based and ground-based survey methods, based on a man-hour rate of 40 €, over a five-year period (20 sessions). B. Ongoing difference in cost between ground-based (‘manual’) and drone-based methods of survey over a duration of five years (20 sessions).

Discussion

Cost Differentials

The preliminary results obtained during this study suggest that the use of UAVs to map vegetation cover using multispectral imagery gave results that were detailed enough for the intended purpose, whilst being achieved in a much shorter time period, and therefore, at lower cost, than ground-based methods. Naturally, there are other factors that need to be taken into consideration in an overall assessment. The role of meteorological factors neds to be considered in more detail. Rainy and windy conditions that would not impair a ground-based survey may render a drone flight risky. Similarly, if a study site is situated in a no-fly zone, this would make the method unfeasible. However, away from these outlier conditions, the results may be generalised to support a more widespread and economically viable use of UAVs in mapping the physiological condition of vegetation.

Sensitivity to Changes in Vegetation Cover

The multispectral imagery was able to provide very clear indications of the change in cover across seasons, in theory, down to the centimetre scale. In practice, the modified-NDVI image is an approximation of the ‘real vegetation’ and is dependent on the effectiveness of the raster transformation in recognising scales of reflectivity and on the ability of simple filters to make a binary distinction between vegetation and non-vegetation pixels in the vectorised images.

The preliminary results were also able to demonstrate that the relationship between meteorological conditions and vegetation cover is not a linear one. As a case in point, in February 2023 and April 2024, the vegetation cover was not very different even though the rainfall differed considerably, suggesting that adaptations of vegetation to dry conditions may be more important predictors of vegetation cover.

Nonetheless, this data was collected over a relatively short period of time and while it might be adequate to generate a benchmark for a pre-reinforcement phytocoenosis, long-term monitoring is required to assess the success of a reinforcement programme and allow for the implementation of adaptive management. Understanding these patterns can help in developing strategies for climate resilience, e.g. introducing drought-resistant plant species or implementing water conservation measures to mitigate the adverse effects of the dry seasons.

Importance of Chlorophyll Concentration

In general, chlorophyll content is expected to follow a general trend of initial variability and possible decline due to transplant shock [14], environmental stressors, plantlets still developing an extensive root system for optimal nutrient and water uptake [8], or not having yet adjusted to the new soil microbiome [12]. Subsequently, the chlorophyll-a content in the leaves of plants stabilises and increases, reaching a saturation point as the plants become fully acclimatised and benefit from optimal growing condition. This trend was observed in this study. Additionally, seasonal changes are also expected to impact chlorophyll levels, with lower content during dry periods and higher content during wet seasons. Eventually a season with peak photosynthetic activity is expected to be reached, generally during or post-wet season [3, 15].

Empirical assessment of re-introduced plants through the measurement of chlorophyll concentration in the leaf is considered a reliable indicator of general plant health. Chlorophyll content is directly linked to the photosynthetic capacity of plants, as it is the primary pigment involved in capturing light energy. High chlorophyll levels generally correlate with better plant vigour, productivity, and overall health. Thus, measuring chlorophyll concentration can help identify nutrient deficiencies and stress factors in plants, and chlorophyl reading methods have been employed in several studies with diverse contexts [7, 16, 18]. Moreover, the chlorophyll content is species dependent and can fluctuate dynamically with the age of the leaves, light exposure, environmental conditions and seasonal changes [3, 15].

Knowledge of the chlorophyll-a content of individual species may permit the correlation of the modified-NDVI regions with actual chlorophyll-a values, facilitating large scale assessment of the physiological performance of introduced plants in a short period of time. This study has not attempted that step but has provided data that may be used to construct a specific workflow for that purpose. It is interesting to note that the variability in chlorophyll content of the leaves in the comparison sample was higher than that recorded from the experimental plots. While this may be attributable to the difference in sample size, it could also be a result of stress that plants within the experimental plots may have been subjected to and that was not controlled for. The chlorophyll-a content of perennial species across seasons also varied synchronously with the observed modified-NDVI values, suggesting that the latter can be used as a broad proxy for the former if a specific calibration curve is constructed.

Conclusion

The general conclusion of this study is that the use of UAVs provides a cost-effective way to map, quantify and detect changes in vegetation cover and, in broad terms, to assess the physiological performance once a calibration procedure has been carried out. However, whilst providing effective methods by reducing time expenditure and capturing real-time representations of landscapes, the use of UAVs needs to be implemented with careful planning and consideration of project-specific goals so as to achieve their maximum successful integration in a vegetation reinforcement programme.

References

[1] Agisoft LLC. (2023). Agisoft Metashape Professional, Version 2.0.1. In https://www.agisoft.com/

[2] Almalki, R., Khaki, M., Saco, P. M., & Rodriguez, J. F. (2022). Monitoring and mapping vegetation cover changes in arid and semi-arid areas using remote sensing technology: a review. Remote Sensing, 14(20), 5143.

[3] Atar, F., Güney, D., Bayraktar, A., Yıldırım, N., & Turna, İ. (2020). Seasonal change of chlorophyll content (spad value) in some tree and shrub species. Turkish Journal of Forest Science, 4(2), 245-256.

[4] Bradshaw, A. (1997). Restoration of mined lands—using natural processes. Ecological Engineering, 8(4), 255-269.

[5] Brullo, S., Brullo, C., Cambria, S., & del Galdo, G. G. (2020). The Vegetation of the Maltese Islands. Springer.

[6] Camilleri, L. (2023). Ecological Restoration in Inwadar National Park. Unpublished Master of Science dissertation. Faculty of Science, University of Malta. Malta.

[7] Cervena, L., Pinlová, G., Lhotáková, Z., Neuwirthová, E., Kupková, L., Potucková, M., Lysák, J., Campbell, P., & Albrechtová, J. (2022). Determination of Chlorophyll Content in Selected Grass Communities of KRKONOŠE Mts. Tundra Based on Laboratory Spectroscopy and Aerial Hyperspectral data. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 43.

[8] Chaves, M. M., Maroco, J. P., & Pereira, J. S. (2003). Understanding plant responses to drought—from genes to the whole plant. Functional Plant Biology, 30(3), 239-264.

[9] Chazdon, R. L. (2008). Beyond deforestation: restoring forests and ecosystem services on degraded lands. Science, 320(5882), 1458-1460.

[10] Fernández-Guisuraga, J. M., Sanz-Ablanedo, E., Suárez-Seoane, S., & Calvo, L. (2018). Using Unmanned Aerial Vehicles in Postfire Vegetation Survey Campaigns through Large and Heterogeneous Areas: Opportunities and Challenges. Sensors, 18(2), 586. https://www.mdpi.com/1424-8220/18/2/586

[11] Gitelson, A. A., Buschmann, C., & Lichtenthaler, H. K. (1999). The chlorophyll fluorescence ratio F735/F700 as an accurate measure of the chlorophyll content in plants. Remote Sensing of Environment, 69(3), 296-302.

[12] Hartmann, M., Frey, B., Mayer, J., Mäder, P., & Widmer, F. (2015). Distinct soil microbial diversity under long-term organic and conventional farming. The ISME journal, 9(5), 1177-1194.

[13] Heywood, V., Shaw, K., Harvey-Brown, Y., & Smith, P. (2018). BGCI and IABG's species recovery manual. Botanic Gardens Conservation International.

[14] Lee, H., Hwang, W., Jeong, J., Yang, S., Jeong, N., Lee, C., & Choi, M. (2021). Physiological causes of transplantation shock on rice growth inhibition and delayed heading. Scientific reports, 11(1), 16818.

[15] Li, J., Lu, X., Ju, W., Li, J., Zhu, S., & Zhou, Y. (2022). Seasonal changes of leaf chlorophyll content as a proxy of photosynthetic capacity in winter wheat and paddy rice. Ecological Indicators, 140, 109018.

[16] Liu, S., Li, S., Fan, X.-Y., Yuan, G.-D., Hu, T., Shi, X.-M., Huang, J.-B., Pu, X.-Y., & Wu, C.-S. (2019). Comparison of two noninvasive methods for measuring the pigment content in foliose macrolichens. Photosynthesis Research, 141, 245-257.

[17] QGIS Development Team. (2024). QGIS Geographic Information System Version 3.36.3. In Open-Source Geospatial Foundation Project. https://www.qgis.org.

[18] Rastogi, A., Stróżecki, M., Kalaji, H. M., Łuców, D., Lamentowicz, M., & Juszczak, R. (2019). Impact of warming and reduced precipitation on photosynthetic and remote sensing properties of peatland vegetation. Environmental and Experimental Botany, 160, 71-80.

[19] Robinson, J. M., Harrison, P. A., Mavoa, S., & Breed, M. F. (2022). Existing and emerging uses of drones in restoration ecology. Methods in Ecology and Evolution, 13(9), 1899-1911.

[20] Rouse, J. W., Haas, R. H., Schell, J. A., & Deering, D. W. (1974). Monitoring vegetation systems in the Great Plains with ERTS. NASA Spec. Publ, 351(1), 309.

[21] Sparrow, B. D., Foulkes, J. N., Wardle, G. M., Leitch, E. J., Caddy-Retalic, S., van Leeuwen, S. J., Tokmakoff, A., Thurgate, N. Y., Guerin, G. R., & Lowe, A. J. (2020). A Vegetation and Soil Survey Method for Surveillance Monitoring of Rangeland Environments [Methods]. Frontiers in Ecology and Evolution, 8. https://doi.org/10.3389/fevo.2020.00157

[22] Tavilla, G., Crisafulli, A., Minissale, P., Tomaselli, V., & Adamo, M. (2024). The Use of Drones for Cost-Effective Surveys in Natura 2000 Protected Areas: A Case Study on Monitoring Plant Diversity in Sicily (Italy). Land, 13(6), 804. https://www.mdpi.com/2073-445X/13/6/804

[23] Walker, L. R., & Del Moral, R. (2003). Primary succession and ecosystem rehabilitation. Cambridge University Press.