MAPPING *YUCCA GLORIOSA* IN COASTAL DUNES: EVALUATING THE COST AND TIME EFFICIENCY OF PHOTOINTERPRETATION, MACHINE LEARNING AND FIELD DETECTION APPROACHES

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Abstract: Biological invasions threaten biodiversity and cause significant economic and ecological damages. Effective management of invasive species is crucial, as highlighted by the European Community's Regulation 1143/2014 on Invasive Alien Species (IAS). This study focuses on coastal dune ecosystems, particularly assessing the time and cost-effectiveness of three monitoring methods for detecting and mapping alien plants: photointerpretation, machine learning classification, and field monitoring. *Yucca gloriosa* L., an invasive plant in Regional Park of Migliarino-San Rossore-Massaciuccoli (Tuscany, Italy), served as the target species. Using RGB DJI Phantom 4 Pro v. 2.0 and DJI P4 Multispectral drones, images were analyzed via photointerpretation and machine learning. Photointerpretation, though precise, was time-consuming and subjective. Machine learning minimized human effort but required extensive computing. Field monitoring produced accurate maps but was labor-intensive and limited by accessibility issues. This study concludes that UAV-based monitoring of *Y. gloriosa* is optimal for balancing cost and time efficiency in coastal dune ecosystems.

Keywords: alien plants, drones, monitoring, RGB and multispectral, mapping

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Introduction

Coastal dunes are dynamic transitional environments characterized by strong sea-to-inland gradients, which profoundly shape the composition of plant communities [1,9]. Serving as primary barriers against the impacts of climate change, encompassing rising sea levels and extreme weather phenomena, coastal ecosystems provide invaluable services such as coastal protection and carbon sequestration [2,29,31]. However, these habitats face substantial global threats due to human-induced activities, notably urbanization, tourism, and coastal erosion [10,14]. According to the 4th European report on habitat conservation, over 85% of coastal habitats are in poor conservation status, with a deteriorating trend [34].

Of considerable concern is the phenomenon of biological invasions, facilitated by human mobility, resulting in the translocation and colonization of species from their native areas to new regions [35]. Invasions by alien plant species often lead to flora homogenization, biodiversity loss driven by competition for space and other resources, as well as changes in biogeochemical cycles [11,21,37]. Beyond biodiversity implications, invasions pose significant economic challenges. A previously estimated 20 billion euros annually are required for monitoring, controlling, and mitigating the impacts of alien species in Europe [18], and to date the costs are almost certainly increased. To address this, the European Community enacted Regulation 1143/2014, providing explicit outlines for the prevention, reduction, and mitigation of alien species impacts on ecosystems. Effective management of alien species includes prevention, early detection and eradication, and control [7]. Prevention is paramount to mitigate the introduction of new species, while early detection and eradication protocols are crucial when preventive measures fail. Conversely, established populations of alien species require ongoing management and control efforts [7,38]. Monitoring plays a vital role in assessing species propagation and devising strategies to safeguard native biodiversity [7].

Field monitoring predominates as the method for tracking alien plant species distribution, often requiring substantial sampling efforts and the involvement of botanical experts. This entails significant temporal and economic investments, compounded by potential inaccessibility in certain areas. Field monitoring is particularly favored in contexts like forest ecosystems, especially for examining canopy-inhabiting species [8,13].

In recent decades, innovative methodologies have emerged for surveilling alien plant species, notably through satellite or drone imagery analysis [28,41]. A multitude of such images are now readily accessible, offering crucial high resolutions for coastal habitat studies [19,27]. Remote Sensing assumes significance for its seamless acquisition of continuous spatial data over time [17,20,39]. Utilizing drone or satellite imagery, for photointerpretation, and semi-automatic or automatic monitoring tools for alien species, allows for reduced time and cost in monitoring activities, expanded study areas, and access to previously inaccessible regions [25].

Along Mediterranean coastal dunes, particularly in Tuscany (Italy), *Yucca gloriosa* L. stands out as one of the most invasive alien plants. Native to the eastern coasts of North America, this species was introduced to Europe primarily for its ornamental qualities, notably its large whitish inflorescence [15,33]. Characterized by a caespitose growth habit and elongated ribbon-like foliage, *Y. gloriosa* faces challenges in sexual reproduction due to the absence of *Yucca* pollinators in European ecosystems. Instead, it relies on rhizome propagation, leading to rapid expansion and the formation of dense monospecific nuclei. Physiologically, *Y. gloriosa* displays an intermediate photosynthetic pathway between C3 and CAM, enhancing its resilience to drought conditions [36]. Moreover, its unique photosynthetic metabolism yields distinct spectral characteristics, which can be exploited for monitoring via multispectral imaging techniques [5]. In Tuscany, *Y. gloriosa* predominantly colonizes fixed dunes alongside *Juniperus* sp. pl., habitats of priority relevance to the European Community, necessitating ongoing monitoring efforts for effective management.

The aim of this work is to compare three methodologies used for monitoring *Y. gloriosa* in coastal dunes within Tuscany: field monitoring, image photointerpretation, and machine learning. The evaluation will focus on their cost and time efficiencies to suggest effective management measures.

Figure 1 – Study area highlighted in red within Bufalina Reserve in the Regional Park of Migliarino - San Rossore - Massaciuccoli from Google Satellite image (2024 Airbus).

Materials and methods

Study area

The study area encompasses a portion of coastal dunes within the Regional Park of Migliarino-San Rossore-Massaciuccoli in northern Tuscany. This park, spanning approximately 230 km^2, features a Mediterranean climate, with an average temperature of 15.2 °C and average annual rainfall of 879 mm recorded between 1991 and 2020 (https://www.lamma.toscana.it/clima-e-energia/climatologia/clima-pisa). Specifically, our focus lies on the coastal area of 3-ha inside the Bufalina Reserve, which spans 4 km of coast between Marina di Vecchiano (Pisa) and Torre del Lago (Lucca), covering a total area of about 30 ha (Fig. 1). The dune ecosystems within our study area represent some of the best preserved in Tuscany, hosting the whole psammophilous series and a variety of endemic species, such as *Centaurea aplolepa* Moretti subsp. *subciliata* (DC.) Arcang and *Solidago virgaurea* L. subsp. *litoralis* (Savi) Briq. & Cavill. However, since the 2000s, the Bufalina Reserve has faced biological invasions by plant species such as *Oenothera* sp. pl., *Amorpha fruticosa* L. and *Yucca gloriosa* L., leading to the initiation of the LIFE project DUNETOSCA (2005-2009) aimed at monitoring and eradicating these invasive species [32].

Remote sensing and field monitoring

To map the distribution of *Y. gloriosa* within the study area using Remote Sensing, we employed Unmanned Aerial Vehicles (UAVs) to collect drone imagery, utilizing two distinct types: the DJI Phantom 4 Pro v. 2.0 for Red-Green-Blue (RGB) images, and the DJI P4 Multispectral for multispectral imagery. The first UAV is equipped with a 20-megapixel RGB camera and a 1-inch CMOS sensor, enabling the capture of high-resolution images (less than 1 cm/px), with a flight autonomy of approximately 30 minutes contingent upon altitude and weather conditions. Conversely, the multispectral UAV features six 2 Mpx sensors, including five for spectral bands (Blue 450 nm ± 16 nm, Green 560 nm ± 16 nm, Red 650 nm ± 16 nm, Red Edge 730 nm ± 16 nm, and Near Infrared 840 nm ± 26 nm) and one for RGB. To standardize multispectral data, calibration panels with specific reflectance values were positioned on the ground. These images obtained with this drone were subjected to a 5 cm/px resampling due to the large amount of data related to multispectral images; furthermore, the DJI P4 Multispectral was employed to capture data for the Digital Surface Model (DSM) using a Structure-from-Motion (SfM) approach. This method accurately depicts the terrain's topography and surface features, including vegetation and structures, by generating a dense point cloud. To acquire UAV images, the open-source software PIX4DCapture (https://www.pix4d.com/it/) was employed. This software facilitates the planning and execution of flights, allowing for the selection of the study area and the overlap between collected images. The UAV flights were performed at 30 m and 35 m respectively for multispectral and RGB images, setting their image overlap to 90 % and 80 %. All flights were conducted between 12:00 a.m. and 2:00 p.m. to minimize the shading effect, which could impact photointerpretation [30]. Subsequently, Agisoft Metashape (https://www.agisoft.com/) was utilized for the image orthorectification phase. This involved generating large orthophotos for both RGB monitoring and all spectral bands. For all the processing phases, an IntelCore i7 computer with 64 GB RAM and 4 TB hard memory was employed.

The RGB orthophotos collected were used for mapping *Y. gloriosa* in the study area through photointerpretation. This method was developed by uploading the orthophotos on the open-source geographic information system QGIS (https://qgis.org/it/site/, versions 3.16 and subsequent). This software allowed an easily manual creation of polygons around the shape of the invaded nuclei; further details are described in [4].

A machine learning approach was developed to monitor *Y. gloriosa*'s distribution in the study area by using DSM, RGB and multispectral images [5]. Vegetation indices, such as Green Normalized Differences Vegetation Index (GNDVI), Normalized Differences Vegetation Index (NDVI) and Optimized Soil Adjusted Vegetation Index (OSAVI) were extracted from multispectral images and were employed for the analysis. Those indices furnish ecological and physiological information about the environment, and all are suggested for monitoring biomass and photosynthetic efficiency. Those three indices are suggested in other studies about alien plant monitoring through images [16,23,24].

Firstly, the RGB orthophoto of 1-ha inside the study area was subjected to image segmentation following a Geographic Object Based Image Analysis approach (GEOBIA), which is recognized as successful in alien plants detecting [3,16,23]. Then for classification, we employed Random Forest algorithm on R (https://www.r-project.org/) by reference photointerpreted classified points to distinguish between invaded and non-invaded areas. The information learnt by the algorithm was used for predicting *Y. gloriosa*'s cover in the remaining 2 ha.

On the other hand, monitoring of alien plants primarily occurs in the field through visual identification and coverage estimation utilizing transects or vegetation plots, such as those employing the Braun-Blanquet cover scale. In our investigation, we merged information gathered from various projects to compare the time and resource expenditure associated with this monitoring methodology. Initially, we sourced data from the LIFE project "DUNETOSCA" report [32] for obtaining information about the costs of creating *Yucca gloriosa* maps across the study area through merging pre- and post-eradication field phytosociological monitoring with aerial image analysis for shapefile generation. Subsequently, information regarding time and costs for field monitoring was obtained from an ongoing project. In this project, three botanical experts deployed 302 random points in the study area to assess the field effort and validate the maps created using photointerpretation and machine learning.

Costs, time, and accuracy assessment

Regarding the cost estimations for monitoring, they have been derived through a comprehensive survey evaluating the pricing quoted by experienced professionals within the pertinent field. On average, the remuneration per hour for an operator is approximately 50 euros. Conversely, the cost projections for field monitoring within the LIFE project DUNETOSCA were estimated at approximately 7500 € for the whole Bufalina Reserve [32], while the expense for identifying field points corresponding to 1 % of the study area was about 750 € for 5 hours. For UAV monitoring, acquiring the licensed application for orthomosaics generation, Agisoft Metashape, costs approximately 200 €.

Regarding the temporal requirements for conducting the monitoring, data has been amassed from flight planning and execution, reports from Agisoft Metashape, and personal field experience pertaining to photointerpretation and the GEOBIA approach. For assessing the accuracy of the photointerpretation and machine learning maps, we involved the 302 random points. Typical accuracy metrics suggested for Remote Sensing were calculated [6,40], such as:

- Overall Accuracy (OA): (TP+TN)/(TP+FN+TN+FP);
- Cohen's Kappa (K): (Po-Pe)/(1-Pe)
- True Skills Statistics: TP/(TP+FN)+TN/(TN+FP)-1
- Balanced Accuracy: 0.5 × TSS + 0.5.

Here, True Positives (TP) and True Negatives (TN) represent the correctly classified points in comparison to field identification. False Positive (FP) are points classified on the map as invaded, but in reality, they are not, while False Negative represents the opposite situation.

Results and Discussion

In this project, we collected information from different studies on *Yucca gloriosa* monitoring in the study area for assessing the time- and cost-effectiveness of those methodologies and offering recommendations for management strategies.

Regarding methodologies employing UAV imagery, the expenses primarily involve the procurement of software for orthorectification, Agisoft Metashape, which amounts to approximately 200 €, exclusive of drone-related costs. Notably, other software utilized, including QGIS, PIX4DCapture, Orfeo ToolBox, and R, are open-source alternatives. The duration necessary for acquiring UAV imagery and generating orthomosaics over the 3-hectare expanse spans approximately one hour for both flight planning and execution, with an additional hour for orthomosaic generation. These procedures demand minimal human involvement, primarily centered around organizational tasks and conducting the UAV flight operations.

Regarding photointerpreting the distribution of *Yucca gloriosa* within the 3-hectare zone, our estimation indicates that a single expert operator would require approximately 40 hours of work, corresponding to an approximate cost of 2300 €, considering also the costs related to the drone operator.

The adoption of this methodology unveils challenges associated with human operator subjectivity and the shadow effect. Mitigating the influence of these challenges entails the option of conducting subsequent photointerpretation by the same operator and strategically scheduling UAV monitoring sessions between the hours of 11:00 and 14:00 to minimize the impact of shadows [4,25,30].

Conversely, the application of machine learning through Geographic Object-Based Image Analysis (GEOBIA) and the Random Forest approach requires less human intervention compared to the alternative methodologies under consideration. Upon acquisition of UAV imagery, the process of generating high accuracy prediction maps typically spans approximately three days, with related costs estimate to about 1200 €. Nevertheless, this methodology entails substantial computational resources and a foundational understanding of spectral variable combinations to effectively discern the target species.

On the other side, data pertaining to the expenditure associated with field monitoring of *Yucca gloriosa*'s cenosis within the scope of the LIFE project "DUNETOSCA" revealed considerable financial implications. Specifically, the project report delineated an estimated expenditure of 7500€ for botanical monitoring activities. This methodology provided phytosociological relevés, enabling the creation of vegetation maps and floristic inventories within Bufalina Reserve [32]. Alternatively, to ascertain the temporal demands associated with botanical monitoring, data was acquired from an ongoing project in which certain members of our team were involved. Within this context, the evaluation of *Y. gloriosa* distribution of 302 random points across the study area within the Bufalina Reserve engaged the expertise of three botanical specialists for approximately 5 hours. This calculation indicates that, at an average rate of 50 € per hour for each botanical expert, an expenditure of 750 € is necessitated for monitoring *Y. gloriosa* coverage across an area spanning 300 m^2, which corresponds to 1 % of the whole study area. Beyond the substantial investments in time and human resources, field monitoring offers the distinct advantage of accurately identifying species and producing maps of exceptional precision (Tab. 1). Conversely, accessing certain unreachable areas poses challenges for field monitoring, a limitation effectively circumvented by the utilization of Unmanned Aerial Vehicles.

Table 1 – Comparison between costs and accuracy of three *Yucca gloriosa* mapping methodologies

	Costs	Time	Accuracy
Field monitoring	7500 €	500 hours	-
Photointerpretation	2300 €	42 hours	OA 0.95 | K 0.87 TSS 0.85 | BA 0.93
Machine learning	1200 €	20 hours	OA 0.97 | K 0.91 TSS 0.873 | BA 0.94

In summary, the selection of suitable methodologies for monitoring alien plant species in imagery relies primarily on their morphological, phenological, and spectral attributes, alongside image resolution [26]. Within coastal dune environments, the utilization of very high-resolution imagery is essential for distinguishing species within fragmented habitats and drives to high accuracy maps (Fig. 2). In this regard, Unmanned Aerial Vehicles offer the capability to acquire high-resolution images in a flexible and reproducible manner [16,22].

Figure 2 – Comparison between field, photointerpretation and machine learning monitoring of *Yucca gloriosa*.

Conclusions

In conclusion, through a comparative analysis of three mapping methodologies for the invasive alien plant *Yucca gloriosa* within a designated area on coastal dunes, it was determined that field monitoring is the most resource-intensive in terms of time and cost for generating accurate maps. Consequently, we recommend monitoring the distribution of the target species by strategically scheduling annual UAV flights to assess trends in its distribution over time. The methods exhibited high accuracy rates and cost reductions, rendering photointerpretation or machine learning more favorable alternatives to field monitoring. Nonetheless, we suggest that field monitoring could be used one-off and concentrating in small areas for assessing the accuracy of Remote Sensing.

An intriguing avenue for further exploration involves repeating both photointerpretation and machine learning processes on images acquired during different months. This approach aims to identify the most effective month for distinguishing *Yucca gloriosa*, considering its distinctive phenological and physiological characteristics, which may enhance its differentiation from the surrounding environment.

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