Individual Tree Species Classification in a Mediterranean Ecosystem using UAV-Acquired Multispectral Images and Machine Learning

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Abstract

This study investigates the classification of individual tree and shrub species within a complex Mediterranean ecosystem using UAV-acquired multispectral imagery and machine learning techniques. Conducted on Culuccia Island (Sardinia, Italy), the research integrates high-resolution photogrammetric products with Object-Based Image Analysis (OBIA) and a Random Forest classifier to delineate and identify vegetation species at the crown level. A total of 272 geo-referenced samples from 16 species were used to train and validate the model, which achieved an overall accuracy of 0.71. The workflow demonstrates the effectiveness of single tree segmentation in highly heterogeneous environments and highlights the potential of phenology-informed feature sets for improving classification. The results underscore the value of UAV-based methods in conservation monitoring, ecological assessment, and habitat management. Future research directions include the integration of LiDAR data, deep learning architectures, and multi-temporal observations to enhance scalability and model interpretability.

1. Introduction

The classification and monitoring of vegetation species in coastal and insular ecosystems are critical for biodiversity conservation, sustainable resource management, and compliance with European directives such as the Habitats Directive 92/43/EEC. These areas are characterised by unique ecological features, including high salinity, poor and shallow soils, strong seasonal dynamics, and a diverse mosaic of vegetation structures. Accurate recognition of plant species, particularly at the individual level, is essential for assessing conservation status, understanding successional processes, and supporting restoration or mitigation planning. While field-based surveys remain the traditional approach for species-level monitoring, they are often labour-intensive, time-consuming, and logistically challenging, particularly in complex or remote terrain. As such, remote sensing technologies, including high-resolution UAV (Uncrewed Aerial Vehicle) imagery and satellite observations, are increasingly leveraged to overcome these limitations. UAV-based approaches, in particular, offer significant advantages in terms of spatial, spectral, and temporal resolution, providing a flexible and cost-effective means of capturing fine-scale ecological information (Belcore et al., 2021; Fassnacht et al., 2016).

In recent years, the integration of UAV-acquired multispectral and hyperspectral imagery with advanced machine learning (ML) techniques has significantly advanced the capabilities of species-level vegetation mapping. Object-Based Image Analysis (OBIA), coupled with supervised classifiers such as Random Forest (RF) and Support Vector Machines (SVM), has proven effective for delineating individual tree crowns and assigning them to species categories based on spectral, geometric, and textural features (Takahashi Miyoshi et al., 2020; Michez et al., 2016). These methods can incorporate both spectral reflectance characteristics (e.g., red-edge, NIR) and phenological traits derived from multi-temporal datasets, enabling improved species discrimination even in structurally complex environments

UAV platforms enable tailored, high-frequency data acquisition that is especially valuable for phenology-based classification, wherein plant species are characterised by their seasonal growth stages. Studies have demonstrated that UAV data collected at key phenological epochs, such as pre-green-up, flowering, and full canopy development, can significantly increase classification accuracy. For instance, Belcore et al. (2021) showed that the overall F1-score for species classification in riparian habitats increased by 0.3 when three phenological epochs were included instead of two.

Nevertheless, species classification using UAV and AI technologies still faces critical challenges. Mediterranean ecosystems, such as those in coastal and insular areas, often consist of dense, multi-layered vegetation with low height variation and overlapping canopies. These conditions lead to common issues such as under-segmentation, high intra-species spectral variability, and limited spectral separability among different species. Moreover, the accuracy of classification models is often constrained by the availability of balanced, high-quality ground-truth data and the need for extensive feature engineering (Belcore et al., 2021; Xu et al., 2020).

Recent studies have emphasized the benefits of employing data balancing strategies—such as SMOTE (Synthetic Minority Oversampling Technique)—and of integrating canopy height models (CHMs) derived from UAV photogrammetry or LiDAR to enhance vertical differentiation among species (Shi et al., 2020). These approaches are especially relevant for detecting less dominant or structurally distinct species, such as Pinus sylvestris or Salicornia europaea, which may otherwise be underrepresented. Looking forward, the incorporation of deep learning architectures—particularly convolutional neural networks (CNNs)—offers promising avenues for automated and scalable vegetation mapping. CNNs have demonstrated superior performance in tasks involving complex spatial patterns and can learn hierarchical features directly from image data without extensive manual preprocessing (Egli and Hopke, 2020; Kattenborn et al., 2021; Boston et al, 2024).

Moreover, recent advances in explainable artificial intelligence (XAI) are beginning to peel back deep learning models' "black-box" nature providing interpretable visualizations such as saliency maps, Class Activation Maps (CAM), and feature attribution techniques that help elucidate which image features most influence model decisions (Samek et al., 2017; Montavon et al., 2018). For instance, Matrone et al. (2022) introduced BubblEX, an XAI framework that produces saliency-style visualisations and interpretability modules for 3D point-cloud data, showing how specific features and neighbourhoods contribute to model decisions. These methods are highly relevant in ecological settings, where transparency and interpretable model outputs are essential for scientific validation and practical environmental management.

Despite the increasing adoption and interest in these analyses, several challenges persist in species classification, which can be grouped into technological limitations and the specific characteristics of the forest types under examination. The most significant challenges include: low detection rates for small trees and shrubs, under-segmentation caused by high vegetation density and limited height differences among specimens, over-segmentation and limited classification precision, low spectral variability between species, and high intra-class spectral variability at very high resolutions.

These challenges are especially pronounced in Mediterranean woodlands, which are characterized by small trees and shrubs, a complex and stratified structure, and patchy vegetation cover. Moreover, due to the unique nature of the Mediterranean Ecosystem and the high variability in structure and composition, developing a generalizable species classification and detection model remains highly complex.

2. Materials and Methods

2.1 Study site

Culuccia Island, also known as *Isola delle Vacche*, is a promontory spanning approximately 320 hectares connected to the mainland by a narrow sandy isthmus. It is located in the Gallura region, along the northeastern coast of Sardinia, Italy (Figure 1). Geographically, the island is situated within the Gulf of Arzachena, near the La Maddalena Archipelago National Park. This area holds significant conservation interest, having been designated as a Site of Community Importance (SCI) with code ITB010008, under the Habitats Directive 92/43/EEC, due to its high biodiversity and the presence of priority habitats.

Climatically, the island is characterised by a thermo-temperate Mediterranean climate (Csa type according to the Köppen-Geiger classification), featuring hot, arid summers and mild, moderately rainy winters. Intrusive rocks of the Hercynian basement dominate the site's geology, primarily granites and granodiorites, which give rise to an undulating landscape with rocky outcrops and shallow, acidic sandy soils with limited water retention capacity (Figure 2).

The vegetation is a typical example of Mediterranean maquis, a complex mosaic of plant communities whose structure and composition are determined by topography, exposure to dominant winds, particularly the Mistral. The vegetation cover is dominated by evergreen sclerophyllous formations, which can be distinguished into: tall maqui, a dense scrubland up to 4-5 meters high, dominated by tree and shrub species such as Phoenicean juniper (*Juniperus phoenicea*), wild olive (*Olea europaea var. sylvestris*), mastic tree (*Pistacia lentiscus*), and broad-leaved phillyrea (*Phillyrea latifolia*); Low maquis and garrigue: more open and lower-height formations (0.5-1.5 meters), where prevalent species include common myrtle (*Myrtus communis*), various cistus species (*Cistus spp.*), spiny broom (*Calicotome villosa*), and Italian everlasting (*Helichrysum italicum*).

A salient feature of this vegetation landscape is its high structural heterogeneity, with individuals of different species growing in dense aggregates, often with overlapping and interpenetrating canopies. This complexity represents a significant challenge for remote sensing techniques for Individual Tree Detection. Culuccia Island constitutes an ideal study site; it is a representative, ecologically intact, and sufficiently circumscribed ecosystem to test and validate a high-resolution single tree classification methodology.

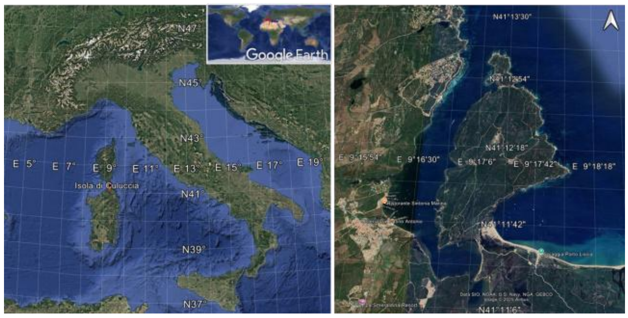

Figure 1. Geographic context of the study site, Culuccia Island, in the northern part of Sardinia.

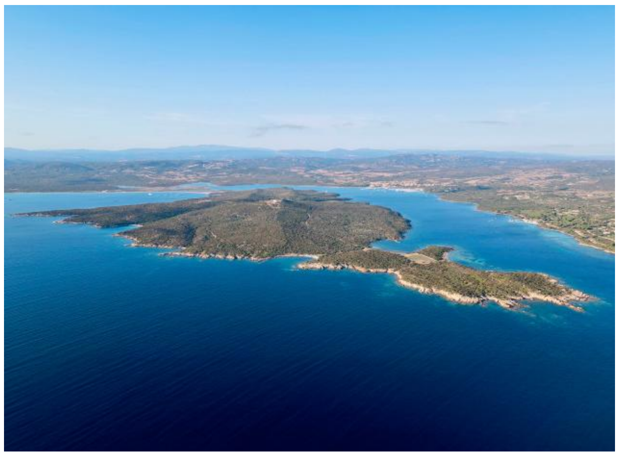

Figure 2. Aerial view of Culuccia Island.

2.2 UAV Data Collection and Pre-Processing

UAV data were collected using a DJI Mavic 3M RTK multirotor drone, equipped with four 1/2.8-inch CMOS 5 MP multispectral sensors, specifically capturing Green (560 ± 12.5 nm), Red (650 ± 10 nm), Red Edge (730 ± 10 nm), and Near-Infrared (860 ± 13 nm) bands. Additionally, a wide-angle camera with a 4/3 CMOS 20 MP sensor and a 24 mm (35 mm equivalent) lens was utilized to capture RGB (Red, Green, Blue) information, providing high-resolution visual context.

Flight missions were executed autonomously, ensuring consistent data acquisition parameters (Figure 3). An average flight altitude of 70 m above ground level was maintained, resulting in an average Ground Sample Distance (GSD) of approximately 1.50 cm/pixel for the RGB camera, while the multispectral cameras produced a GSD of approximately 3 cm/pixel. To ensure comprehensive coverage and sufficient data for accurate photogrammetric reconstruction, images were acquired with substantial longitudinal and transverse overlap of 80% and 60% respectively. Over 40,000 images were captured, collectively covering the entire 3.2 km² study area.

The acquired UAV data underwent a standard Structure-from-Motion (SfM) photogrammetric workflow (Turner et al., 2012; Calantropio et al., 2018; Cortesi et al., 2022; Giordano et al, 2025) using Agisoft Metashape Professional software (version 2.1.0).

The processing pipeline included several key steps: initial image alignment, generation of a dense 3D point cloud (Figure 3), construction of a Digital Surface Model (DSM) (Figure 4) and a Digital Terrain Model (DTM), and a high-resolution multispectral orthomosaic (Figure 4).

Georeferencing of the final products was achieved directly through the drone's integrated dual-frequency GNSS receiver. To further verify and optimise the geometric accuracy of the measurements and to refine the alignment of images and the 3D model, 38 known ground coordinate points were used. These included 26 Ground Control Points (GCPs) and 12 Check Points (CPs), all easily identifiable within the imagery. These points were measured in the field using the Network Real-Time Kinematic (NRTK) GNSS technique. The rigorous georeferencing process resulted in a remarkable final accuracy of 1.5 cm in the planimetric component and 3 cm in the altimetric one.

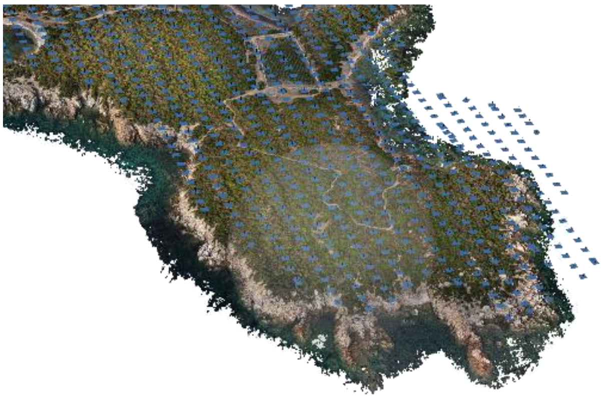

Figure 3. Flight plan and dense point cloud of the island's northern part.

Figure 4. Digital Surface Model, on the left, and Orthomosaic, on the right, of the northern part of Culuccia Island with a spatial resolution of 3 cm/pixel.

2.3 Ground-Truth Vegetation Species Data Collection

A comprehensive geodatabase of tree and shrub species present was compiled to train and validate the vegetation classification. This involved extensive ground-truthing, during which 272 individual samples of 16 distinct species were identified and geo-referenced (Figure 5). These samples were meticulously selected based on their clear discernibility in the high-resolution RGB orthophotos and multispectral imagery, ensuring that their spectral and geometric characteristics could be accurately extracted for machine learning training and validation.

Each sampled tree or shrub's crown centroid was recorded with a high-precision Leica GS18 GNSS RTK receiver, achieving sub-centimetre positional accuracy. This precise georeferencing of individual tree locations served as the ground truth data. The composition of the sampled species highlights the dominance of a few key taxa within the study area. Phoenicean juniper (*Juniperus phoenicea*) was the most frequently sampled species, accounting for 96 individuals (35% of the total). Following this, Common myrtle (*Myrtus communis*) represented a significant portion with 49 samples (18%). Other notable species included Lentisk (*Pistacia lentiscus*) and a variety of other Mediterranean maquis components, each contributing a smaller percentage to the overall sample count, such as *Spartium junceum*, *Juncus acutus*, *Salicornia europaea*, *Cistus monspeliensis*, *Helichrysum italicum*, *Limonium sp.*, *Phillyrea angustifolia*, *Inula crithmoides*, *Arbutus unedo*, *Erica arborea*, *Lavandula stoechas*, and *Olea europaea var. sylvestris*. The cumulative samples for these other 14 species accounted for the remaining 47% of the geodatabase.

This robust geodatabase, compiled with high-precision NRTK GNSS measurements and combined with the accurately processed UAV imagery, provided the essential foundation for developing and validating the individual tree species classification methodology.

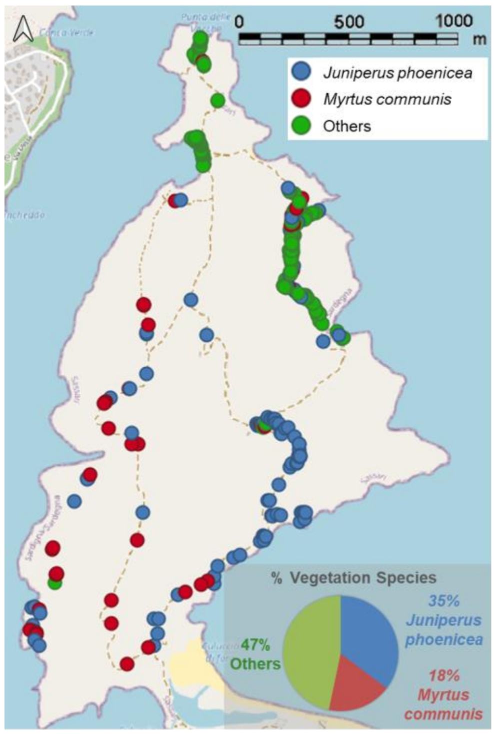

Figure 5. Distribution of ground-truth vegetation samples collected for model training and validation.

2.4 Vegetation Classification Methodology

The methodological workflow for classifying individual tree species involved a multi-stage approach encompassing initial vegetation segmentation, individual tree crown delineation, comprehensive feature extraction, and a machine learning classification algorithm.

2.4.1 Individual Tree Detection and Feature Extraction

This section details the methodology used to accurately identify individual trees and extract a comprehensive set of descriptive features crucial for vegetation characterisation. This process was implemented within the Trimble eCognition Developer software.

Firstly, a preliminary vegetation segmentation was performed to distinguish vegetated areas from bare soil and other non-vegetated surfaces. This step utilized an object-based approach that applied multi-thresholding techniques on spectral indices, such as the Normalized Difference Vegetation Index (NDVI), and height information derived from the Normalized Digital Surface Model (NDSM) (Figure 6). This allowed for the effective separation of ground cover from vegetation (Figure 7a) and a subsequent differentiation between low-lying herbaceous and shrub vegetation and taller arboreal structures (Figure 7b), optimising the subsequent individual tree detection.

Following this initial segmentation, individual tree crown detection and delineation (Figure 7c) were achieved using a multi-resolution segmentation algorithm. This Object-Based Image Analysis (OBIA) approach was tailored to identify and segment individual tree objects by analysing homogeneity criteria based on pixel values from various image layers (e.g., multispectral bands, NDVI, and NDSM). The segmentation parameters were dynamically optimised for different vegetation strata (i.e., low vs. high vegetation) to ensure accurate crown delineation across the diverse structural complexity of the Mediterranean maquis. This process resulted in the generation of numerous spatially distinct vegetation segments, each representing a potential individual tree or a defined vegetation clump.

For each individual tree vegetation object, a comprehensive set of 72 descriptive features was extracted. This included spectral features such as the mean, skewness, and standard deviation of pixel values across all multispectral (Green, Red, Red Edge, Near-Infrared) and RGB bands. Various established spectral indices were also calculated, including NDVI, NDSM, GRVI (Green-Red Vegetation Index), NDWI (Normalized Difference Water Index), and SAVI (Soil-Adjusted Vegetation Index), which offer key insights into vegetation health, photosynthetic activity, and water content. To characterize the spatial arrangement and perceived roughness of tree crowns, texture features were derived from the Haralick Co-occurrence Matrix (Haralick et al., 1973). These included metrics such as Angular Second Moment, Contrast, Correlation, Dissimilarity, Entropy, Homogeneity, Mean, and Standard Deviation, computed from significant bands like Green and Near-Infrared. Texture features are essential for differentiating species that may have similar spectral signatures but distinct canopy structures. Additionally, geometric features like compactness and colour transformation features, such as hue derived from various band combinations, further enhanced the descriptive power of each segmented object. This extensive feature set provides a multi-dimensional representation for each vegetation species, forming the foundation for subsequent machine learning classification.

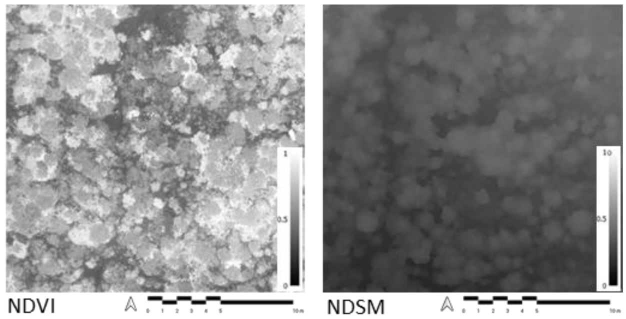

Figure 6. NDVI map (left) and NDSM (right) used for vegetation analysis.

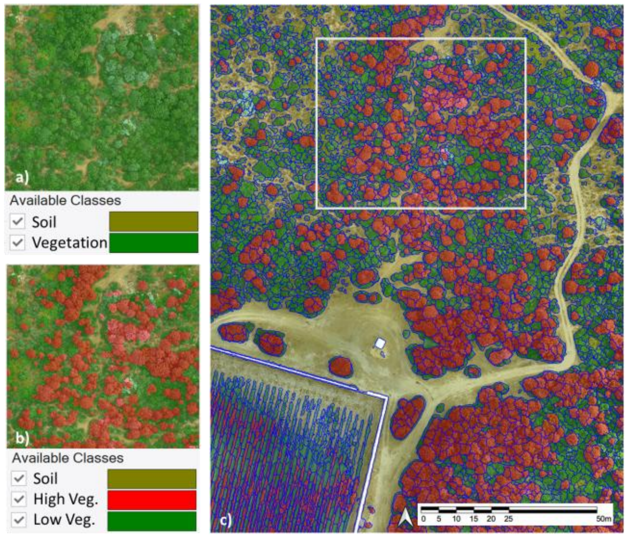

Figure 7. Sequential segmentation strategy for vegetation analysis: a) Bare soil and vegetation segmentation; b) High and low vegetation segmentation; c) Individual tree segmentation.

2.4.2 Classification Algorithm

The extracted features from the individual vegetation objects were subsequently used as input for the classification model. The Random Forest (RF) algorithm (Breiman, 2001) was selected for its robustness, proven ability to handle high-dimensional data, effective management of complex non-linear relationships, and reduced susceptibility to overfitting, making it particularly suitable for this classification application. Prior to training the RF model, the ground-truth dataset underwent several crucial preparation steps to optimize classification performance. The collected ground-truth samples were thoroughly prepared and cleaned, ensuring data quality and consistency for model input. To enhance the representation of minority classes and prevent algorithmic bias towards dominant species, oversampling techniques were applied to augment the training dataset for these underrepresented categories. The model was configured with a specific number of estimators designed to ensure stable and robust predictions, utilizing the GINI impurity criterion for optimal node splitting within each tree. A feature selection process, based on the GINI impurity metric, was also applied to identify and retain the most discriminative features, thereby reducing dimensionality and enhancing computational efficiency without compromising classification accuracy. For model validation, the Leave-One-Out (LOO) cross-validation strategy was implemented, providing a comprehensive assessment of the model's generalization capabilities by iteratively training on nearly the entire dataset and testing on a single, independent sample.

3. Results and Discussion

The application of the developed OBIA and Random Forest classification workflow yielded comprehensive results regarding the identification and spatial distribution of vegetation species within the Culuccia Island study area. The Random Forest model's overall accuracy was 0.71, with a standard deviation of 0.18. Table 3 presents a more detailed performance assessment of the individual species classes, providing insights into Precision, Recall, and F1-score.

Metrics	*Juniperus phoenicea*	*Myrtus communis*	*Salicornia europea*	*Juncus acutus*	Other
Precision	0.77	0.65	0.95	0.74	0.75
Recall	0.82	0.58	0.95	0.86	0.73
F1-Score	0.80	0.55	0.95	0.80	0.74

Table 1. Per-class accuracy metrics, including Precision, Recall, and F1-score, for the classified vegetation species (Juniperus phoenicea, Myrtus communis, Salicornia europaea, Juncus acutus) and the aggregated 'Other' class

Juniperus phoenicea demonstrated strong classification performance, achieving an impressive F1-score of 0.80. This excellent result is mainly due to its distinct morphological features and unique vertical structure; it typically grows as a taller shrub or small tree, reaching heights that make it stand out and clearly differentiate from surrounding lower vegetation or mixed stands. This distinct vertical profile, captured by the Canopy Height Model (CHM) and influencing various extracted features, plays a significant role in its accurate identification.

Conversely, *Myrtus communis* showed moderate classification accuracy, with an F1-score of 0.55. This comparatively lower performance can be attributed to its more variable growth habit and density. *Myrtus communis* often appears as a shorter shrub, usually between 0.5 to 1.5 meters tall. It frequently grows in denser, more interconnected stands or as understory within mixed vegetation, making it more difficult to delineate individual crowns and classify them accurately. While valuable, the spectral and textural information may be less distinct in these mixed and structurally complex environments compared to more isolated or taller specimens.

Notably, *Salicornia europaea* and *Juncus acutus* exhibited exceptionally high classification accuracy, with F1-scores of 0.95 and 0.80, respectively. Several factors likely contribute to this strong performance. Both species typically grow in isolated clumps or form distinct, homogeneous patches that are well-separated from other vegetation types. This spatial separation simplifies individual object delineation during segmentation, reducing issues related to overlapping canopies. Additionally, these species have unique spectral features that make them easy to distinguish from the broader Mediterranean maquis flora; Salicornia, as a halophyte, shows specific spectral responses related to its physiological adaptations to saline environments, while Juncus acutus, as a rush, also has a distinctive spectral signature due to its unique leaf structure and often wetland habitat. Their growth forms also produce unique texture patterns easily captured by Haralick texture features, such as Salicornia's succulent nature or Juncus's rigid, upright culms. These spectral and textural properties and their spatial isolation reduce spectral overlap with dominant shrub species, enhancing their separability by the classification model. The combined 'Other' class also performed well, with an F1-score of 0.74, demonstrating the usefulness of grouping various less dominant species.

The application of the Random Forest model across the study area generated a detailed spatial map illustrating the predicted distribution of the classified vegetation species. This map (Figure 8) visually represents the spatial patterns of *Juniperus phoenicea*, *Myrtus communis*, and the 'Other' vegetation class, providing a foundational understanding of their distribution across Culuccia Island. Specific regions of high density for *Juniperus phoenicea* are discernible, often forming extensive, homogeneous patches. *Myrtus communis* appears more dispersed, frequently found in smaller, fragmented stands or interspersed within mixed vegetation areas. The 'Other' class delineates areas comprising the remaining aggregated species, which exhibit a heterogeneous spatial distribution. The visual inspection of the map confirms the model's ability to delineate individual vegetation objects and classify them according to the defined species categories, providing a valuable spatial representation of the island's vegetation composition.

Figure 8. Spatial classification map of vegetation species across Culuccia Island, illustrating the predicted distribution of *Juniperus phoenicea*, *Myrtus communis*, and other vegetation classes, with zoomed-in examples of classified Juniper and Myrtle species in the northern part of the island.

3.1 Strengths and Limitations of the Approach

The methodology employed in this study, UAV-acquired multispectral imagery and ML techniques, demonstrates significant strengths in addressing the intricate challenges of detailed vegetation classification within complex Mediterranean ecosystems. A primary advantage lies in the capacity of UAV-based platforms to acquire very high-resolution data, which is crucial for individual tree detection and the subsequent classification at the single-species level. The rigorous georeferencing process, achieved through NRTK GNSS measurements, ensured a remarkable final accuracy of 1.5 cm in the planimetric component and 3 cm in the altimetric one, providing a robust foundation for accurate spatial analysis. This high spatial detail and multispectral capabilities allowed for extracting a comprehensive set of 72 descriptive features, encompassing spectral, textural, and geometric attributes. Integrating these diverse features proved essential for differentiating species that may exhibit similar spectral signatures but possess distinct canopy structures, as evidenced by the robust classification performance observed for species such as *Juniperus phoenicea* and *Salicornia europaea*. Furthermore, the Random Forest algorithm's inherent robustness and proven ability to effectively manage high-dimensional data and complex non-linear relationships contributed to the model's overall efficacy. The approach is particularly valuable for conducting detailed vegetation surveys in inaccessible areas, overcoming limitations of traditional field methods.

Despite these strengths, the methodology also presents limitations. The model's overall accuracy, while indicative of reasonable performance for a complex environment, suggests that challenges persist in achieving higher classification precision across all species. This moderate accuracy can be attributed to the inherent complexity and high structural heterogeneity of Mediterranean woodlands, which are characterised by small-sized trees and shrubs, dense aggregates, and often overlapping and interpenetrating canopies. These conditions can lead to difficulties in accurate individual tree crown delineation, potentially causing under- or over-segmentation and impacting subsequent classification. The relatively lower performance observed for species like *Myrtus communis* exemplifies these challenges, stemming from its variable growth habit and density.

Additionally, the process requires extensive ground truthing, as highlighted by the collection of 272 individual samples across 16 species. While crucial for model training and validation, this labour-intensive step can limit the scalability of such detailed analyses to much larger geographical areas.

3.2 Potential Methodological Improvements

Several methodological improvements can be explored to enhance the classification precision and address the inherent complexities encountered in Mediterranean maquis ecosystems.

A significant advancement involves integrating LiDAR (Light Detection and Ranging) data. The precise three-dimensional information LiDAR provides, particularly through enhanced Canopy Height Models (CHM), offers a superior capability for accurate individual tree crown delineation and improved vertical differentiation among species. This is particularly crucial in structurally complex and stratified environments, where distinguishing between species based solely on spectral and two-dimensional features can be challenging. Another promising avenue lies in the exploitation of multi-temporal and phenological data. By acquiring UAV data across different seasons or key phenological stages, it is possible to capture the spectral variations associated with plant growth cycles. This approach can effectively differentiate species that might exhibit similar spectral signatures at a single point in time but display distinct phenological changes (e.g., flowering, leaf senescence, or canopy development) throughout the year, thereby adding a crucial temporal dimension to the classification process.

Further improvements can be achieved by focusing on the refinement of segmentation techniques. Enhancing the algorithms used for object delineation is paramount, especially in areas characterized by high vegetation density or significant canopy overlap. Exploring more advanced segmentation algorithms or integrating deep learning approaches, such as semantic segmentation, could lead to more robust and accurate individual tree crown identification, mitigating issues of under- or over-segmentation.

Moreover, a sophisticated approach to advanced feature selection can significantly benefit the model. While a comprehensive set of features is valuable, developing more discriminative features through engineering or employing advanced selection techniques can reduce data dimensionality while simultaneously improving model performance and computational efficiency. This involves identifying the most informative variables that best separate the target species.

Concurrently, increasing and diversifying the ground-truth dataset is fundamental for enhancing model training and validation robustness. Collecting additional samples under varying environmental conditions, such as different lighting or distinct growth phases, can significantly increase the model's ability to generalize across diverse scenarios and improve its overall reliability, especially for minority or spectrally ambiguous classes.

Finally, the exploration of Deep Learning algorithms, particularly Convolutional Neural Networks (CNNs) for semantic segmentation or classification, represents a cutting-edge direction. These algorithms possess the capacity to automatically learn complex hierarchical features directly from raw image data, potentially surpassing the limitations of traditional object-based approaches that rely on manually engineered features. CNNs have demonstrated superior performance in various complex remote sensing tasks and could offer a powerful framework for more accurate and automated vegetation species mapping.

4. Conclusion

This study demonstrates the effectiveness of UAV-based multispectral imagery combined with machine learning techniques for detailed vegetation classification in a structurally complex Mediterranean ecosystem. Integrating high-resolution remote sensing data with object-based image analysis and Random Forest classification enabled the accurate identification of multiple tree and shrub species at the individual crown level within Culuccia Island, a highly heterogeneous and ecologically sensitive site.

The results reaffirm the value of Single Tree Segmentation and Classification (STSC) approaches, which allow for precise species-level discrimination in environments where conventional field methods are impractical or insufficient. By leveraging spatial, spectral, and textural features derived from UAV imagery, the proposed methodology effectively addressed the challenges posed by overlapping canopies, small crown sizes, and high intra- and inter-species variability typical of Mediterranean maquis systems. Beyond the technical achievements, this work underscores the broader significance of STSC methods for the sustainable management of complex ecosystems. Detailed and spatially explicit vegetation maps—such as those produced in this study—offer critical inputs for biodiversity assessment, habitat monitoring, conservation planning, and the implementation of environmental policies, particularly in Natura 2000 sites like Culuccia Island. Such datasets are essential for tracking ecosystem changes and guiding adaptive management in response to anthropogenic pressures and climate change. Despite the promising results, several limitations emerged, including segmentation challenges in dense vegetation, moderate classification performance for less abundant species, and the need for substantial ground truth data.

Future research should integrate complementary data sources like LiDAR to enhance three-dimensional structural analysis and improve crown delineation. Furthermore, incorporating multi-temporal and phenologically relevant observations could enhance classification performance by capturing species-specific seasonal variability. Advanced deep learning models, particularly explainable convolutional neural networks, also hold potential for improving accuracy and interpretability in species mapping.

In conclusion, UAV-based STSC methods provide a robust and scalable framework for fine-scale vegetation analysis, particularly suited to ecologically rich but structurally complex Mediterranean environments. Continued methodological refinement and broader implementation will strengthen their role in ecological research and landscape-level conservation strategies.

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