The Role of Land Use Intensity on Vegetation Recovery Gradients After Land Abandonment in the Semiarid SE Alentejo, Portugal

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Abstract

Understanding how land use history shapes secondary succession is crucial for semiarid regions, where human pressures intersect with climatic variability. This study examines the Serra de Serpa e Mértola, in SE Alentejo, Portugal, an area marked by extensive land conversion and degradation over the 20th century. Drawing on long-term monitoring of experimental plots at the Vale Formoso Soil Erosion Centre, we leverage UAV-based photogrammetry to quantify vegetation recovery dynamics from 2018 to 2024. By focusing on canopy height models (CHM), we move beyond traditional spectral indices to directly assess biomass accumulation over time. Preliminary findings reveal clear differences in recovery trajectories linked to historical land use intensity and climate conditions. Plots with lower historical disturbance, such as light grazing or spontaneous vegetation, exhibit faster recovery, while intensively managed plots show slower biomass gains and signs of ecological thresholds. Our results highlight the value of UAV monitoring for understanding how abandonment starting points influence ecosystem resilience under varying climatic pressures, offering insights for restoration strategies in Mediterranean semiarid landscapes.

1. Introduction

Land abandonment has been a defining trajectory of landscape transformation across the Mediterranean region since the mid-20th century. Driven by a complex interplay of political, environmental, and socio-economic factors, abandonment profoundly reshapes ecological processes, soil dynamics, and biodiversity patterns. Mediterranean landscapes, historically characterized by diverse agricultural mosaics such as dryland cereals, rotational fallows, and extensive silvopastoral systems, are now increasingly subject to the cessation of traditional agricultural practices.

Environmental factors, particularly in marginal and mountainous areas, strongly influence land abandonment dynamics. Areas with steep slopes, poor soil fertility, and challenging climatic conditions are particularly susceptible, as they yield lower agricultural productivity and face greater management difficulties (Kerckhof et al., 2016; Peña-Angulo et al., 2019). Moreover, the progressive intensification of climatic variability—marked by prolonged drought periods and erratic rainfall events—has exacerbated agricultural vulnerabilities, making dryland farming increasingly unviable (Kiziridis et al., 2022).

Socioeconomic drivers compound these environmental stresses, accelerating abandonment trends. Rural depopulation, ageing farming populations, low agricultural profitability, and fragmented land ownership patterns contribute to the ongoing decline of agricultural activities in these marginal regions. This socio-economic erosion of rural areas often leads to fragmented landscapes, characterized by uneven patterns of land use, where traditional farming practices become economically and socially unsustainable (Lasanta et al., 2021; Salvia et al., 2025).

The ecological consequences of land abandonment are profound and varied, impacting soil processes, biodiversity, and landscape structure. Initially, abandoned lands often experience increased erosion risks due to reduced vegetation cover. However, as succession progresses, vegetation typically establishes itself, enhancing soil stability and reducing erosion rates significantly over time (Arnaez et al., 2011; García-Ruiz & Lana-Renault, 2011). The recovery of vegetation also promotes the sequestration of carbon in the soil, contributing positively to climate mitigation efforts (Novara et al., 2017; Bell et al., 2021).

Ecological succession following abandonment typically progresses from early colonization by herbaceous pioneer species to more structurally complex shrub and woody plant communities. This transition enhances biodiversity, particularly during intermediate succession stages, when heterogeneous habitats support diverse species assemblages. However, unmanaged succession may also heighten risks associated with invasive species proliferation and increased fire frequency, both of which can threaten ecosystem stability and biodiversity gains (Lasanta et al., 2020).

Moreover, abandoned agricultural landscapes often shift from heterogeneous mosaics to structurally simpler ecosystems dominated by shrubs or forests. While this shift can enhance some ecosystem services such as carbon storage and erosion control, it may also negatively impact water resources by altering hydrological dynamics, reducing runoff, and decreasing streamflow availability in downstream areas (Otero et al., 2011).

Understanding these complex recovery dynamics requires advanced methodological approaches capable of capturing detailed structural and ecological changes across broad spatial scales. Recent advances in remote sensing technologies, particularly unmanned aerial vehicles (UAVs), have significantly improved the monitoring of vegetation dynamics and soil processes. UAV-derived Canopy Height Models (CHMs) enable the detailed characterization of vegetation structural changes, providing direct insights into biomass accumulation and vegetation succession patterns, thereby surpassing traditional spectral remote sensing indices such as

NDVI, which offer limited structural detail (Bendig et al., 2015).

This study aims to utilize UAV-based CHM data collected since 2018 to investigate how different historical land use intensities and abandonment starting points shape vegetation recovery trajectories in semiarid Mediterranean environments. By linking detailed UAV-derived structural data to the legacy of agricultural management and climatic variability, this research seeks to elucidate key factors driving ecosystem recovery, with implications for sustainable land management and ecological restoration strategies in semiarid Mediterranean landscapes (Bonet, 2004; Lozano et al., 2014; Paz-Kagan et al., 2014).

2. Methods

2.1 Study area and experimental setup

The research was conducted at the Vale Formoso Soil Erosion Centre, located in the Serra de Serpa e Mértola region (SE Alentejo, Portugal). This semiarid region, underlain by Devonian schist soils and characterized by undulating topography, has experienced extensive historical land use conversions, from spontaneous Mediterranean vegetation to intensive wheat production in the early 20th century, followed by varied practices including rotational cereals, ploughed fallows, grazing pastures, and managed afforestation plots (*Pinus pinea*, *Quercus rotundifolia*, and *Quercus suber*), especially due to the agricultural policy setting since joining the common market. However, over the last 30 years, parts of this area have been subject to agricultural land abandonment due to a complex mosaic of environmental, economic, political and demographic factors.

The Vale Formoso Soil Erosion Centre was established in 1961 to study the erosional effects of different types of management practices and cereal-based rotations, aiming to promote conservation knowledge in this region. The experimental setup is comprised of 18 USLE-Wischmeier plots (20m x 8m, with one being 20m x 4m) divided in two groups. Group 1 is exposed between SSW and ESE with slopes ranging from 10 to 13%, and Group 2 is exposed to ESE with slopes ranging from 15 to 20%. Over the years, the experimental setting was continuously adapted to include other types of land uses and management practices that already were or were starting to become relevant in the Serra: continuously ploughed land and spontaneous vegetation were included to have a control of maximum and minimum human-induced degradation. In the early 21st century, three plots were afforested with *Pinus pinea* and *Quercus rotundifolia* to mimic a politically induced afforestation of agricultural areas.

However, due to the degradation of the sediment collection tanks, and consecutive setbacks in recovering these costly structures, the ability to collect data was limited. For this reason, agricultural management ceased in all plots in 2008, allowing natural secondary succession to proceed from different starting points without intervention. Therefore, these plots provided an ideal opportunity to study the effects of past land use intensity and land abandonment starting conditions, enabling a comparative analysis of vegetation recovery dynamics under semiarid conditions, enhanced by the increased aridity due to climate change.

2.2 UAV data acquisition

UAV data collection started systematically in 2018, aiming to capture fine-scale structural changes in vegetation over time. The flights were planned using *DroneDeploy* software and conducted using a UAV platform equipped with a high-resolution RGB camera. UAV surveys covered all experimental plots regularly (at least annually), with additional seasonal flights to better capture vegetation responses to climatic variability. During the COVID-19 lockdowns, data collection was possible but limited. However, no flight campaigns were held between august 2020 and august 2021, which limits data analysis in this particular year.

Flight parameters were carefully chosen to balance spatial resolution and coverage efficiency. All flights were conducted at around solar noon or under overcast to minimize shadow effects and maintain consistent lighting conditions for image quality. Flight altitude was kept between 20-40m above ground level, to maintain a ground sampling distance well below 1cm, and images were taken at nadir orientation (90°) with 80% front overlap and 75% side overlap to ensure robust photogrammetric reconstruction. Ground Control Points (GCPs) were collected twice for each plot using a high-precision GNSS-RTK system connected to the Portuguese National Permanent GNSS Network (ReNEP), ensuring positional accuracy of photogrammetric products. The GCP were marked in a flat concrete surface in two opposing corners and were covered by fixed 3D printed markers to allow for precise allocation of the points in the processing workflow.

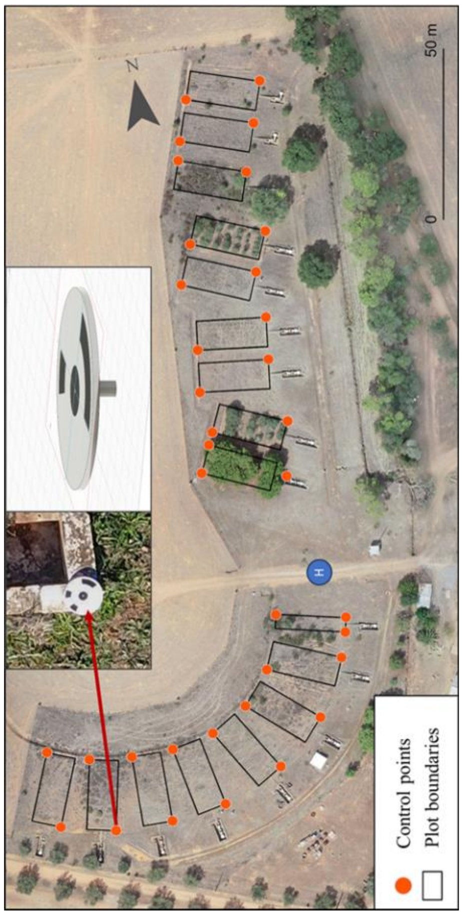

Figure 1. Layout of the experimental plots

2.3 Photogrammetric Processing and CHM Generation

UAV images were processed using the Structure-from-Motion (SfM) workflow implemented in *Agisoft Metashape* software. This workflow consisted of the following sequential steps: Image alignment, for detecting and matching common features across overlapping images to generate a sparse 3D point cloud; dense cloud generation, creating a detailed 3D representation of the surveyed area, using multi-view stereo reconstruction; and digital elevation model (DEM) and orthophoto creation, producing georeferenced digital surface models (DSM), representing the vegetation canopy and terrain features. All digital models were resampled to 5cm so that processing resolution is at least half the total RMSE to reduce noise while maintaining all meaningful terrain and vegetation features, optimizing accuracy and workflow efficiency in subsequent analyses.

GSD (cm)	*GCP*	*Average Error (RMSE, cm)*					*DEM (cm)*
		X	*Y*	*Z*	*XY*	*Total*	
0.82	n = 36	1.38	1.57	0.75	2.09	2.27	1.74

Table 1. Average model processing results

To accurately quantify vegetation structure, it was essential to produce a reliable digital terrain model (DTM). Given the complexity of vegetative structures and the insufficient accuracy of automatic ground point classification in Metashape, a custom Triangulated Irregular Network (TIN)-based approach was developed. First, visible bare-ground points were manually digitized from the UAV-derived DEM imagery. These points were carefully chosen in areas clearly identifiable as bare soil to avoid interference from vegetation. Secondly, precise elevations for key points (plot corners and permanent infrastructure) were collected using GNSS-RTK and corrected based on field measurements, ensuring ground-truth accuracy. Finally, a TIN interpolation was performed using these combined points (field-measured and digitized bare-ground points) to produce a refined DTM free of vegetative artifacts. The Canopy Height Model (CHM), representing the vegetation height and biomass volume, was generated by subtracting the TIN-based DTM from the original DEM, providing accurate quantifications of vegetation growth over time.

2.4 Analysis of vegetation cover dynamics

Vegetation recovery trajectories were analysed by extracting mean canopy height values from the CHMs for each plot and each monitoring period (2018–2024). The plots were grouped according to their historical land use intensity and predominant vegetation type emerging after abandonment, including *Pinus pinea*, *Quercus rotundifolia*, *Cistus ladanifer* shrublands, mixed shrubland communities, and formerly agricultural plots.

Annual CHM data were further analysed in the context of interannual climatic variability, distinguishing between dry and wet years to assess vegetation sensitivity and resilience to climatic stress. Total annual rainfall was compiled for the Vale Formoso site over the last 30 years, and each year was classified by quintiles based on dryness. These results were synthesized into temporal graphs illustrating biomass recovery trajectories

3. Results

3.1 Vegetation Recovery Patterns by Abandonment Starting Point

Analysis of UAV-derived CHMs from 2018 to 2024 clearly differentiated recovery trajectories among plots grouped by their abandonment starting points, reflecting distinct legacies of historical land use intensity and subsequent species assemblages.

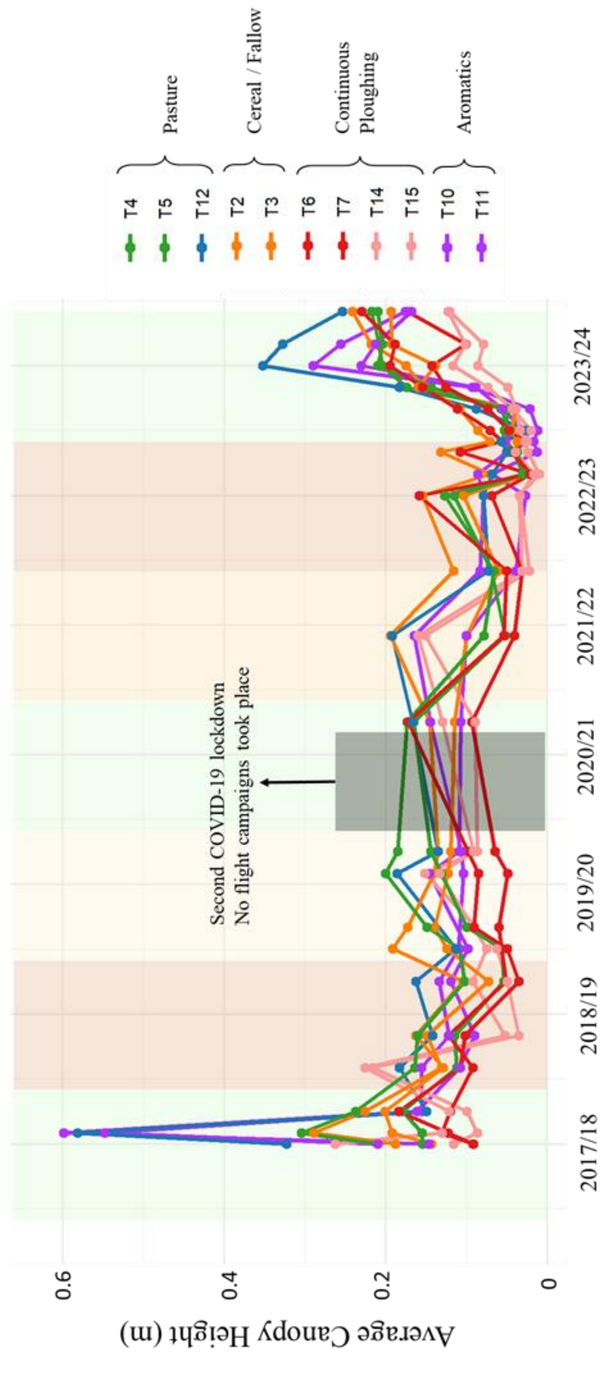

Figure 2. UAV-derived CHMs from 2018 to 2024 for agricultural plots in the study site, based on historical rotation. Coloured backgrounds indicate the rainfall quintiles for the year: green = normal; red = severe drought; orange = moderate drought; yellow = drought. No statistically wet years were recorded during the study duration

3.1.1. Pasture

Plots abandoned from pasture (T4, T5, and T12) exhibited the most rapid and uniform vegetation recovery, characterized by dominant shrub species such as *Lavandula stoechas subs. luisieri*, *Phagnalon saxatile*, and grasses including *Briza maxima* and *Holcus annuus*. These species consistently showed high Braun-Blanquet cover scores across pasture plots, indicating strong competitive advantage and resilience. CHM analysis highlighted continuous growth across the monitoring period, particularly in wetter years, where vegetation height increments were notably accelerated, underscoring the responsiveness of these plots to favourable climatic conditions.

3.1.2. Cereal

Former cereal plots (T1, not shown, and T3) displayed a markedly slower and more variable recovery trajectory (e.g. see Figure 3). These plots were primarily colonized by pioneer and annual herbaceous species, notably *Dactylis glomerata subs. lusitanica*, a hemicryptophyte found in bushes and understory, always in cool or shaded places, and *Andryala integrifolia*, also a hemicryptophyte, usually found in disturbed places such as uncultivated agricultural fields. Despite these species showing moderate-to-high Braun-Blanquet cover, their structural growth, as captured by CHM data, was relatively limited and irregular, particularly constrained during years with reduced rainfall. The limited establishment of woody shrubs in these plots reflects the enduring effects of historical intensive agricultural practices, with evident difficulty in overcoming ecological thresholds imposed by prior soil disturbance.

Two plots originally abandoned with cereal cover in 2008 (T10, T11) represent unique cases: both underwent a brief phase of aromatic plant cultivation in 2015, which subsequently failed due to a severe drought year. This enriched seedbank composition and resulted in a species assemblage similar to other cereal plots, dominated by annual grasses and herbaceous pioneers, indicating a persistent difficulty in structural biomass accumulation in drier years, further confirmed by UAV-derived CHMs. However, both these plots present high system resiliency to wetter conditions, as can be seen between the very low average canopy height displayed in the summer of 2023, and how vegetation recovered immediately after a wetter autumn and winter between 2023 and 2024.

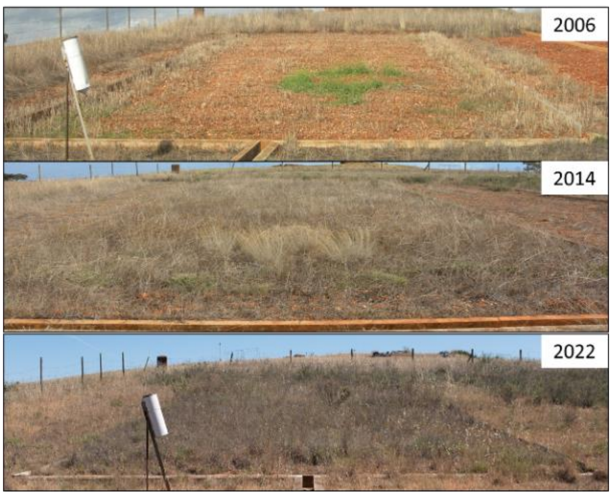

Figure 3. Plot T1 vegetation recovery 2006-2022

3.1.3. Fallow

The plot abandoned in the fallow year of the cereal rotation (T2) showed an intermediate recovery trajectory (e.g. see Figure 2). Dominant species included *Lavandula stoechas subs. Luisieri* (especially at the top) *Phagnalon saxatile*, and perennial grasses such as *Dactylis glomerata subs. lusitanica* (especially at the bottom). CHM-derived vegetation height data indicated moderate, steady growth throughout the monitoring period, with noticeable gains during wetter periods. This suggests that moderate soil disturbance associated with traditional fallowing practices allowed for relatively stable and consistent vegetation development, placing this plot between pasture and cereal/continuous ploughing in terms of recovery potential and biomass accumulation rates.

Figure 4. Plot T2 vegetation recovery 2006-2022

3.1.4. Continuous Ploughing

Plots with a history of continuous ploughing before abandonment (T6, T7, T14, and T15) showed the slowest overall vegetation recovery. Dominant species such as *Andryala integrifolia*, *Carlina racemosa*, and *Tolpis umbellata* emerged prominently, reflecting early-stage successional communities adapted to highly disturbed environments. However, pioneer shrub species were quick to dominate in the higher sections of these plots, similarly to what was observed in the fallow abandonment. However, the shrub species that appeared varied between groups: *Cistus ladanifer* appeared in Group 1, likely due to the distance between this plot and a former *Cistus* plot; whereas *Lavandula stoechas subs. Luisieri* appeared in Group 2, despite no other plot nearby displayed this species. CHM data revealed minimal structural development, with only slight increases in vegetation height over the monitoring period, except for the plots where shrub species appeared. This limited recovery was particularly pronounced during dry climatic years, suggesting that prolonged and intense soil disturbance significantly hampers natural regeneration processes and resilience.

3.2 Influence of Climatic Variability

UAV-derived CHM results underscored distinct responses of vegetation recovery to interannual climatic variability across all abandonment categories. Vegetation in plots with historically lower disturbance (e.g. pasture) showed resilience and rapid growth responses during wetter years, whereas plots with histories of intensive disturbance (e.g. continuous ploughing) exhibited heightened sensitivity and significantly reduced growth during drier years. This differential response highlights critical interactions between historical land use intensity, species composition, and climatic variability in shaping recovery trajectories in semiarid Mediterranean landscapes.

4. Discussion

The UAV-based analysis of vegetation recovery in the Vale Formoso experimental plots reveals how historical land use intensity and ecological legacies dictate the pace and pattern of natural regeneration in semiarid landscapes. By focusing on canopy height models (CHMs), this study provides structural insights that complement traditional ecological assessments, illustrating how vegetation structure responds dynamically to both antecedent land management and climatic variability.

Pasture plots emerged as the most resilient among the abandonment categories, demonstrating both ecological memory and regenerative capacity. Consequently, these areas responded quickly to favourable climatic conditions, achieving greater canopy heights in wetter years. This underscores the importance of historical land use in mediating recovery pathways, where low intensity uses leave behind ecological capital that accelerates succession. This finding aligns with Bonet (2004), who observed accelerated secondary succession in low-disturbance Mediterranean old fields, emphasizing the role of ecological memory in pasture-dominated systems.

Conversely, cereal plots, albeit with similar land use legacies and degradation gradients (continuous cereal-fallow rotation), displayed different trajectories based on the last cover before abandonment. In the plots where cereal was left on the soil cover, there is the development of a herbaceous-dominated community of annual grasses and pioneers, coupled with limited structural development in UAV-derived CHMs (Figure 2). On the other hand, the plot abandoned in the fallow year, with the soil ploughed, showed greater structural development, with pioneer shrub species appearing on the higher sectors where soil loss is more pronounced. This contrast aligns with insights from Pérez-Hernandez and Gavillán (2021), who discussed how different abandonment contexts in Mediterranean semi-arid environments yield divergent secondary succession pathways.

This observation points to an initial degradation of the soil structure in the cereal plot without plant cover, resetting seedbed conditions and creating the depleted conditions for these deep-rooted species to grow. This is confirmed by the observations in the plots that were continuously ploughed, as these pioneer shrub species also established themselves, however reaching lower sections of the plot. The temporary introduction of aromatic species in two plots seven years after abandonment failed to establish a lasting vegetative cover, setting back biomass recovery trajectories and effectively creating a situation where vegetation growth is very limited in drier years. However, these plot's vigorous response to a wetter autumn after a severe drought indicates high system resiliency
This reinforces the challenge of reversing degradation in these contexts, where intensive cultivation may create long-lasting ecological inertia, impeding natural succession.

The most pronounced limitations were observed in continuously ploughed plots, where vegetation height gains were lower. The persistence of early successional, disturbance-adapted species, such as *Andryala integrifolia* and *Carlina racemosa*, which tend to favour poorer and drier soil conditions, highlights a system locked in a degraded state. However, there are some contrasting trajectories, as in both groups one of the plots was ploughed with a shallower plough, resulting in lower historical soil loss and contrasting vegetation recovery gradients. Where ploughing was deeper and/or the slope gradients were higher (T7, T14, T15), UAV-derived CHMs effectively captured ecological inertia, emphasizing the utility of high-resolution remote sensing in detecting subtle structural dynamics that may not be evident from cover-based assessments alone. Where ploughing was shallower and gradients were lower (T6), shrub-encroachment with *Lavandula luisieri* was widespread, indicating a slightly better recovery trajectory. This observation aligns with what happened in the fallow abandonment plot (T2): the initial erosional activity, especially in the plot's higher sections, resulted in a seedbed depleted of herbaceous species and drier and coarser soil. In the continuous ploughed plot, *Lavandula luisieri* extends over 10m from the top, whereas in the fallow plot, it extends approximately 5m from the top.

Climatic variability further modulated these recovery patterns. While all plots showed some sensitivity to interannual rainfall fluctuations, the response was most marked in the more degraded systems, where drought years compounded existing recovery constraints. This highlights the compounded vulnerability of historically degraded areas to ongoing climate change, reinforcing the necessity of considering both historical land use legacies and future climatic scenarios in restoration planning.

Overall, the integration of UAV photogrammetry with ecological field data offers a powerful approach to understanding the complex trajectories of vegetation recovery in semiarid regions. By revealing how past land use and climatic variability interact to shape biomass accumulation, this study provides actionable insights for land managers aiming to enhance ecosystem resilience and accelerate natural regeneration processes.

5. Conclusions

This study demonstrates the effectiveness of UAV-derived canopy height models in capturing the nuanced dynamics of vegetation recovery following land abandonment in semiarid Mediterranean environments. By focusing on structural vegetation metrics, rather than traditional spectral proxies, we were able to elucidate clear differences in recovery trajectories driven by historical land use intensity and species composition.

Plots with lower historical disturbance, such as pastures, displayed faster biomass accumulation and greater resilience to climatic variability, leveraging existing ecological capital to respond effectively to favourable conditions. In contrast, plots with intensive historical management, including cereal cultivation and continuous ploughing, exhibited slow, irregular, and drought-sensitive recovery trajectories, reflecting persistent ecological degradation and inertia.

The UAV-based monitoring approach proved invaluable in detecting these patterns, offering fine-scale temporal insights that are essential for informing restoration strategies. By linking structural vegetation data to historical land use and climate variability, our findings emphasize the need for context-specific restoration planning that accounts for both past degradation legacies and future climatic challenges.

Looking ahead, integrating UAV data with other remote sensing platforms, as well as soil analyses and continuous erosional and hydrological monitoring will further enhance our understanding of ecosystem resilience and succession dynamics. Such integrative approaches will be critical for guiding effective land management and restoration efforts in Mediterranean drylands facing accelerating environmental pressures.

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