environmental sciences proceedings

MDPI

Proceeding Paper

A Methodological Approach for Assessing the Resilience of *Pinus halepensis* Mill. Plant Communities Using UAV-LiDAR Data †

Fernando Pérez-Cabello [1,2,*], Cristian Iranzo [1,2], Raúl Hoffrén [1,2], María Adell [1,2], Antonio Montealegre [2,3], Raquel Montorio [1,2], Alberto García-Martín [2,3] and Luis A. Longares [1,2]

1 Department of Geography and Land Management, University of Zaragoza, Pedro Cerbuna 12, 50009 Zaragoza, Spain; c.iranzo@unizar.es (C.I.); rhoffren@unizar.es (R.H.); madell@unizar.es (M.A.); montorio@unizar.es (R.M.); lalongar@unizar.es (L.A.L.)
2 University Institute of Research in Environmental Sciences (IUCA), University of Zaragoza, 50009 Zaragoza, Spain; montealegre@unizar.es (A.M.); algarcia@unizar.es (A.G.-M.)
3 Centro Universitario de la Defensa, Academia General Militar, 50090 Zaragoza, Spain
* Correspondence: fcabello@unizar.es; Tel.: +34-876553926

† Presented at the 5th International Electronic Conference on Remote Sensing, 7–21 November 2023; Available online: https://ecrs2023.sciforum.net/.

Abstract: The assessment of fire effects in Aleppo pine forests is crucial for guiding the recovery of burned areas. This study presents a methodology using UAV-LiDAR data to quantify malleability in three burned areas (1970, 1995, 2008) through the statistical analysis of tree height and *Profile Area Change* (PAC) metrics. Significant differences in vegetation height (99th percentile) among the three fires, with specific maximum absolute differences (D) depending on the fire year, have been identified. Positive PAC values in 2008 indicate deeper LiDAR penetration, resulting in lower regeneration, while values close to 0 in 1970 suggest more uniform regeneration. The use of LiDAR metrics and uni-temporal sampling between burned sectors and controls aids in understanding community resilience and identifying recovery stages in *P. halepensis* forests.

Keywords: forest fire; malleability; recovery; vegetation structure; drone; Aleppo pine forests

Citation: Pérez-Cabello, F.; Iranzo, C.; Hoffrén, R.; Adell, M.; Montealegre, A.; Montorio, R.; García-Martín, A.; Longares, L.A. A Methodological Approach for Assessing the Resilience of *Pinus halepensis* Mill. Plant Communities Using UAV-LiDAR Data. *Environ. Sci. Proc.* **2024**, *29*, 32. https://doi.org/10.3390/ECRS2023-15855

Academic Editor: Alexander Kokhanovsky

Published: 6 November 2023

1. Introduction

The assessment of fire effects and recovery capacity becomes a key element in guiding the strategic orientation of burned areas, encompassing comprehensive management, adaptation, and mitigation, etc. The reproductive strategies of most plant species in Mediterranean ecosystems exhibit efficient mechanisms of germination and/or resprouting, ensuring the development of formations similar to those affected by fire based on models of ecological plant succession and auto-succession [1].

The tree formations of a Aleppo pine forest (*Pinus halpensis* Mill.) with kermes oak (*Quercus coccifera* L.) are a good example of plant self-succession due to the mechanisms of thermodiscence and serotinity that allow a massive release of seeds after a fire in the case of *P. halepensis* [2], and the regrowth from dormant buds in its trunk and/or roots in the case of *Q. coccifera* [3].

Malleability is a quantifiable property of resilience that describes the similarity between two steady states separated by a disturbance [4], enabling the assessment of the degree of recovery of affected plant formations. The analysis of vegetation structure (i.e., the variability in vegetation height) is one of the key pieces of information for its evaluation.

Active remote sensing technology, particularly LiDAR (Light Detection and Ranging) data, is one of the most suitable methods for analyzing the vertical distribution of vegetation strata, due to its ability to penetrate the tree canopy [5,6]. Indeed, in recent decades, LiDAR sensor data, mounted on aircraft, have been used as a primary resource for conducting forest inventories [7], determining fuel characteristics [8], or more directly related to the effects of fire, analyzing the diversity of forest structure [9,10].

In this context, this study aims to evaluate post-fire vegetation recovery by comparing burned and control sectors using LiDAR metrics related to vegetation structure (canopy height and physiognomic complexity). The study focuses on Aleppo pine with kermes oak formations (Ph-Qcc) affected by three forest wildfires that occurred in three different years over the last approximately 50 years.

2. Materials and Methods

2.1. Study Area

The study focuses on three wildfires that occurred in 1970, 1995, and 2008 that affected Aleppo pine (*P. halepensis*) stands with *Q. coccifera*. in the Montes de Zuera region (Zaragoza, Spain). Fire perimeters are closely situated to ensure the environmental homogeneity of their characteristics. Additionally, the burned areas are spatially connected to unburned areas that can serve as controls (i.e., areas with the same characteristics prior to the disturbance). The study area is located approximately 35 km north-east of Zaragoza, Spain, on a structural platform developed on Miocene carbonate and marl sediments, arranged on horizontal strata. The climate is Mediterranean continental, with a mean annual rainfall of about 400 mm and frequent droughts.

2.2. Methods

The analysis must adhere to the uni-temporal nature of the measurements, which, from a linear matrix approach, implies the absence of corresponding elements (pixels) since the images are from the same date. To address this circumstance, comparisons are made between burned (SQ) and control sectors (SC) selected for each wildfire with regard to vegetation structures (Figure 1).

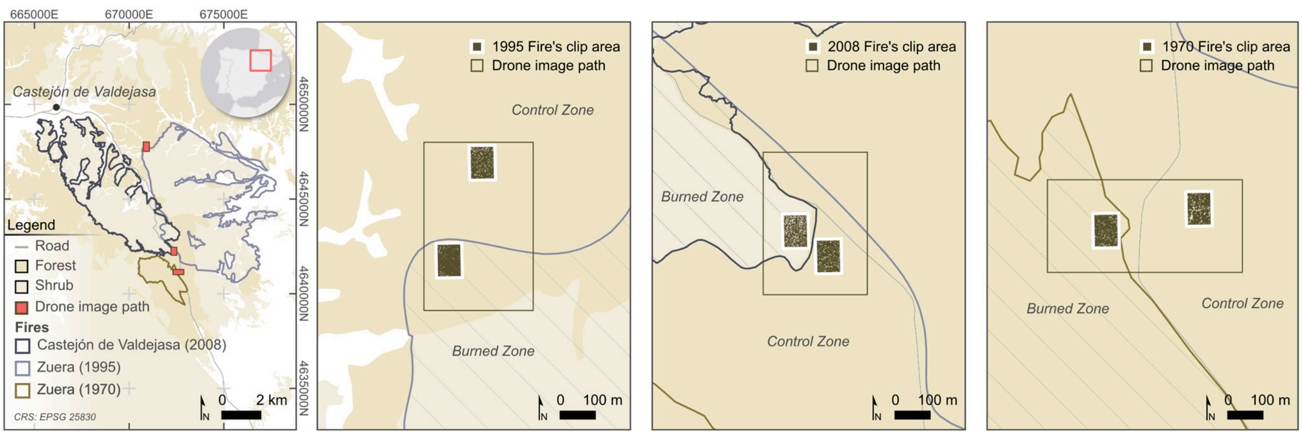

Figure 1. Study area localization, flight footprints corresponding to the fires (1970, 1995, and 2008), and experimental scheme with quadrangular sectors corresponding to the burned and control sectors (EPSG:25830). European Union and Esri.

The methodology involves the following phases of work: (1) In the spring of 2023, three flights were conducted using an unmanned aerial vehicle (DJI Matrice 300 RTK) equipped with the DJI Zenmuse-L1 LiDAR sensor. These flights simultaneously covered both burned and unburned areas, and field-based floristic and physiognomic inventories were conducted concurrently with the flights, utilizing sampling units of 20 m^2 (10 $\times$ 2 m). (2) Within the flight footprints, smaller homogeneous areas (8000 m^2) in square shape were selected for the extraction of LiDAR metrics using DJI Terra v.3.6.7 and FUSION-LDV v.4.21 software: (a) canopy height (99th percentile), and (b) Profile Area Change (PAC), a multitemporal LiDAR metric introduced by Hu et al., (2019) [11]. Profile Area (PA) assesses biomass at different height strata by means of the vertical distribution of LiDAR returns. PA uses the area delineated using the height percentile curves (Equation (1)), and to describe changes between burned and control sectors (PAC) a simple subtraction is applied (Equation (2)). (3) Random sampling (10% of pixels, 0.5 m in side length) is performed, which will be used to analyze comparisons between burned and control sectors. This analysis involves similarity testing using the Kolmogorov–Smirnov test, the generation of descriptive statistics, and the construction of cumulative frequency distribution diagrams (cumulative relative frequency plots).

$$PA = \int_{0}^{100\%} f(percentil)\, d(percentil) \quad (1)$$

$$PAC = PApre - PApost \quad (2)$$

where *PA* is the integrated area below the percentile–profile curve.

3. Results

The analysis of UAV-LiDAR metrics (ElevP99 y Profile Area), has enabled the identification of significant differences, varying in magnitude, between post-fire regenerated vegetation structures and their corresponding controls. Using the D values (MaximumAbsolute Differences) derived from the application of K-S tests (Two-sample Kolmogorov–Smirnov test), a ranking of these differences is identified based on the fire year (D = 0.26/0.14, 0.31/0.39, 0.76/0.51, for the fires of 1970, 1995 and 2008, respectively).

Table 1 presents descriptive statistics differentiated by sectors and fire year for the two LiDAR metrics. Overall, the maximum canopy heights of SCs range between 9 and 14 m, with 25% of the sample exceeding 8 m. In the case of SQs, the values are much more heterogeneous and significantly lower, ranging from 4 to 12 m. Notably, in the 2008 wildfire, only 25% of the sample exceeds 0.5 m. The PA variable exhibits greater differences between SCs and SQs. While SCs are around 54 m^2, SQs range from 22 to 70 m^2, and only in the case of the 1970 wildfire, SQs and SCs show similar averages.

Table 1. Descriptive statistics, differencing by sectors and fire year, for the two metrics employed (Elev99 and PA).

ElevP99	**Control 1970**	**Burned 1970**	**Control 1995**	**Burned 1995**	**Control 2008**	**Burned 2008**
Minimum	0.0562	0.0642	0.0650	0.0986	0.0588	0.0569
Maximum	9.2703	7.6976	13.9178	12.2990	10.1488	4.3553
1st Quart.	3.0122	1.9680	0.5315	3.8251	3.2532	0.1722
Median	5.7469	3.0165	4.8842	4.7910	7.1307	0.2851
3rd Quart.	7.0713	3.9005	8.3971	5.4869	8.1554	0.4791
Mean	4.9486	2.9278	4.8515	4.5965	5.8140	0.4258
Stand. dev	2.6476	1.5389	4.0406	1.8880	3.0945	0.4720
PA	**Control 1970**	**Burned 1970**	**Control 1995**	**Burned 1995**	**Control 2008**	**Burned 2008**
Minimum	0.5000	0.5000	0.5000	1.2746	0.5000	0.5000
Maximum	99.0000	97.8572	99.0000	99.0000	99.0000	93.1167
1st Quart.	29.8299	32.1804	23.4218	61.8800	29.1407	9.0068
Median	66.6925	59.6434	49.7100	81.7845	60.4331	18.0050
3rd Quart.	85.3110	77.7740	74.3119	88.2870	83.6535	31.2728
Mean	58.2385	54.5450	49.0479	71.6360	56.1484	22.4017
Stand. dev	30.2969	26.3943	27.9808	23.4284	29.8251	17.4625

Derived from the KS test, the cumulative relative frequency plots for each wildfire (Figure 2) illustrate the degree of disparity among the regenerated structures and their respective controls.

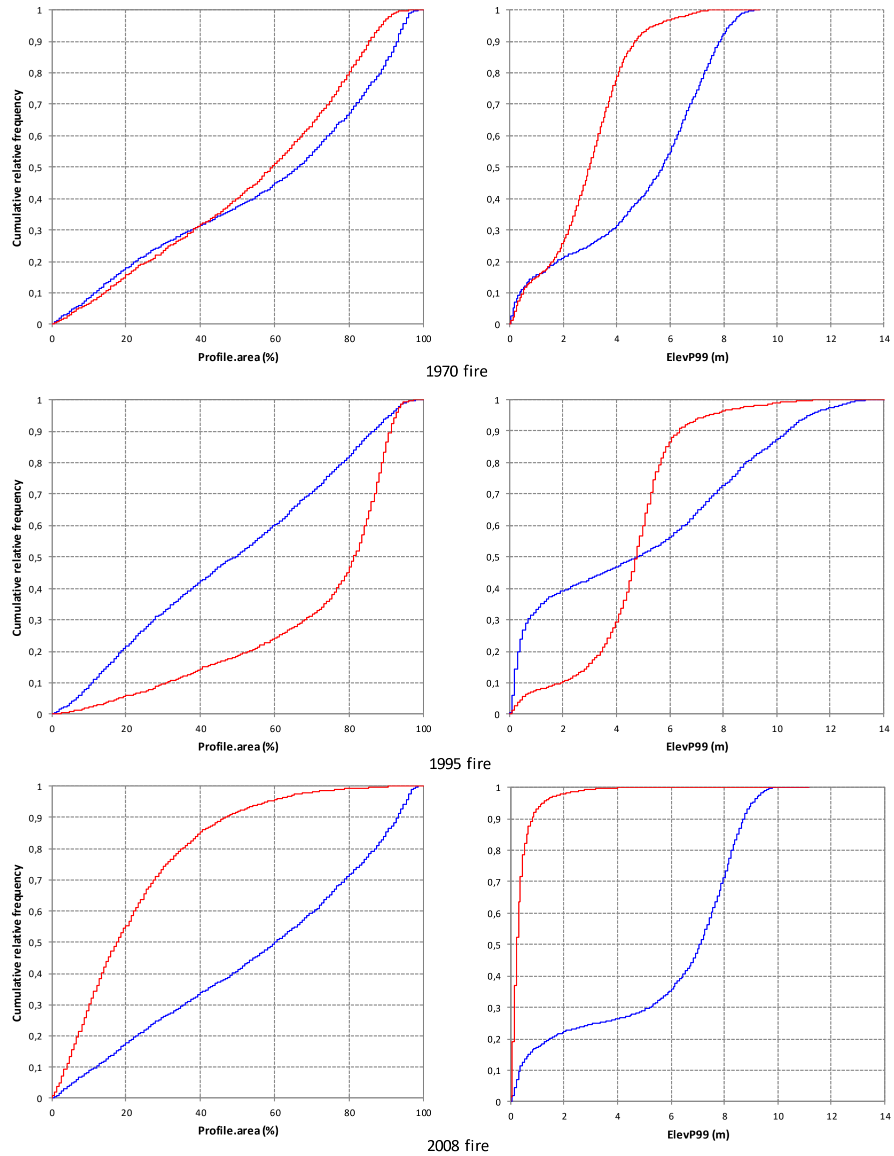

Figure 2. Distribution of cumulative relative frequencies (in blue Control Sectors; in red Burned Sectors) by wildfire for ElevP99 (**right**) and PA (**left**). Top: 1970 wildfire; middle: 1995 wildfire; bottom: 2008 wildfire.

In this regard, for the ElevP99 variable (right column), the greatest differences are observed in the most recent (15 years after the fire), which manifest a scarcity of pixels with high heights (<5) and a high frequency of pixels with heights < 1 m. The 1995 control sample has a normal distribution, although with some accumulation of pixels with vegetation of short stature (<1 m). This contrasts with the logistic distribution exhibited by the canopy of colonizing communities, where the dominant height ranges between 4 and 6 m. Finally, in the case of the 1970 wildfire, the profiles of SCs and SQs describe much more similar trajectories. However, a breakpoint is observed from 2 m in elevation, highlighting the even greater height of the SC canopy, while the SQ exhibits a higher frequency of pixels with heights around 2–4 m; in the SQ, the most represented values oscillate between 5 and 8 m.

For the PA variable (left column), in all three wildfires, we observe the normal distribution of the SCs and the different trajectory of the SQs, with the exception of the 1970 wildfire, where the two distributions are clearly associated. In the wildfires closer in time, very different regenerative phases are identified: while the SQ profile in 2008 exhibits a logarithmic character and is situated above the SC trajectory, in the 1995 wildfire, the profile shows a highly asymmetrical character, running below the SC. The subtraction between the pre-fire (control) and post-fire (burned) conditions (Equation (2)) proposed by Hu et al. (2019) results in values close to 0 for the 1970 wildfire, negative values for the 1995 wildfire (−22), and positive values in the case of 2008 (33). In the latter case, the positive sign of the subtraction indicates greater penetrability of LiDAR pulses in the burned area and, therefore, less reconstitution of the structures when compared to the negative values of 1995, associated with a greater complexity and density of regenerated vegetation. Meanwhile, the values close to 0 for the 1970 wildfire indicate a greater homogeneity between the regenerated structures and their control.

The field data obtained from inventories provide results consistent with the PAC values, in the sense that the inventories of the 2008 wildfire recorded the lowest number of Ph individuals (2), the smallest DBH (0.025 m), and height (0.8 m), compared to the >4 individuals, 0.09 m DBH, and 2.8 m in the 1995 and 1970 wildfires.

4. Discussion

The employed LiDAR metrics (ElevP99 and PA) along with the split-zone scheme design, in which randomized pixels were distributed in burned and control sectors for each fire 2008 (15 years after fire), 1995 (28 years), and 1970 (53 years), have facilitated the quantification of the degree of malleability exhibited by Aleppo pine forest.

Generally speaking, it is observed that the magnitude of differences between sectors decreases as more time elapses after the fire. However, cumulative graphical representations of the relative frequency of high-resolution LiDAR metrics allow us to identify anomalies in the structure regeneration process. These anomalies, manifested in the 1995 wildfire, may be related to the interaction of other factors (severity, post-fire treatments, . . .), although they could also be interpreted as an intermediate phase in the maturation process of burned structures.

The pine forests burned in the 2008 wildfire exhibit a high degree of malleability as they show significant differences from their control counterparts: elevated D values and distinctly differentiated cumulative relative frequency profiles. Notably, there is a substantial presence of pixels measuring less than 1 m and having lower structural complexity (fewer rebounds) in the SQ, which is more indicative of an initial phase of the regeneration process rather than the state of regeneration 15 years after the fire. In this sense, although an average of 20 years has been indicated to reach the mature stage prior to burning [12], it should be considered that the development of the vegetation structure in the 2008 fire has been influenced by other factors that may have limited its reproductive capacity (post-fire seedling density) and height development, such as pre- and post-fire climatic variations or severity [13–15]. On the opposite end, the 1970 fire, the furthest in time, exhibits the lowest levels of malleability, as both structures display similar distributions and PAC value close to 0. However, differences in canopy height are still observable.

5. Conclusions

The acquisition of high-density LiDAR point clouds from remotely piloted aerial systems has been very useful in characterizing the vertical structure from Aleppo pine forests affected by wildfires in different years, enabling the analysis of their recovery over time using two UAV-LiDAR metrics (ElevP99 and Profile Area Change). Although PAC was originally designed to analyze fire severity, its use in this study to quantify differences between control and burned sectors from the perspective of the physiognomic complexity of regeneration has allowed the differentiation of different regeneration models based on the fire date.

The proposed methodology and the split zone scheme design have highlighted the degree of disparity among regenerated structures themselves and in relation to their respective controls, as well as the possibility of interpreting the malleability dynamics of

P. halepensis forests over time. Despite the high negative correlation between time and the intensity of differences between vegetation structures, the higher complexity of vegetation structures identified in the 1995 wildfire (an intermediate phase) could be related to the role played by other variables such as severity, post-fire hydro-thermal parameters, or postfire treatments.

Author Contributions: Conceptualization, F.P.-C., L.A.L. and R.M.; methodology, C.I. and F.P.-C.; software, R.H. and C.I.; formal analysis, A.M. and A.G.-M.; investigation, M.A.; resources, R.H.; data curation, C.I. and R.H.; writing—original draft preparation, F.P.-C. and R.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by MCIN/AEI/10.13039/501100011033, grant number PID2020-118886RB-I00. And the predoctoral contracts from the Ministry of Universities (FPU18/05027) and the 2022–2026 Convocatory (Government of Aragon), corresponding to Raúl Hoffrén and Cristian Iranzo, respectively.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data available on request.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Keeley, J.E.; Pausas, J.G.; Rundel, P.W.; Bond, W.J.; Bradstock, R.A. Fire as an evolutionary pressure shaping plant traits. *Trends Plant Sci.* **2011**, *16*, 406–411. [CrossRef] [PubMed]
2. Daskalakou, E.; Thanos, C. Postfire Regeneration: The Role of Canopy and Soil Seed Banks. *Int. J. Wildl. Fire* **1996**, *6*, 59. [CrossRef]
3. Buhk, C.; Hensen, I. Processes of post-fire vegetation regeneration in south-eastern Spain: Searching for fire adaptation. *For. Ecol. Manag.* **2006**, *234*, S156. [CrossRef]
4. Westman, W.E. Measuring the Inertia and Resilience of Ecosystems. *Bioscience* **1978**, *28*, 705–710. [CrossRef]
5. Mandl, L. Spaceborne LiDAR for characterizing forest structure across scales in the European Alps. *Remote Sens. Ecol. Conserv.* **2023**, *9*, 599–614. [CrossRef]
6. Jarron, L.R.; Coops, N.C.; MacKenzie, W.H.; Tompalski, P.; Dykstra, P. Detection of sub-canopy forest structure using airborne LiDAR. *Remote Sens. Environ.* **2020**, *244*, 111770. [CrossRef]
7. Bouvier, M.; Durrieu, S.; Fournier, R.A.; Renaud, J.P. Generalizing predictive models of forest inventory attributes using an area-based approach with airborne LiDAR data. *Remote Sens. Environ.* **2015**, *156*, 322–334. [CrossRef]
8. Arkin, J.; Coops, N.C.; Daniels, L.D.; Plowright, A. Estimation of vertical fuel layers in tree crowns using high density lidar data. *Remote Sens.* **2021**, *13*, 4598. [CrossRef]
9. Gelabert, P.J.; Montealegre, A.L.; Lamelas, M.T.; Domingo, D. Forest structural diversity characterization in Mediterranean landscapes affected by fires using Airborne Laser Scanning data. *GIScience Remote Sens.* **2020**, *57*, 497–509. [CrossRef]
10. Viana-Soto, A.; García, M.; Aguado, I.; Salas, J. Assessing post-fire forest structure recovery by combining LiDAR data and Landsat time series in Mediterranean pine forests. *Int. J. Appl. Earth Obs. Geoinf.* **2022**, *108*, 102754. [CrossRef]
11. Hu, T.; Ma, Q.; Su, Y.; Battles, J.J.; Collins, B.M.; Stephens, S.L.; Kelly, M.; Guo, Q. A simple and integrated approach for fire severity assessment using bi-temporal airborne LiDAR data. *Int. J. Appl. Earth Obs. Geoinf.* **2019**, *78*, 25–38. [CrossRef]
12. Rodrigues, M.; Ibarra, P.; Echeverría, M.; Pérez-Cabello, F.; Riva, J. A method for regional-scale assessment of vegetation recovery time after high-severity wildfires: Case study of Spain. *Prog. Phys. Geogr.* **2014**, *38*, 556–575. [CrossRef]
13. Elvira, N.J.; Lloret, F.; Jaime, L.; Margalef-Marrase, J.; Pérez Navarro, M.Á.; Batllori, E. Species climatic niche explains post-fire regeneration of Aleppo pine (*Pinus halepensis* Mill.) under compounded effects of fire and drought in east Spain. *Sci. Total Environ.* **2021**, *798*, 149308. [CrossRef] [PubMed]
14. Pausas, J.G.; Ribeiro, E.; Vallejo, R. Post-fire regeneration variability of Pinus halepensis in the eastern Iberian Peninsula. *For. Ecol. Manag.* **2004**, *203*, 251–259. [CrossRef]
15. González-De Vega, S.; De las Heras, J.; Moya, D. Resilience of Mediterranean terrestrial ecosystems and fire severity in semiarid areas: Responses of Aleppo pine forests in the short, mid and long term. *Sci. Total Environ.* **2016**, *573*, 1171–1177. [CrossRef] [PubMed]