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Human-Impact Gradients through Anthropogenic Pollen Indicators in a Mediterranean Mosaic Landscape (Balearic Islands)

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Abstract: This paper proposes new anthropogenic pollen indicators for the Balearic Islands and attempts to assess gradients of human impact on vegetation in Mediterranean islands. A combination of modern pollen analogue studies, complemented by phytosociological descriptions and ordination techniques using quantitative and presence/absence data was used. Redundancy analysis allowed us to evaluate the relationships between pollen types and significant environmental variables and propose regional (e.g., *Centaurea*, *Rubus, Plantago lanceolata*-t) and local/microregional anthropogenic pollen indicators (e.g., Cerealia, *Poygonum aviculare*, *Matricaria*-t). Additionally, an anthropogenic index score (AIS) for each sampled location was calculated to correlate each pollen type to a specific degree of human impact: (a) low (e.g., *Cerastium*-t, *Erica arborea*-t, *Cistus albidus*), (b) moderate (e.g, *Sinapis*-t, *Sanguisorba minor*-t, *Plantago bellardii*-t), (c) high (e.g., Papaveraceae undiff., Dipsacaceae, *Secale*-t). This paper contributes to a further understanding of land-use dynamics and to defining the degree of impact, which is especially necessary to assess colonization and anthropization rhythms in Mediterranean island environments.

Keywords: Mediterranean; anthropogenic pollen indicators; palynology; modern analogues; human impact gradients; mosaic landscape; islands

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1. Introduction

The long-term history of human impacts on vegetation and the development of cultural landscapes have been a major research topic in Europe since the second half of the 20th century [1]. In this context, anthropogenic pollen indicators (API) and the indicator-species approach have been valuable tools for understanding human-induced vegetation changes in the past. Karl-Ernst Behre's [2] seminal approach proposed a list of taxa indicators of anthropogenic vegetation types and land use, providing a way to identify human impact through time via pollen assemblages. While regional and local-specific anthropogenic pollen indicators have proven to be essential in evaluating human impacts, classical indicators, such as those proposed by Behre, are still of great value and common in the palynological praxis for characterizing main trends in anthropogenic dynamics recorded on pollen diagrams, especially for detecting ancient human activities occurring in a forest-dominated environment [3]. Nevertheless, several authors suggest the necessity of establishing region-specific anthropogenic pollen indicators to further decipher past human practices through pollen analysis [4]. In this sense, significant research on modern pollen analogues has been developed in many areas of the world to further understand source areas (regional vs. local indicators) and human activities, namely pollen types that are indicators of specific practices such as agriculture or grazing [4–6]. Instead, Mercuri et al. [7] observed which synanthropic plants are always or recurrently represented in the historical and prehistoric contexts they studied, being evidence of human presence and activities in a certain area. While this bioindicator-based approach is common in many Central and Northern European areas, it has scarcely been applied in the Mediterranean region. Recent research also proposes new indices such as LUP (agricultural land use probability) as a general index to assess and quantify human impact intensity on European ecosystems [8]. Detailed reviews on different human impact indices and ratios have been published in Deza-Araujo et al. [8,9].

Overall, Mediterranean landscapes are characterized by a mosaic-like landscape structure, characterized by alternating forests, shrubby vegetation, and open-lands where a wide range of human activities have traditionally been developed (e.g., forestry, agriculture, grazing, mining, etc.). This type of landscape physiognomy in the Mediterranean region results in highly valuable environments due to its great biodiversity [10–12]. The origin of mosaic landscapes is linked to the onset of sylvoagropastoral activities during the Neolithic period, and especially since the mid-Holocene [13,14]. These legacy landscapes result from long-term sustainable practices through time and require rural landholders to preserve them [15].

Mediterranean island environments are particularly interesting for the study of Holocene plant–cultural interactions due to their particular biogeographical and sociocultural histories and because islands are more vulnerable to human and climate-induced changes [16]. Islands may be considered fragile environments where human impact and other environmental triggers may cause a tipping point, breaking their resilience status due to specific evolutionary adaptations that make to island species particularly vulnerable to human pressure [17]. For instance, the Balearic Archipelago seems to have been settled by humans relatively late when compared to other Mediterranean islands, with the scholarly accepted date for human arrival at ca. 2500 cal BC. Moreover, early agropastoral activities occurring in a context of forested environments and small-scale shifting human activities are difficult to detect from solely a palynological point of view, and therefore require multiproxy and interdisciplinary research to evaluate robust evidence of land use. In this sense, it has been suggested that the transition “from influence to impact”, during the Late Holocene and the development of Chalcolithic and Bronze Age cultures (III-II millennium cal BC for the Balearics), has been detected through pollen analysis in different Mediterranean contexts [14]. In general, to assess human impact on past environments, especially to further assess cultural change and island colonization processes in Mediterranean island environments, it is necessary to obtain reliable bioindicators.

In this paper, we present research on modern pollen analogues conducted in the Balearic Islands to determine pollen types related to local/microregional and regional anthropogenic activities, which in turn provide useful indicators of human land use for Mediterranean and circum-Mediterranean sites. In previous research, we analyzed pollen–vegetation relationships for specific vegetation types from the Balearic mosaic landscape, proposing their indicator value and degree of representativity [18]. However, the identification of anthropogenic pollen indicators still needs an exhaustive evaluation to assess their role and significance as apophytes in Mediterranean environments. We investigate the potential indicator value of pollen types to interpret pollen-derived human impact gradients in Mediterranean island environments.

2. Study Area

The Balearic Islands are an archipelago located in the Western Mediterranean Sea formed by a group of 151 islands and islets, with only the four largest being inhabited. The vegetation of the Balearic Islands is characterized by a mosaic-like pattern (Figure 1) which results from environmental and anthropogenic dynamics [19]. The climate of the Balearic Archipelago is typically Mediterranean, with seasonality (dry and hot summers and maximal rainfall during the autumn season). The highest rainfall is recorded in the Serra de Tramuntana mountain range (ca. 1500–1400 mm) in Mallorca, while the lowest values (300–450 mm) are recorded in Formentera [20]. These Mediterranean mosaics have been constructed through natural and social processes since the middle Holocene and are best understood using a *longue durée* perspective [21,22]. Therefore, the Balearic landscape is primarily composed of heterogeneous forests, shrublands, grasslands, tree orchards, agricultural, and pastoral areas. The prevalent tree vegetation are evergreen forests, woodlands, and sclerophyllous shrublands dominated by holm oaks, pins, olive trees, mastic, and junipers [23]. The primary agropastoral uses are based on dry extensive farming including annual cereal crops, with dispersed orchards and post-cereal-harvest livestock grazing [19]. Arboreal cultivars have traditionally been based on fig, olive, carob, and almond tree agriculture. Since the second half of the 20th century, many coastal areas have been widely urbanized in response to the tourism boom, and former crop fields and pastures are used for non-farming and touristic activities [24].

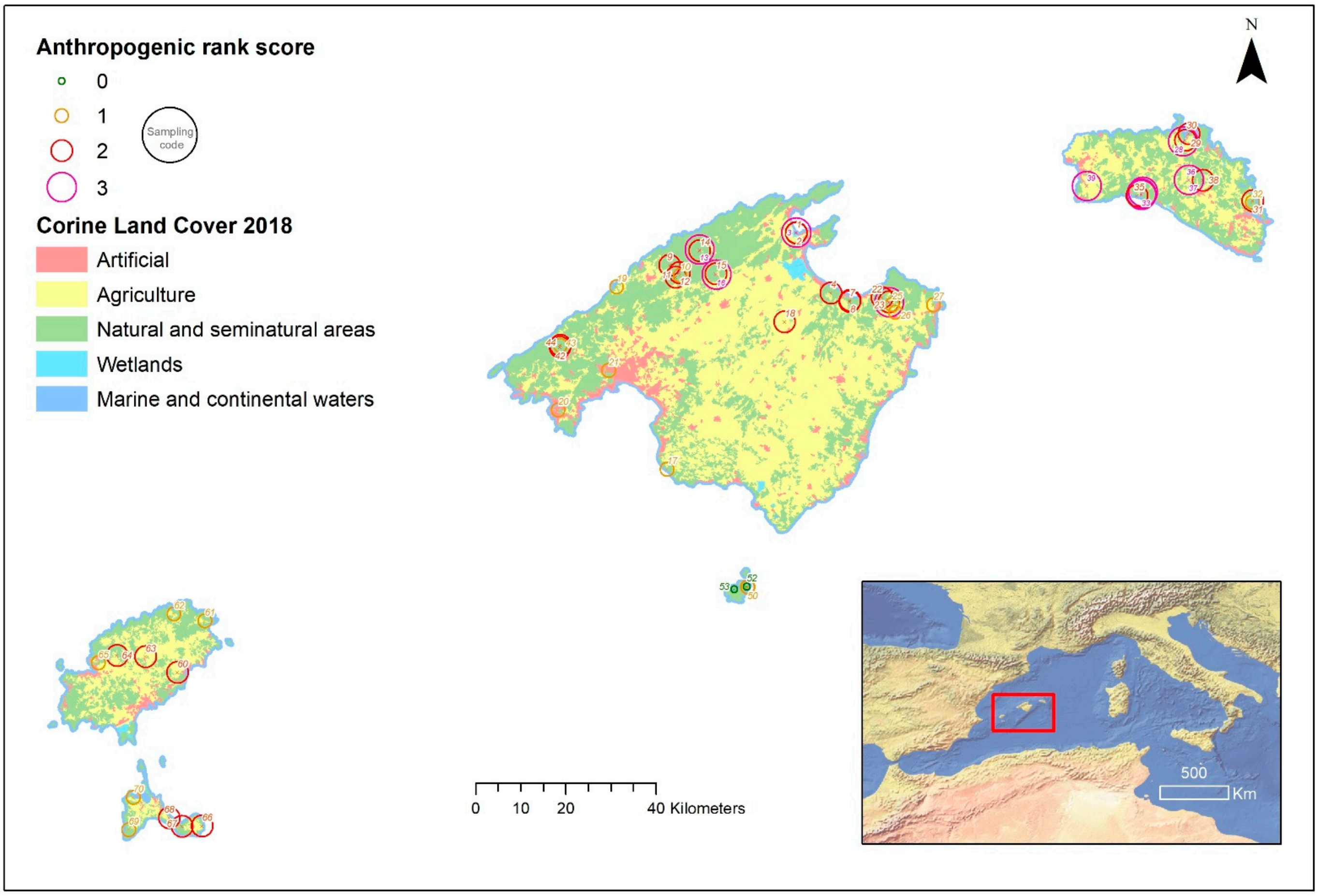

Figure 1. Map showing sampling locations of modern pollen samples with the estimated anthropogenic rank score (discussed in Section 3). Vegetation categories are based on Corine Land Cover 2018 classes.

As a result of this long-term, co-dependent relationship between people and ecosystems, Balearic landscapes and vegetation are well adapted to human-caused disturbances, such as the preference or tolerance of sclerophyllous dry-adapted species for grazing environments [25,26] (Figure 2). The spread of garrigues and maquis during the Late Holocene seems to be correlated to both drier climate conditions and an increase in agropastoral activities [22]. Vegetation community distribution may be explained through heterogeneous environmental conditions and different degrees of impact. Some synanthropic communities include *Urtico membranaceae-Smyrnietum olusatri* A. & O. Bolòs in O. Bolòs & Molinier 1958, *Resedo albae-Chrysanthemetum coronarii* O. Bolòs & Molinier 1958 or *Reichardio gracilis-Stipetum capensis* Costa & Loidi 1992 corr. [23], while key synanthropic taxa from the Balearic landscape include *Centaurea cyanus* L., *Asphodelus fistulosus* L., *Diplotaxis erucoides* (L.) DC, *Galactites tormentosa* Moench or *Plantago lanceolata* L. Vegetation community distribution may be explained through heterogeneous environmental conditions and different degrees of impact. Synanthropic vegetation is broadly present in the archipelago, including communities of *Artemisietea vulgaris* Lohmeyer, Preising & Tüxen ex von Rochow 1951 and *Stellarietea medie* Tüxen, Lohmeyer & Preising ex von Rochow 1951 classes, xerophytic grasslands of the *Lygeo-Stipetea* Rivas-Martínez 1978 class or meadow grasslands communities of *Molinio-Arrhenatheretea* Tüxen 1937 [23]. In addition to some export of synanthropic taxa to other neighboring natural communities with the characteristic mosaic vegetation arrangement of the Balearic Islands, there are species that intrude deeply as companions of plant formations favored by human disturbances; we highlight taxa such *Asphodelus aestivus* Brot., *Arisarum vulgare* Targ.-Torz., *Carlina corymbosa* L., or *Plantago lanceolata* L. Additionally, many non-native species are listed in Balearic botanical research on natural vegetation communities, resulting from intentional and unintended anthropogenic introduction [26–28], which are clearly favored by human activities. Nevertheless, it is still difficult to discern between archaeophytes and neophytes in the current state of botanical-paleoenvironmental research integration.

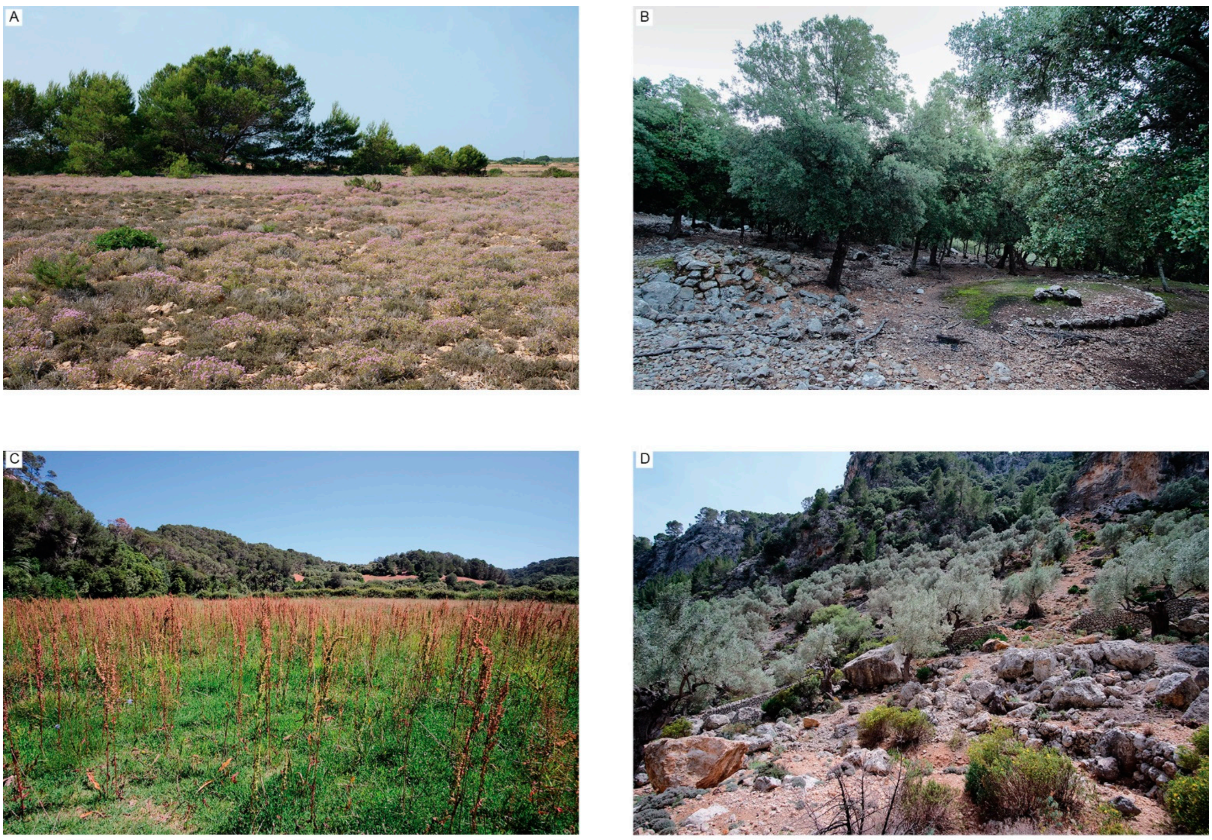

Figure 2. *Cont.*

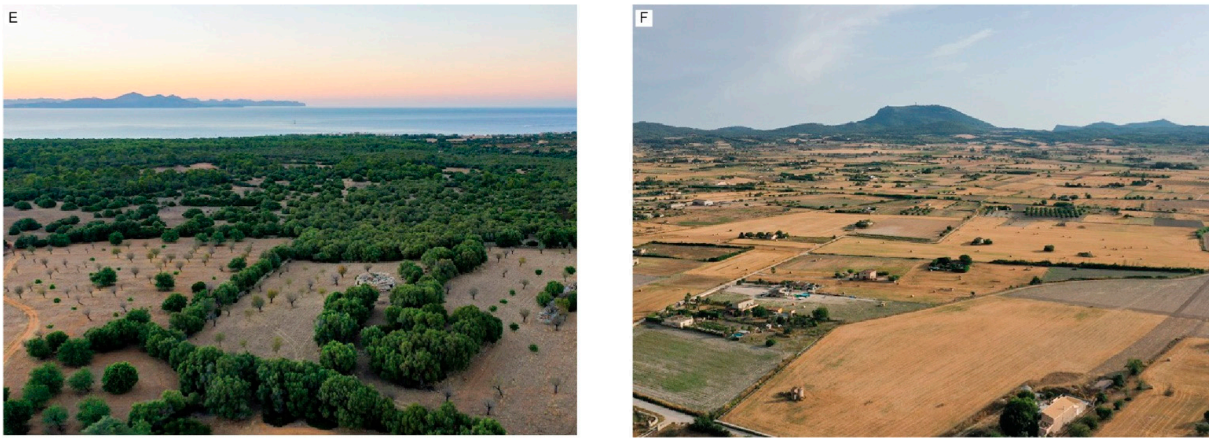

Figure 2. Example of several landscape types from the Balearic Islands: (**A**) xeric thyme-garrigue coastal vegetation (frigolar) from the Pytiusic Islands; (**B**) holm oak formations from the Serra de Tramuntana (Mallorca); (**C**) *Rumex* pasture in a ravine wetland from Barranc de Trebalúger (Menorca); (**D**) mountain olive orchards from the Serra de Tramuntana (Mallorca); (**E**) aerial view of a mosaic landscape with macchia and crop fields (north-eastern Mallorca); (**F**) aerial view of extensive agricultural fields from the interior of Mallorca.

3. Materials and Methods

Our methods rely on a combination of vegetation surveys, high-morphological resolution pollen identification and numerical analyses to propose anthropogenic indicators to evaluate long-term Holocene human impacts and environmental sustainability in Mediterranean island environments. Further details of fieldwork, laboratory treatment and the selection of environmental variables are reported in Servera-Vives et al. [18].

3.1. Fieldwork

Fifty-six modern pollen samples were collected within the main islands of the Balearic Archipelago: Mallorca, Menorca, Eivissa, Formentera and Cabrera, in 2016 and 2018 [18]. The locations were chosen to document the heterogeneity of major vegetation types of the Balearic mosaic-like landscapes in relation to a wide range of human activities and anthropization intensity. The studied samples consisted of moss cushions, as they may record several years of pollen rain on the sampling location [29,30]. Surface sedimentary samples were collected when local environmental constraints prevented the moss cushions from growing [31]. At least 5 moss cushions or surface sedimentary samples were combined into one sample from each sampling point and phytosociological descriptions were conducted in a 100 m^2 square using the Braun-Blanquet [32] system.

3.2. Environmental Variables

Environmental variables were recorded at each sampling site to explore the modern pollen–vegetation–anthropization relationship. Additional variables were also acquired through regional and international geospatial databases of landcover and other landscape metrics. A total of 34 environmental variables were collected for each sampling point, including vegetation type, meteorology, soil, landscape openness, fire activity, topography, landscape metrics and land use information. Detailed information for all environmental variables is described in Table S1 of the Supplementary Material.

3.3. Pollen Analysis

Both moss cushions and surface sedimentary samples were collected to perform pollen analyses on the current pollen rain. Pollen samples were dried overnight. While moss samples were treated following the standard procedures in palynology, including KOH, 200-µm sieving and acetolysis [33,34], surface sedimentary samples were analyzed using a 7-µm nylon handheld sieve and heavy-liquid separation. Pollen counts and identification were performed using a 400×, 600× and 1000× light microscope. Pollen percentages are based on pollen sum, excluding *Pinus* due to its overrepresentation. The taxonomic identification of pollen grains was based on pollen atlases [35,36], morphological keys [37,38] and the pollen reference collection of the Laboratorio di Palinologia e Paleobotanica (Università degli Studi di Modena e Reggio Emilia). In this work, cereals are recognized as Poaceae pollen grains with diameter larger than 40 µm, a pore annulus ≥ 12 µm [34] and scabrate exine decoration [35,39].

3.4. Statistical Analysis

3.4.1. Data Preparation and Statistical Software

A total of 63 pollen types were selected from all modern pollen sampling locations based on their role as potential anthropogenic indicators, as identified in the specialized literature (see, e.g., [2,4,6–9,40,41]). A square-root transformation was applied to the selected data to reduce the influence of the most abundant taxa, following Ejarque et al. [6], López-Sáez et al. [42] and Servera-Vives et al. [18]. All data transformations, analyses and visualizations were performed using R, version 4.2.0 [43], the vegan package, version 2.6-4 [44] and the ggplot2 package version 3.4.0 [45].

3.4.2. Redundancy Analysis (RDA) of Pollen Taxa and Environmental Variables

Ordination techniques were used to evaluate the relationship between modern pollen sampling sites, selected pollen taxa and the environmental variables recorded at each sampling site. Detrended correspondence analysis (DCA) was performed to determine the most appropriate ordination techniques for these data, following Smilauer and Lepš [46], Ejarque et al. [6], López-Sáez et al. [47] and others. The resulting gradient length of the selected pollen dataset was 2.58 standard deviation of species turnover units, indicating that a linear ordination method, such as redundancy analysis, is suitable for these data. Additionally, the numerous environmental variables compiled for this analysis (n = 48) increases the likelihood of multicollinearity among each of these predictors, which in turn can obscure relationships between all variables. Variance inflation factors (VIF) were calculated for all environmental variables to assess redundancy in our measures. Environmental variables with VIF values greater than 20.0 were considered highly collinear and removed, leaving eight variables for redundancy analysis. The RDA of pollen, sites, and environmental variables was conducted using a combination forward/backward stepwise model selection, after which ANOVA permutation tests were performed to identify the influential of each predictor on the structure of the pollen dataset. Pearson's correlation coefficients (r) were calculated to evaluate the relationship between pollen taxa and each environmental variable using the orthogonal linear combinations of the explanatory variables from the RDA.

3.4.3. Constructing the Anthropogenic Intensity Score (AIS) for Sample Sites

We evaluate the degree of anthropization at each sample site by creating an anthropogenic intensity score (AIS), which accounts for the values of the most influential environmental variables at each site, as identified through the RDA. The steps in creating the AIS are outlined below:

(1) At each sample site, the values of the 8 most influential environmental variables were compiled and transformed to equalize the magnitude of each measure. For example, *agropastoral use* is a binary variable with values ranging from 0 to 1, while *herbivory pressure* is an ordinal variable with values ranging from 0 to 2. To give both variables equal magnitude in constructing the AIS, the values of the *agropastoral use* variable are multiplied by 2 to match the range of values of the *herbivory pressure* variable. This logic was applied to all variables in our dataset.

(2) The resulting values of each environmental variable were weighted by the p-values calculated by the ANOVA permutation tests applied to the results of the RDA,

following Equation (1). Weighting these variables gave the more influential environmental predictors greater effect in determining the AIS than less influential environmental variables.

$$Weighted\ Variable = Transformed\ Variable \times (1 - p - \text{value}) \quad (1)$$

(3) Weighted environmental variables were then summed for each sample site to create a raw anthropogenic intensity score value.
(4) The final AIS was calculated by rescaling the raw anthropogenic intensity values for each site to a 0 to 1 index, with 1 representing the highest anthropogenic intensity score and 0 the lowest anthropogenic intensity score.

3.4.4. Evaluating Anthropogenic Indicator Gradients

Final anthropogenic intensity scores were ranked by dividing the values into three equal quantiles to represent low (0.00–>0.33), moderate (≤0.33–>0.66) and high (≤0.66–1.00) degrees of anthropogenic influence on vegetation communities at each sample site (Figure 1). Pollen taxa were then summed by their abundance (%) in sample sites belonging to each AIS quantile rank category. Principal components analysis (PCA) and a biplot were used to visually illustrate species abundance by AIS rank.

The relationship between each pollen taxon and AIS rank category provides information on its strength as a potential indicator of diverse anthropogenic activities in the fossil pollen record. We constructed an initial categorization of the taxa that are the most correlated to high, moderate and low AIS using K-means clustering (K = 4) of the summed pollen taxa by gradient category. Four clusters were used to group these data to allow for taxa that were weakly correlated with high, moderate and low AIS to be captured in an intermediate category. While K-means provides a general indicator of a pollen taxon's relationship to anthropogenic activities, it does not specifically evaluate a taxon's indicator strength. Subsequently, each pollen taxon's indicator strength was evaluated by mapping its distance in the PCA factorial plane to an "idealized" taxon that is perfectly correlated with either high, moderate or low AIS values. The distances between taxa and the idealized taxon were calculated and scaled between 0 and 1, which illustrates the indicator strength of each taxon for its AIS group. These values were then displayed as a color gradient in a PCA biplot and in a series of silhouette plots for each group. Finally, pollen sums of key ruderal and nitrophilous taxa were plotted in the PCA biplot as supplementary passive variables (e.g., *Plantago* SUM) to assess the potential role of some pollen aggregations in lower taxonomic resolution than pollen types as potential API. This is especially important to be able to evaluate human impact through pollen analysis in on-site sedimentary records, where palynomorph's preservation generally do not allow high taxonomic resolution [7,48].

Additionally, the local/microregional vs. regional indicator value of each pollen type was evaluated by considering the Davis [49] and fidelity/dispersibility [50,51] indices obtained in Servera-Vives et al. 2022. More specifically, in this paper, local vs. regional indicators are proposed either considering pollen types classed as strongly associated taxa (SAT) or associated taxa (AT) in the Davis indices calculation or high fidelity (>50) + low dispersibility (<50) values. Davis indices and fidelity/dispersibility indices were calculated for all taxa based on their presence or absence in both the pollen and observed vegetation datasets [18].

4. Results

4.1. Pollen Type-Environmental Variables Correlation

Pearson's correlation coefficients (r) and redundancy analysis values indicating moderate to high (>0.5) correlation between pollen types and environmental variables are shown in Table 1. Pasture area (sqm) and landscape openness show similar correlations with PC1 and PC2 and includes comparable pollen types such as Papaveraceae undiff., Dipsacaceae, *Vitis* and *Trifolium*-t. Distance to forest shows the highest correlation with *Plantago* cf. *crassifolia, Verbascum*-t, *Cistus salviifolius* and *Hornungia*-t, while agropastoral use correlates with *Avena-Triticum*-group, *Plantago lanceolata*-t, *Rubus* and *Galium*-t. Here, we also propose potential local/microregional and regional indicators based on fidelity/dispersibility, and Davis indices obtained in Servera-Vives et al. [18] and discussed in Section 5.1. Potential local indicators of open and anthropized habitats include Poaceae undiff., *Polygonum aviculare*-t, *Avena/Triticum*-group, *Matricaria*-t, and *Urtica dioica*-t.

Table 1. List of taxa showing positive Pearson correlation r values higher than 0.5 to significant environmental variables. The list of pollen types is listed in decreasing correlation order for each category, while the order of environmental variables follows the RDA *p*-values. Local indicators vs. regional are proposed either considering pollen types classed as SAT or AT in the Davis indices calculation or high fidelity (>50) + low dispersibility (<50) values resulting from Servera-Vives et al. [18]. Taxa linked to the agropastoral use variable are highlighted in bold in the text.

	Regional Indicators	Local/Microregional Indicators
Distance to forest	*Plantago* cf. *crassifolia*, *Verbascum*-t, *Hornungia*-t, *Plantago coronopus*-t, *Lotus*-t, Apiaceae, *Plantago bellardii*-t, *Centaurea jacea*-t, *Linaria*-t, Chenopodiaceae, Brassicaceae SUM	*Cistus salviifolius*, *Artemisia*
Pasture area	Papaveraceae undiff, Dipsacaceae, *Vitis*, *Trifolium*-t, *Plantago* sp., *Cirsium*-t, *Senecio*-t, Cichorieae, Brassicaceae SUM, Chenopodiaceae, *Rumex*, *Carduus*-t, Apiaceae, *Sinapis*-t, *Lotus*-t, *Plantago albicans*, *Plantago coronopus*-t, *Hornungia*-t, *Plantago major/media*, *Echium*, *Centaurea*	Poaceae undiff., *Polygonum aviculare*-t, Cerealia SUM, *Matricaria*-t, *Urtica dioica*-t
Landscape openness	*Trifolium*-t, *Vitis*, Papaveraceae undiff, Dipsacaceae, *Plantago* sp., *Cirsium*-t, *Senecio*-t, Brassicaceae SUM, Chenopodiaceae, Cichorieae, Apiaceae, *Lotus*-t, *Rumex*, *Plantago coronopus*-t, *Carduus*-t, *Sinapis*-t, *Hornungia*-t, *Plantago albicans*	Poaceae undiff., *Polygonum aviculare*-t, Cerealia SUM, *Matricaria*-t
Agropastoral use	*Plantago lanceolata*-t, *Rubus*, *Galium*-t, Caryophyllaceae undiff., *Centaurea*, *Echium*, *Plantago major/media*	*Avena/Triticum*-group
List of potential local/microregional indicators of anthropized habitats	Poaceae undiff., *Polygonum aviculare*-t, ***Avena/Triticum*-group,** Cerealia SUM, *Matricaria*-t, *Urtica dioica*-t	
List of potential regional indicators of anthropized habitats	***Plantago lanceolata*-t, *Rubus*, *Galium*-t, Caryophyllaceae undiff., *Centaurea*, *Echium*, *Plantago major/media***, Papaveraceae undiff, Dipsacaceae, *Vitis*, *Trifolium*-t, *Plantago* sp., *Cirsium*-t, *Senecio*-t, Cichorieae, Brassicaceae SUM, Chenopodiaceae, *Rumex*, *Carduus*-t, Apiaceae, *Sinapis*-t, *Lotus*-t, *Plantago albicans*, *Plantago coronopus*-t, *Hornungia*-t	

4.2. Redundancy Analysis (RDA)

After the calculation of VIF to test for collinearity, a total of eight environmental variables were retained for redundancy analysis. The two first RDA axes explain a total of 18.63% of the variance within the dataset. Forward–backward selection results in three statistically significant environmental variables (p-value ≤ 0.05), namely distance to forest, pasture size (square meters) and landscape openness. While less significant, agropastoral use shows noticeable importance in structuring our dataset, while trampling, fire, distance to urban and herbivory pressure demonstrate low significance (Table 2).

Table 2. ANOVA permutation test results for the environmental variables selected for the RDA using the forward/backward method for stepwise model selection. Significant *p*-values (≤0.05) appear in bold. Significance codes: 0.001 = "**", 0.05 = "*" and 0.05 = "·"

Environmental Variable	Df	Variance	F	*p*-Value
Herbivory pressure	1	0.35	0.83	0.603
Agropastoral use	1	0.72	1.69	0.057·
Trampling	1	0.50	1.18	0.230
Landscape openness	1	0.73	1.72	**0.036** *
EFFIS Fire Occurrence	1	0.51	1.21	0.250
Distance to urban	1	0.28	0.65	0.803
Distance to forest	1	1.09	2.56	**0.009** **
Pasture area	1	0.96	2.25	**0.021** *

The first RDA axis shows a gradient from closed to open environments (Figure 3). It contrasts most of the sites, from maquis, garrigues, oak forest and *Buxus* formations demonstrating positive values to coastal saltmarshes, some anthropized habitats, dune habitats and wet pastures in tall humid grassland and freshwater riverine scrubs showing negative values on the axis. The second RDA axis is most related to anthropogenic environments, with garrigues and maquis demonstrating positive values and oak forest, box formations and coastal salt environments with negative values. Pollen types in the negative RDA1 and positive RDA2 values quadrant (upper left) are related to pastoral activity (pasture square meters and agropastoral use) and landscape openness. In this sense, *Plantago lanceolata*-t, Cichorieae, *Avena/Triticum*-group, *Plantago albicans, Rumex, Plantago* sp. and, to a lesser extent, *Hordeum*-t, *Cistus monspeliensis*, *Asphodelus*, *Erica arborea*-t, *Matricaria*-t and *Sinapis*-t are correlated to agropastoral use. Other taxa placed in the negative RDA1 and RDA2 axis values (lower left quadrant), such as *Verbascum*-t, *Plantago* cf. *crassifolia* and *Plantago coronopus*-t, are related to open areas (distance to forest) and, less significatively, to trampling. Ranunculaceae undiff. *Artemisia*, *Linaria*-t and *Erica arborea* seem to be correlated with fire occurrence (lower right quadrant), and *Plantago* SUM and *Plantago afra* to distance to urban areas and herbivory pressure (upper right quadrant).

4.3. K-means Clustering and Unconstrained PCA with Anthropogenic Impact Gradient Categories

K-means clustering was used to create four groups to describe the types and intensity of anthropogenic activities characterizing the sample sites, which we have termed (i) low, (ii) moderate, (iii) high and (iv) intermediate anthropogenic impacts. (i) The first group is comprised of indicators of low-levels of anthropogenic impacts on vegetation and includes a total of 10 pollen types, such as *Erica*, *Cerastium*-t and *Medicago*. (ii) Moderate impact indicators are represented by a group of 15 pollen types, including *Sinapis-t, Sanguisorba minor-t* and *Plantago bellardii*-t. (iii) High anthropogenic impact indicators include 12 pollen types, such as Papaveraceae, Dipsacaceae and *Secale*-t. (iv) The final group of taxa are not clearly associated with a specific degree of human impact, and include a total of 24 pollen types (e.g., *Galium-t, Urtica dioica*-t., *Cistus*, etc.). Pollen sums of key botanic genera and families, also included in this analysis, are for instance sums (SUM) of Brassicaceae, Cerealia-t and *Plantago*, which may be considered good indicators of high human pressure, while Erica SUM is well represented in low impact habitats. The results obtained from K-means clustering are plotted in an unconstrained PCA, where pollen types are drawn as observations and the degrees of impact obtained by the AIS calculation are plotted as variables (Figure 4A). To give more details about the performance of each pollen type within each group, a complementary PCA showing the indicator strength is also shown (Figure 4B). An extensive list of K-means clustering for each impact degree category is presented in Figure 5.

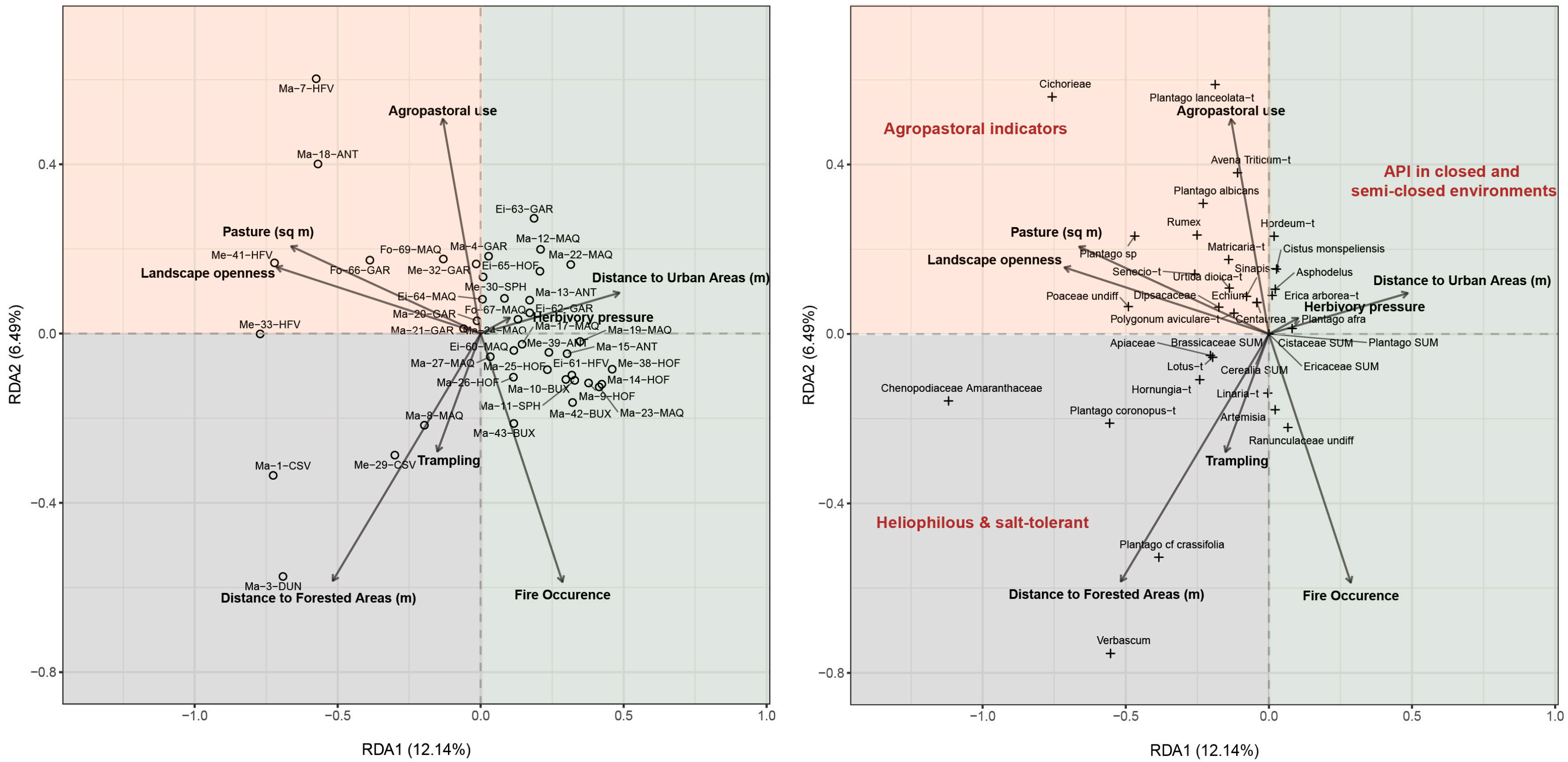

Figure 3. Redundancy analysis results showing the correlation between environmental variables with sites (**left**) and between environmental variables with the top 50% pollen types (**right**). Color-shaded quadrants refers to main interpretative groups.

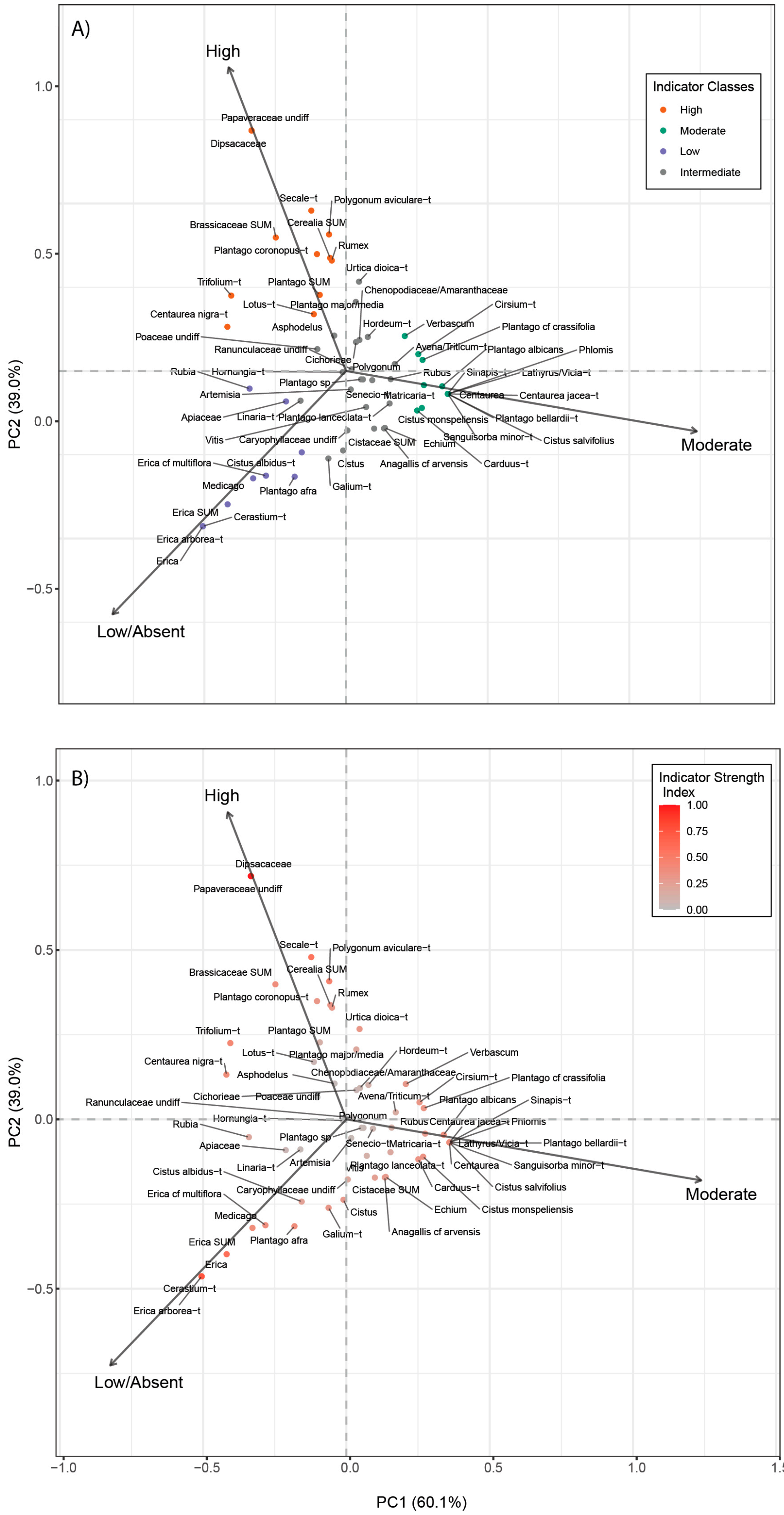

Figure 4. (**A**) Constrained PCA showing the relation between the human impact gradient and the assigned pollen types to each category. (**B**) Constrained PCA based on the indicator strength index for each pollen type.

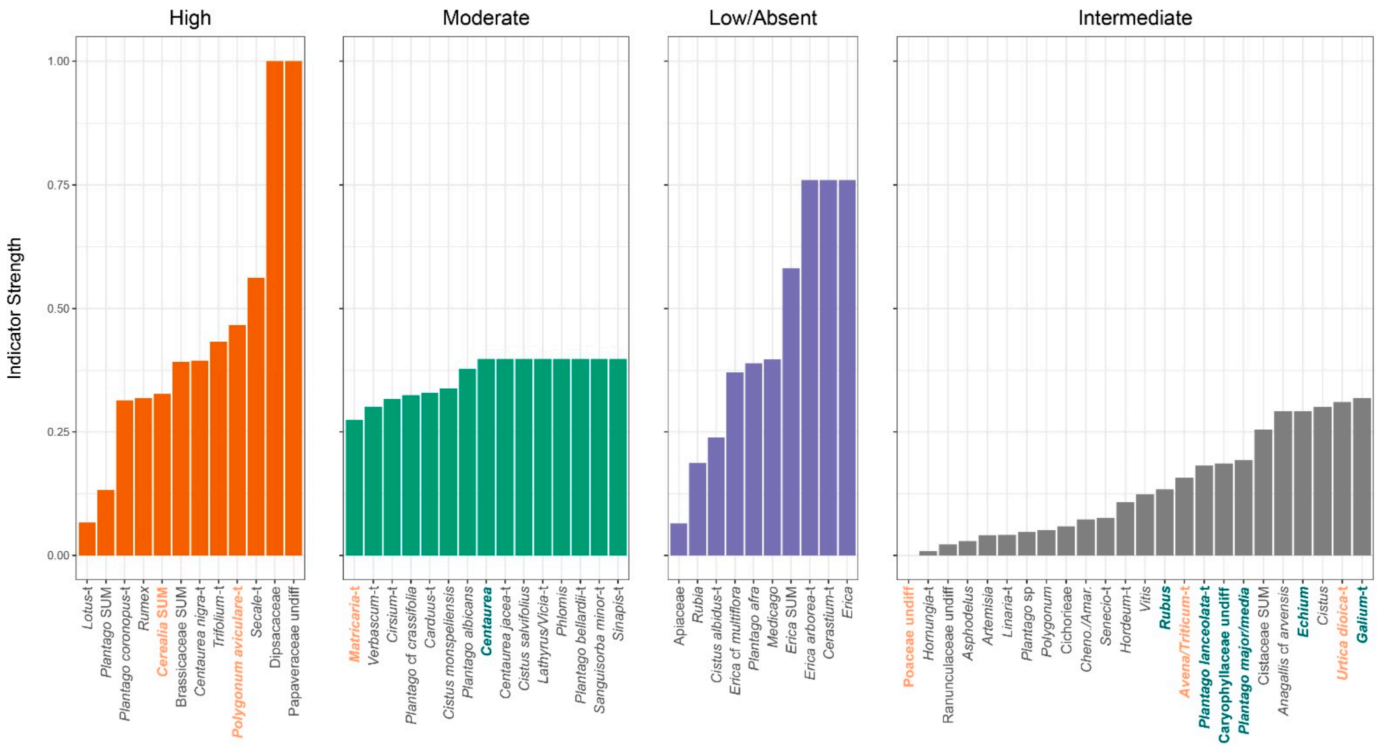

Figure 5. Indicator strength results for pollen types within the correspondent human-impact gradient category. Orange-colored labels correspond to local/microregional agropastoral indicators in the Pearson correlation (Table 1), while dark cyan represent regional agropastoral indicators.

5. Discussion

5.1. Identifying Local/Microregional and Regional Anthropogenic Pollen Indicators

The anthropogenic indicators for the Balearic Islands can be identified based on results obtained from redundancy analysis and Pearson correlation results (Figure 3 and Table 1). The correlation between pollen types and three variables (landscape openness, pasture size and agropastoral use) from our study is especially useful for proposing anthropogenic pollen indicators. Interestingly, *Plantago lanceolata*-t, *Avena/Triticum*-group, *Rubus*, *Galium*-t, Caryophyllaceae undiff., *Centaurea*, *Echium* and *Plantago major/media* are the pollen types with the best performance as agropastoral indicators, as shown by the moderate/high correlation with "agropastoral use". Other taxa, such as Poaceae undiff., *Polygonum aviculare*-t, *Matricaria*-t, Papaveraceae undiff, Dipsacaceae, *Vitis*, *Trifolium*-t, *Plantago* sp., *Cirsium*-t, *Urtica dioica*-t, *Senecio*-t and Cichorieae, are more correlated with large pastures and the degree of landscape openness.

Other heliophilous taxa such as *Verbascum*-t, *Plantago* cf. *crassifolia*, *Plantago coronopus*-t and Chenopodiaceae are correlated to high values of the distance to forest variable, suggesting their preference for open environments. These taxa are especially abundant in samples from coastal, salt-tolerant and dune vegetation in our study, where salt and soil compaction are frequent. In this sense, while not statistically significant, trampling appears correlated to these taxa. *Plantago crassifolia* pollen is included within the *P. coronopus*-t [52]. As the *P. crassifolia* plant mostly grows as a halophyte on shore marshlands [53,54], *Plantago coronopus*-t must be interpreted carefully as an API in coastal paleoenvironmental records [18,22]. This is the same for Chenopodiaceae. Species from this family are salt-tolerant but they are also frequent in ruderal and nitrophilous environments. Nevertheless, its overrepresentation in the modern pollen rain from the Balearic Islands hinders its consideration as an API, when not accompanied by other APIs in pollen assemblages.

A detailed list of potential regional and local indicators is shown in Table 1 and Figure 4. This list is based on the fidelity/dispersibility and Davis indices obtained in Servera-Vives et al. [18] and the statistical work presented in this work. Potential local indicators of open and anthropized habitats include Poaceae undiff., *Polygonum aviculare*-t, *Avena/Triticum*-group, *Matricaria*-t and *Urtica dioica*-t. Otherwise, pollen types identified as potential regional indicators include *Plantago lanceolata*-t, *Rubus*, *Galium*-t, Caryophyllaceae undiff., *Centaurea*, *Echium* and *Plantago major/media*. Modern analogue research carried out in mountain areas such as the Pyrenees also highlighted *that Plantago lanceolata*-t and *Plantago major/media* indicate regional human activity [4]. Even though Poaceae are anemophilous taxa, the high association values in the Davis indices suggest a good plant–pollen association, as has been recorded in similar research [4,6,55,56].

5.2. Pollen Types Related to Different Degrees of Human Impact Intensity

Despite the many studies on modern pollen analogues that have been carried out to understand how pollen types respond to specific human practices, attempts to specify pollen's role in differentiating the degree of human impacts has not yet been explored systematically. Consequently, we explored the potential of pollen indicators to evaluate the degree of human impacts based on an ad hoc AIS index and statistical analysis on modern pollen data from the Balearic Islands (Figures 4 and 6). This work provides insights into comprehensive pollen indicators that may also be applied to other Mediterranean island environments.

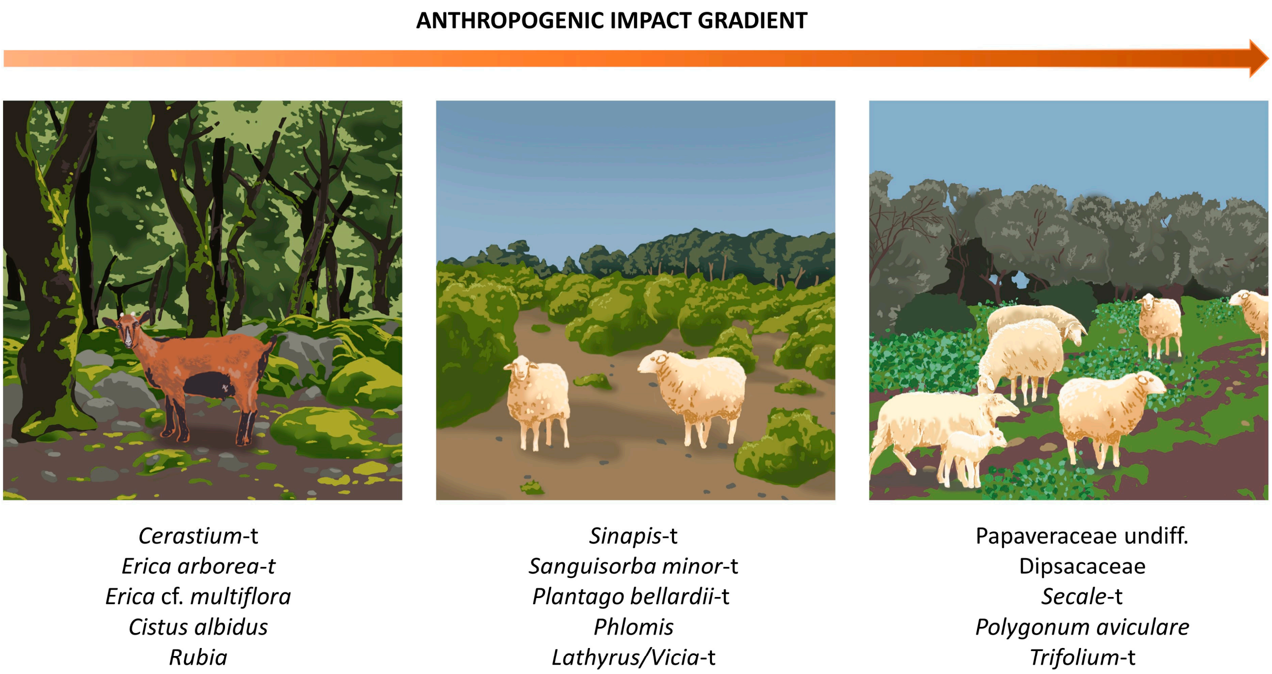

Figure 6. Artistic illustration showing selected pollen types associated with low, moderate, and high human impact degree. An exhaustive list of pollen types for the anthropogenic impact gradient appears in Figure 5.

The group of indicators most related to environments with low anthropogenic impacts aggregates several Ericaceae pollen types (*Erica* sp., *Erica arborea*-t, *Erica* cf. *multiflora*), as well as *Cerastium*-t, *Medicago* and Rubia. Ericaceae pollen curves have regularly been related to early successional vegetation and high fire frequency in pollen analysis from the Mediterranean region [22,57,58]. This may be due to the adaptation of many species of this family to regular fire disturbance through developing lignotubers that allow resprouting after burning [59,60]. In the Balearic Islands, all three *Erica* species are currently present in the landscape, including *E. multiflora* L., *E. arborea* L. and *E. scoparia* L., present lignotubers and are common in sclerophyllous maquis and garrigues formations [59–61]. *Erica* pollen may be considered a local pollen indicator (associated taxa) with low dispersibility and strong fidelity in the Balearic Islands [18]. Moderate to high values of *Erica* pollen types can be associated with repeated burning for pastoral activities [58].

Moderate human impact indicators include *Cistus* pollen types (*C. salvifolius* and *C. monspeliensis),* several *Plantago* types (*P.* cf. *crassifolia*, *P. bellardii*-t and *P. albicans*-t), several Asteroideae types (*Centaurea, C. jacea, Carduus*-t, *Cirsium*-t and *Matricaria*-t), *Verbascum*-t, *Phlomis* and *Sanguisorba minor*. *Centaurea* and *Plantago* types are among the most frequent taxa recorded in Italian archaeopalynological studies, proving their value as cultural pollen indicators [7], and they are both interpreted as pastoral indicator with increased prevalence in grazed areas [5,62]. This study suggests that *Sinapis*-t and *Matricaria*-t are also likely important agropastoral indicators that should be considered in addition to *Centaurea* and *Plantago* types. Balearic *Verbascum* species are recurrent in croplands and roadsides, and therefore *Verbascum* pollen type may be also considered an API based on our research. *Matricaria*-t includes five plant species recorded during the Braun-Blanquet descriptions, among which three develop in ruderal and agricultural environs, namely *Anthemis arvensis* L., *Chrysanthemum segetum* L. and *Glebionis coronaria* (L.) Cass ex Sprach. In previous modern analogue research from the Balearic Islands [18], *Matricaria*-t pollen values higher than 1% were only found in crop fields and pastures. Similarly, *Sinapis*-t has also previously been considered an indicator of weed flora in other modern analogue studies [5], and its role as a cultural indicator is confirmed by the results of both RDA and PCA analyses presented here.

Indicators of high human impact include 12 pollen types: Papaveraceae undiff., Dipsacaceae, *Secale*-t, *Polygonum aviculare*-t, *Trifolium*-t, *Centaurea nigra*-t, Cerealia SUM, *Rumex*, *Plantago coronopus*-t, *Plantago* SUM, *Lotus*-t and Brassicaceae SUM. All these pollen types are frequently referred to as cultural pollen indicators in modern pollen analogue research (e.g, [5–7]. The family of Dipsacaceae includes several synanthropic taxa in the Balearic Islands such as *Centranthus calcitrapae* (L.) Dufresne and *Scabiosa atropurpurea* L., both of which were reported in the Braun-Blanquet descriptions collected during the fieldwork. *Centranthus* and Dipsacaceae pollen were reported with greater values in sites categorized as high impact in the AIS classification. Although Dipsacaceae is not usually considered an anthropogenic pollen indicator, RDA and PCA results suggest it is most related to sites with high AIS values and that it should be considered an indicator of high levels of anthropization. Moreover, Dipsacaceae pollen has also been related to human practices in other palynological research [62–64].

Brassicaceae is also an indicator of high human impact in this study and are commonly related to human-induced environments in pollen-analytic studies [65], but the highest values are related to cultivated fields in modern analogue research [62]. Interestingly, Brassicaceae pollen types are found in high abundance in prehistoric settlements and funerary archaeological sites from the Balearics [21,66], suggesting that humans interacted with Brassicaceae plants through both propagation and cultural uses due to their economic, dietary and symbolic value. In the historical period, Brassicaceae have been found in stratigraphies from the ancient imperial harbors of Rome [67,68] and Naples [69], as well as in rural contexts in Sicily [70]. These taxa have been interpreted as evidence for crop cultivation of cabbage during the Roman period, as attested to by classical authors (e.g., Pliny the Elder) or for oil extraction, as is documented by recovered macroremains [71].

Cereal pollen types are confirmed to be good indicators of both human impact and agropastoral uses by ordination techniques. *Secale*-t and Cerealia SUM (*Avena/Triticum*-group + *Secale*-t + Cerealia-t) are related to high impact, but *Avena/Triticum*-group is included in the intermediate indicator category. Nevertheless, its scores in the two first axes of the constrained PCA were between high and moderate impact, suggesting that this pollen type may potentially be related to both moderate and high impact sites. In this sense, the RDA logically confirms *Avena/Triticum*-group as a good indicator of agropastoral activities. Both *Plantago* SUM and *P. coronopus* pollen types are included in the high impact category. As explained previously, *Plantago* cf. *crassifolia* pollen is included within the *P. coronopus* type, being the first classed as a moderate impact indicator, therefore pointing out that these pollen taxonomical classifications may be associated with cultural activities, especially when they are associated with other anthropogenic pollen indicators.

Finally, the intermediate impact category includes pollen types that are difficult to assign to a specific degree of AIS. This is likely caused by the ubiquity of such taxa in all the studied sites. This should not be understood as their lack of value as anthropogenic pollen indicators, but rather that they should be considered general indicators of a variety of anthropogenic activities. In this sense, some pollen types clearly associated with agropastoral use in the RDA, such as *Urtica dioica*-t or *Plantago lanceolata*-t, do not perform well as reliable indicators for detecting human impact gradients. The intermediate group includes well known API based both on palynological and ecological knowledge. For instance, *Plantago lanceolata*-t, *Avena/Triticum*-t and Cichorieae are included in this general category, but much pollen-analysis research has proved their strong value in detecting human impact [5,8]. *Plantago lanceolata*-t has commonly been used as an anthropogenic pollen indicator in several palynological analyses, especially in North European areas [2] while the interpretations of low values in Mediterranean and circum-Mediterranean areas should be considered carefully [4,6]. *Plantago* species are found in ruderal habitats subjected to soil compaction, therefore being related to human and herd presence [7].

5.3. Reflection on Pollen Morphology Resolution and Productive Cultural Practices

In the palynological interpretations, the co-occurrence of several anthropogenic indicators is needed to detect human impacts on vegetation. Indeed, our interpretations should rely on the accurate integration of off-site bio-indicators (e.g., pollen, non-pollen palynomorphs, charcoals, diatoms, etc.) with archaeobotanical, historical and archaeological data. Disregarding such important sources of information would diminish our ability to understand the inter-relationship between landscape processes and human behavior through time. Nevertheless, pollen morphology is a complex task and occasionally it is not possible to achieve the high-resolution level needed to link pollen types to specific environments or human practices [5,9,62]. This is particularly true in archaeopalynological research, where taphonomy and post-depositional processes amplify the increased deterioration of some palynomorphs, resulting in the frequent morphological identification limited to genus or family-level morphological identifications.

Nevertheless, despite the fact that the species level would always be suitable for palaeoecological reconstruction, this does not mean that lower taxonomical levels (family, subfamily, genus, etc.) cannot be valuable anthropogenic pollen indicators. In this study, we include some morphological aggregations such as Brassicaceae or *Plantago* SUM, which perform even better than the pollen type taxonomic level in the ordination analysis. Another taxon performing well as API is Cichorieae, a tribe of the sub-family Cichorioideae included in the Asteraceae family. Cichorieae has proven to be an indicator of secondary pastures and some types of primary open habitats in the Mediterranean area [41]. In the constrained PCA and k-means clustering, it is included in the intermediate category, but based on the scores on the first PCA axis it seems to be related both to medium and high human impact. Furthermore, Cichorieae in the RDA is clearly linked to larger pastures and agropastoral use. Caryophyllaceae undiff. is also linked to agropastoral use, but not manifestly linked to a determinate degree of landscape impact. Otherwise, other family-level morphological classifications such as Ranunculaceae undiff. do not seem to be clearly associated with either human impact gradients or specific environmental variables in the ordination analysis.

6. Conclusions

This paper constitutes the first proposal of anthropogenic pollen indicators for the Balearic Islands, and a new attempt to assess the human-impact gradient in Mediterranean islands. To do so, we used a combination of modern pollen analogues, phytosociological descriptions and ordination techniques employing quantitative and presence/absence data. Redundancy analysis allowed us to evaluate the relation of pollen types to significant environmental variables, from which we devised an anthropogenic index score (AIS) for each site based on the degree to which it exhibited the most impactful anthropogenic environmental variables.

Comparing the redundancy analysis data and the pollen representation indices (Davis' and fidelity dispersibility indices) used in previous research [18], we proposed local/microregional and regional anthropogenic indicators that will allow us to further spatialize human activities during the Holocene. Local/microregional indicators of human activities are Poaceae undiff., *Polygonum aviculare*-t, *Avena/Triticum*-group, Cerealia SUM, *Matricaria*-t and *Urtica dioica*-t, while regional indicators are *Plantago lanceolata*-t, *Rubus*, *Galium*-t, Caryophyllaceae undiff., *Centaurea*, *Echium*, *Plantago major/media* among others. Additionally, we identified indicators of low anthropogenic impact (i.e., *Erica*, *Cerastium*-t and *Medicago);* moderate anthropogenic impact, (i.e., *Sinapis-t, Sanguisorba minor-t Plantago bellardii*-t); and high anthropogenic impact (i.e., Papaveraceae, Dipsacaceae and *Secale*-t). Some taxa are not clearly related to specific impact gradients, such as *Galium-t*, *Urtica dioica*-t. and *Cistus*, and have been classified as intermediate anthropogenic indicators through this study. Our research also confirmed that lower taxonomical levels in the pollen analysis (genera or family) may also be good indicators of human activities, as for instance with Brassicaceae, *Plantago* SUM or Cichorieae.

Some potential limitations of our research are that current human activities are not easily and directly comparable to those that took place in the past. Therefore, when constructing general indices, possible biases must be considered. In this sense, quality and resolution of environmental variable datasets can also make the interpretation of pollen type-environmental variable correlations difficult. To tackle this issue, it is mandatory to generate narratives on past landscape dynamics, socioenvironmental interactions and anthropization intensity by putting anthropogenic indicators in a broader context including other palaeoecological, historical and archaeological information.

This research may have implications for the environmental, archaeological and palaeoecological fields. As insights into modern pollen analogues provide new perspectives on pollen–vegetation relationships, this paper extends this understanding by leveraging land-use dynamics as a means to define the degree of anthropogenic impact in these landscapes. This process is especially necessary to assess colonization and anthropization rhythms in Mediterranean island environments. The novel methods applied through this study can also be applied to further interdisciplinary research pertaining to environmental restoration and management that are interested in assessing anthropogenic drivers of change in areas with differing ecological and cultural histories. Forthcoming research will further apply the results presented here to more fully understand Holocene anthropogenic dynamics in the Balearic Islands.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su15118807/s1, Table S1: Table with the description and source of environmental variables selected for this research; S2-Code: Rmarkdown with the analytical code used in this paper.

Author Contributions: Conceptualization, G.S.-V. and M.M.A.; methodology, G.S.-V., M.M.A. and G.S.; software, G.S. and M.R.; validation, P.T.; formal analysis, G.S.-V., G.S. and M.R.; investigation, G.S.-V., M.M.A. and P.T.; resources, P.T. and A.M.M.; data curation, G.S.-V., A.F. and A.M.M.; writing—original draft preparation, G.S.-V.; writing—review and editing, M.M.A., G.S., A.F., P.T., M.R. and A.M.M.; visualization, G.S.-V.; supervision, G.S.-V., M.M.A., A.F. and A.M.M.; project administration, A.M.M.; funding acquisition, G.S.-V. All authors have read and agreed to the published version of the manuscript.

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