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Relative Pollen Productivity Estimates for Mediterranean Plant Taxa: A New Study Region in Turkey

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Abstract: This study estimates relative pollen productivity (RPP) for plant taxa from Southern Anatolia, an important region in the Mediterranean with a long history of human settlements. RPP estimates are required for quantitative pollen-based reconstruction of past land cover modelling. The application of the reconstruction by the REVEALS model in the Mediterranean basin is constrained due to the scarcity of the RPP values specific to the region. To better understand the relationship between vegetation cover and land use in the Mediterranean area, the present study aims to provide a set of RPPs for Turkey and the Mediterranean region. The study area centres around Gölhisar Lake in southwestern Turkey. Modern pollen data are collected from moss pollsters from 21 sites together with vegetation surveys. RPP estimates for the main taxa characteristic of the Mediterranean region are obtained (referenced to evergreen *Quercus* t.) using the extended R-value (ERV) model through the analysis of modern pollen assemblages. The most reliable results are acquired with the ERV sub-model 2 and Prentice's taxon-specific method (using a Gaussian plume dispersal model) to distance-weighted vegetation data, corresponding to a Relative Source Area of Pollen (RSAP) value of 102 m. RPPs of dominant taxa in the study area are obtained for *Quercus coccifera*/Fagaceae (1 ± 0), *Juniperus*/Cupressaceae (0.279 ± 0.001), Fabaceae (0.008 ± 0.000), *Pinus*/Pinaceae (5.782 ± 0.011), and Poaceae (0.112 ± 0.001) and are comparable with other RPPs obtained in the Mediterranean region.

Keywords: pollen–vegetation relationships; Mediterranean vegetation; ERV model; pollen-based land cover modelling; southwestern Turkey

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1. Introduction

Holocene vegetation changes in the southwestern Anatolian region hold important records for understanding the specific environmental and historical context of the area [1–3]. Palynological studies in this region have revealed an increase in human activities including agricultural practices, grazing, and fires, during the Holocene, as well as the relationship between human settlements and vegetation changes [1,4–7]. As a result of the human-related influences, the current vegetation comprises a mosaic of highly diverse landscapes characterized by both arboreal and non-arboreal species [5]. However, this high ecological diversity has presented a challenge for interpreting fossil pollen records from the late Holocene period where human impact has been recognized as a factor that has modulated vegetation dynamics for a long time [2]. To overcome these difficulties, modern pollen studies can assist in understanding paleoecological reconstructions based on fossil pollen analysis [3]. So far, modern pollen studies have been conducted in this region to examine the pollen production and dispersal mainly from moss pollsters, along with a limited number of surface soil, surface sediment, and pollen traps. However, these methods have been limited in the integration of modern pollen characteristics on paleoecological reconstructions based on fossil pollen analysis in southwestern Anatolia [2,3,5,8–11]. Therefore, our study introduces an additional approach that has not been applied in Turkey so far.

This study focuses on the area surrounding Gölhisar Lake in southwestern Turkey, which is renowned for its rich historical and cultural heritage. Particularly, the region is abundant in palynological and archaeological evidence, providing insights into human-based vegetation changes [1,4,5,12]. It is known for several ancient settlements such as Kibyra, Balboura, Oenoanda, Bubon, Kremna, and Sagalassos, each with their roots dating back to the Hellenistic period around the 3rd century BC [13]. This period can also be traced in some fossil pollen records, indicating a transition period within the Late Holocene, referred to as the Beyşehir Occupation Phase (3500 to 1300 calendar years ago), and revealing the clearance of *Pinus* and *Quercus* forests and simultaneous expansion due to agricultural practices. The reoccurrence of *Pinus* forests is thought to have occurred later, following the abandonment of the area [2,3,14]. Along with these long-term human-induced vegetation changes, climate changes such as wet and dry periods may have contributed to vegetation shifts, by expanding wetlands, and transforming woodlands into steppes [1–3].

Although fossil pollen evidence is widely recognized for its potential to provide a fundamental framework for understanding the relationships between ancient human settlements and changes in vegetation and climate, it does have certain limitations. One notable constraint is the non-linear relationship between pollen percentages and actual plant abundances [15]. Differences in pollen productivity, morphology, dispersal characteristics among taxa, and the size of sedimentary basins influence the relationship between pollen assemblage and the related plant abundance [16–18]. Therefore, pollen data transformed into quantitative reconstructions of past land cover play an important role in assessing the long-term perspectives of climate and anthropogenic land cover changes [19]. The Landscape Reconstruction Algorithm (LRA) is a method to quantitatively reconstruct vegetation abundance at regional and local spatial scales using pollen counts [16]. This approach reduces biases resulting from variations in pollen productivity and dispersal among different taxa, and differences in basin size. It enables the reconstruction of past abundances of individual plant taxa around pollen sites at a given spatial resolution. Regional Estimates of Vegetation Abundance from Large Sites (REVEALS) is one of the LRA models, a valuable tool for reconstructing past regional vegetation cover based on pollen data. The REVEALS model has been increasingly applied to investigate regional vegetation history across Europe including northern Europe [20], northwestern Europe, western Europe north of the Alps, and eastern Europe [21,22], as well as part of the eastern Mediterranean-Black Sea-Caspian corridor, respectively [23,24]. However, the application of the REVEALS model in the Mediterranean basin has been limited due to the scarcity of the relative pollen productivity estimates (RPPs) values specific to the Mediterranean region. Most of the RPP has been conducted in Europe and the northern hemisphere; however, only two studies have been carried out in southern France and southeastern Romania for the Mediterranean plant taxa so far [23,25]. To enhance the model's applicability and reliability, it is important to gather more data on RPP values specific to the Mediterranean, thus enabling more accurate reconstructions of past vegetation in this area. The study area is situated within a mountainous landscape structure in the Oro-Mediterranean vegetation zone which displays distinctive biodiversity, differing from the European Mediterranean vegetation [3,26,27]. The pollen production can vary due to factors like species, geography, and climate [28–30]. Considering this, it is important to generate RPP values for vegetation reconstruction in southwestern Turkey based on data obtained from this region. To better understand the relationship between vegetation cover and land use in the Mediterranean area, the present study aims to provide a new set of RPPs specific to Turkey and the Mediterranean region.

2. Materials and Methods

2.1. The Study Area

This study encompasses a 50 km radius of Gölhisar Lake, which is geographically located between latitudes 37.58242° and 36.65060° N and longitudes 29.62034° and 29.57386° E (Figure 1a). The study area is situated within a mountainous landscape structure in the Oro-Mediterranean vegetation zone, with elevations ranging from 700 m to 1800 m (Figure 1a) [3,26,31,32]. A 50 km radius vegetation map was created using the data from the forest management plans of the General Directorate of Forestry of Turkey. According to this, prevalent vegetation communities within the 50 km radius are pine forests (*Pinus brutia* and *Pinus nigra*), juniper forests (*Juniperus excelsa*, *Juniperus foetidissima*), high mountain steppe, and *Quercus coccifera* shrublands (Figure 1b) [32,33].

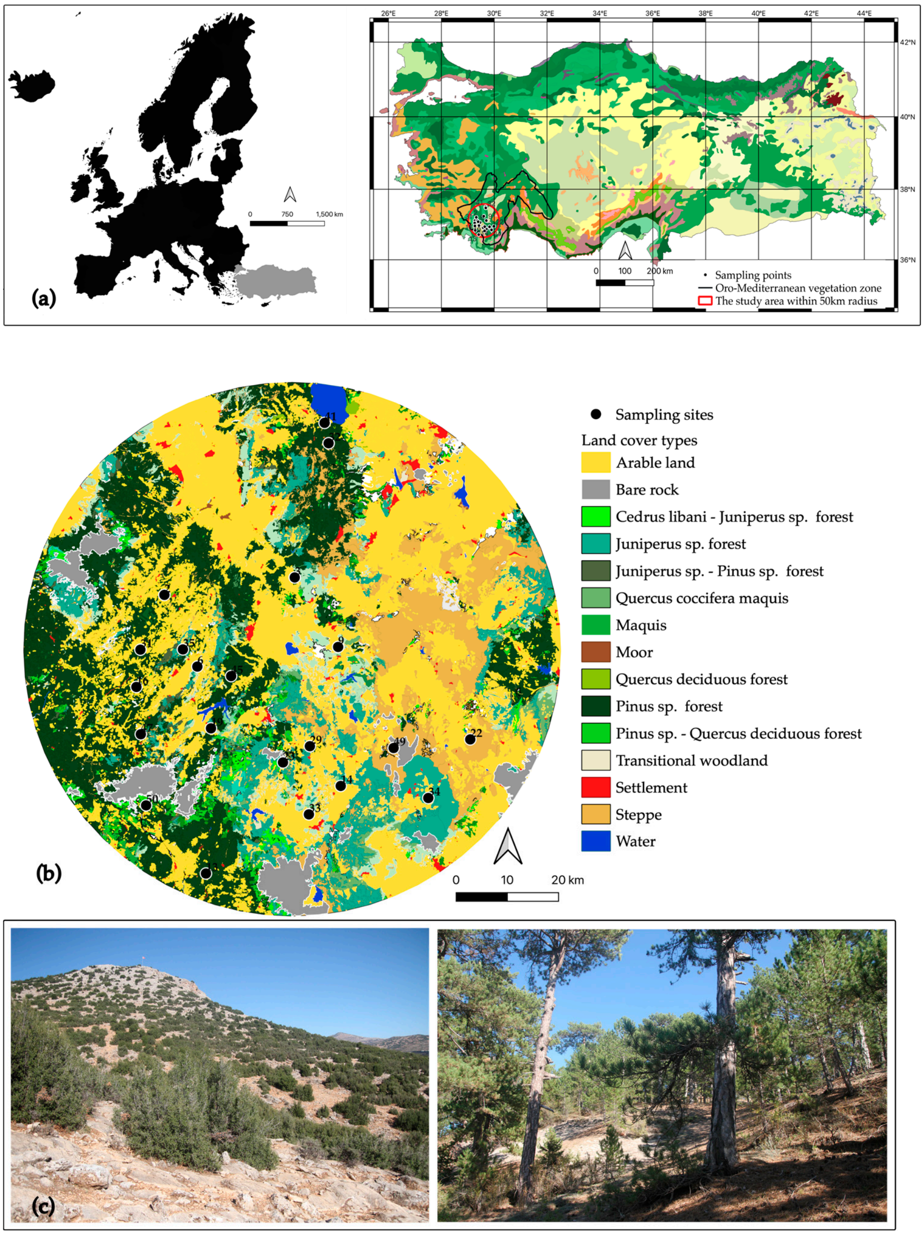


Figure 1. (**a**) Location of the study area and the schematic view of Oro-Mediterranean vegetation zone modified from Atalay I. (2014)) (**b**) Land cover types and distribution of the sampling sites within 50 km radius. (**c**) Land cover types in the study area, *Quercus coccifera* shrubland (**left**), *Pinus nigra* forest (**right**).

In the study area, *Pinus nigra* forests extend between altitudes of 1200 to 2000 m, exhibiting a wide distribution [31–33]. They are generally accompanied by *Cistus latifolius*, especially in areas where black pine forests are typically damaged by fire [33,34]. *Pinus nigra* forests also form mixed forests with species such as *Quercus cerris*, *Q. ithaburensis*, *Q. pubescens*, *Q. coccifera*, as well as *Platanus orientalis* in humid places [33,34]. Juniper forests typically appear at high elevations on limestone cliffs and often mix with *Pinus nigra* in the Oro-Mediterranean vegetation zone [31]. *Juniper* forests have a sparse structure due to the elevation, rocky terrain, and high mountain steppe vegetation prevailing in these clearings [33,35]. *Juniperus foetidissima* is common at higher elevations and *J. excelsa* is dispersed in the lower and middle regions [30]. Another dominant vegetation formation, *Quercus coccifera* maquis vegetation, which is distributed between 800 to 1300 m a.s.l., is seen together with *Berberis crataegina and Juniperus oxycedrus* subsp. *oxycedrus*, often occurring with cushion-like plant communities such as *Astragalus*, *Alyssum*, and *Acantholimon* in the clearings [33]. The high mountain steppe vegetation is mostly located in the eastern part of Gölhisar and is distributed between 800 to 1800 m a.s.l. [35]. This vegetation is characterized by a form of thorny cushion formations comprising *Astragalus*, *Acantholimon*, and also other herbaceous species such as *Verbascum*, *Silene*, *Salvia*, *Thymus*, *Thymbra*, *Origanum*, *Lamium*, *Alyssum*, *Teucrium*, *Fumana*, *Potentilla*, *Centaurea*, and Poaceae family species [33,35].

The long-term climate data for Gölhisar extending from 2005 to 2022, sourced from the Turkish State Meteorological Service for the Gölhisar station (37.14275° N, 29.526° E), reveals that the mean temperature is 2 °C in January and 23 °C in July. The annual average precipitation amounts to 447.85 mm, with approximately 41% occurring during the winter and 13% during the summer (Figure 2).

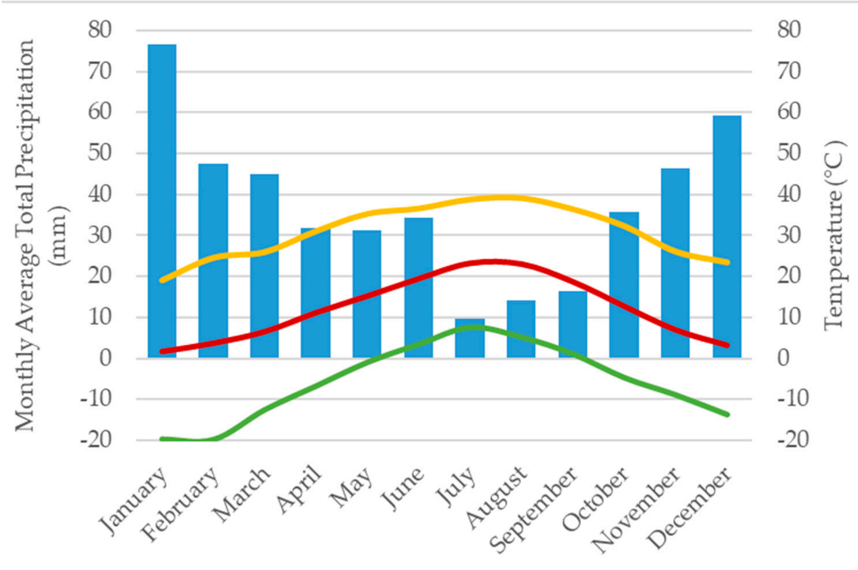


Figure 2. The climatic chart for the Gölhisar meteorological station, encompassing data from 2005 to 2022. Bars indicate precipitation levels in millimeters, while the lines in green, red, and orange represent the minimum, mean, and maximum temperatures in degrees Celsius, respectively.

2.2. Site Selection

Sampling sites were randomly selected within a 50 km radius around Gölhisar Lake using QGIS software version 3.22.9-Białowieża. The random selection criteria ensured a minimum distance of 1500 m between each sampling location to prevent autocorrelation [36]. Out of the randomly selected 50 points, 13 were situated within agricultural zones, 10 were positioned at elevations exceeding 1800 m with access difficulties, and 3 were located in sites near hydroelectric power stations (HES) and tree plantations. Consequently, these specific points were excluded from the fieldwork, which was carried out in September 2021.

Finding moss species in the southern part of Turkey poses certain challenges. Out of the initially selected 50 random sites, a total of 24 sites were deemed suitable for data collection; however, moss samples were collected from 21 sites as no moss samples were encountered at 3 of the sites which were found to be sparsely vegetated, mostly covered with rocks, eroded and located in steppe vegetation formation. The moss samples were typically found in forest areas and *Quercus coccifera* shrublands among sampling sites. The visited 21 sites were situated at elevations ranging from 668 to 1842 m above sea level, as detailed in Table 1.

Table 1. Location of the 21 sites and the major vegetation communities surveyed in the field within a 100 m radius area of the sampling sites. GPS coordinates are expressed as decimal degrees (DD).

Site Name	Latitude (°)	Longitude (°)	Elevation (m)	Major Vegetation Communities within 100 m
2	37.211267	29.322083	1071	*Juniperus excelsa-Quercus coccifera* forest.
3	37.24175	29.606567	1089	*Pinus nigra* mixed forest with *Quercus coccifera* and *Juniperus oxycedrus* shrubs
6	37.085783	29.394033	1296	*Quercus coccifera* vegetation with *Juniperus oxycedrus* and openland area with *Astragalus* and other herbs
9	37.120183	29.701317	1072	*Quercus coccifera* shrubland with *Juniperus oxycedrus* and rocky area with herbaceous plants
13	36.721983	29.4128	668	Mediterranean *Pinus brutia* mixed forest with *Quercus coccifera*, *Olea europea*, and *Phillyrea latifolia*
14	36.87645	29.706967	1666	*Juniperus foetidissima* semi-forest and rocky area with herbaceous plants
16	37.050083	29.26105	1278	*Pinus nigra* forest
19	36.97755	29.42375	1226	*Pinus nigra* mixed forest with *Quercus coccifera* and *Juniperus oxycedrus* shrubs
22	36.958167	29.989683	1773	High mountain steppe
23	36.9177	29.580933	1842	*Cedrus libani* and *Juniperus foetidissima* semi-forest–High Mountain steppe
29	36.9462	29.639617	1412	*Pinus nigra-Juniperus oxycedrus* semi forest
31	37.115417	29.26975	1330	*Pinus nigra-Juniperus oxycedrus* forest
32	37.475983	29.680567	1718	*Pinus nigra* forest
33	36.826467	29.6375	1315	*Quercus coccifera* vegetation with *Juniperus foetidissima*
34	36.855267	29.898133	1468	Steppe area with a few *Juniperus* and *Quercus coccifera*
35	37.11585	29.3625	1822	*Pinus nigra—Juniperus foetidissima* semi-forest–High Mountain steppe
41	37.511467	29.671767	1251	*Pinus nigra-Quercus pubescens* mixed forest
45	37.0691	29.46775	1183	*Pinus nigra* mixed forest with *Platanus orientalis*
47	36.967183	29.270633	1220	*Pinus nigra* mixed forest with *Quercus coccifera* and *Juniperus oxycedrus* shrubs
49	36.94305	29.822433	1788	High mountain steppe
50	36.842283	29.282167	1105	*Pinus brutia* mixed forest with deciduous *Quercus*

It is important to note that the geography of the study area with elevations of 1000 m and above poses physical challenges in accessing the sampling points. The Taurus Mountains constitute an extended mountain range situated in the Mediterranean area of Turkey. Stretching for approximately 560 km in parallel to the Mediterranean shoreline, they are used as the southern boundary of the Anatolian plateau [27].

2.3. Pollen Data

Studies show that moss pollsters preserve several years of pollen loads and they represent modern vegetation according to seasonal variation in species abundance [36–39]. In our study, moss pollsters were collected from a 1-square-meter area at each site, with soil particles removed, before the vegetation survey. In the laboratory, any remaining soil particles in the moss were eliminated prior to pollen extraction. The pollen samples underwent standard procedures outlined in Faegri and Iversen's 1976 protocols [40]. These procedures involved the treatment of samples with a 10% HCl solution to remove carbonates, a 10% KOH solution to eliminate humic acids, a 46% hot HF solution, and a hot acetolysis process to ensure the removal of any remaining cellular content, calcareous and mineral components from the sample. Additionally, after the HCl and KOH treatments, the moss underwent sieving through a 0.25 mm mesh to filter out any larger mineral or organic residues. A minimum of 1000 pollen grains per sample were counted and identified using identification pollen keys [41,42] and the reference pollen collection at the University of Innsbruck (Department of Botany).

2.4. Vegetation Data

A detailed vegetation survey was conducted within a radius of 0–100 m from each pollen sampling point, following the main guideline of the Crackles Bequest Project protocol [36]. To assess the percentage cover of every plant species, including trees, shrubs, and herbs, visual estimations were made within a 1-square-meter quadrat.

Vegetation was surveyed in two main zones. In the first zone, between 0 to 10 m, the survey involved the use of 1-square-meter quadrats (Figure 3). This included a central quadrat positioned around the pollen sample site, along with 20 additional quadrats placed at specific distances of 1, 2.25, 4.5, and 8 m in all four cardinal directions (N, E, S, W), as well as at 7.5 m in the diagonal directions (NE, SE, SW, NW), totalling 21 quadrats. The composition of plant taxa was assessed by estimating the total plant cover as a percentage of the quadrat area.

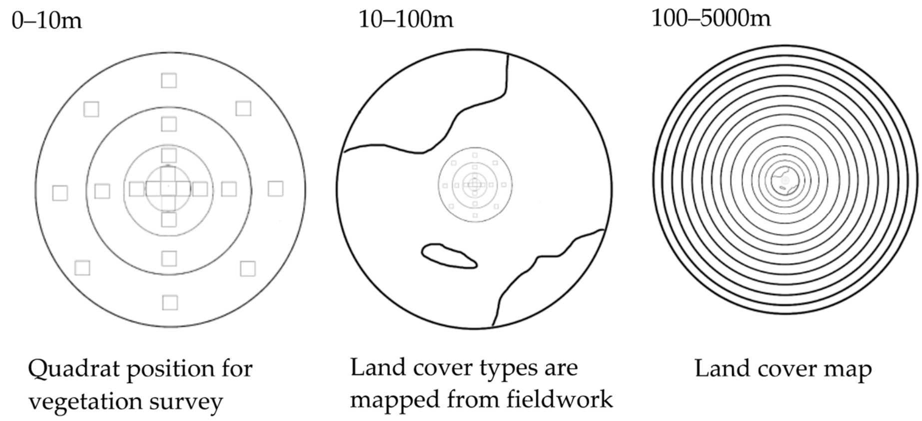


Figure 3. A visual representation of the vegetation survey conducted at each sample site, extending from the central point up to 5000 m. Original protocol can be found in Bunting et al. (2013).

In the second zone, ranging from 10 to 100 m, the boundaries between different vegetation communities were drawn using compass directions and measured distances obtained from a handheld GPS device (Figure 3). Following, and during, the mapping process, the coverage of plant taxa within each community was estimated. For open communities, 1-square-meter quadrats were used, whereas semi-open and forest communities were determined using a 6 m rope in all cardinal directions with point surveys. The major vegetation types identified during the field survey are detailed in Table 1.

For the zones ranging from 100 to 5000 m, a vegetation map was created using the data from the forest management plans of the General Directorate of Forestry of Turkey along with local biodiversity and vegetation studies [33,34]. Subsequently, certain features were associated with specific vegetation and land cover type categories, totalling 16 in all (Table 2). These categories were defined based on the vegetation communities identified during the field surveys. To assign taxa compositions to each land cover type, we assumed that they closely resembled the vegetation communities surveyed within a 100 m radius during fieldwork at each study site. To address vegetation units not covered during the research, botanical expert opinions were formed utilizing information obtained from the flora and vegetation of Turkey. Subsequently, land cover maps for distances ranging from 100 m to 5000 m at the study sites were generated using QGIS software version 3.22.9-Białowieża. The distance increment from the centre of the moss sample area was set at 1 m increments from 100 m to 5000 m. This involves calculating the percentage coverage of each vegetation type within each concentric ring, with increments of 1 m (Figure 3).

Table 2. Plant composition of the land cover types. Percentages are based on vegetation surveys and literature.

Land Cover Types	**Arable Land**	***Cedrus libani*-*Juniperus* sp. Forest**	***Pinus brutia* Forest**	***Pinus* sp. Forest**	***Juniperus* sp. Forest**	***Quercus coccifera* Maquis**	***Pinus* sp.—Deciduous Forest**	***Pinus* sp.—*Juniperus* sp. Forest**	***Quercus* Deciduous Forest**	**Maquis**	**Steppe**	**Transitional Woodland**	**Settlement**	**Bare Soil-Bare Rock**	**Moor**	**Water**
Apiaceae	1															
Asparagus			1													
Asteraceae	1					1	1			1	1	1	2		1	
Berberis					1			1								
Boraginaceae										1					1	
Brassicaceae				1		1				1		1			1	
Caprifoliaceae										1						
Cyperaceae			9				1			1					1	
Caryophyllaceae					2	2				2	2	1			1	
Cedrus		34										1				
Chenopodiaceae										1		1	1		1	
Cistaceae				1			1			1						
Cornaceae									1							
Cotinus				12												
Crassula								1								
Cupressaceae		26	0	4	30	20	14	7	7	5			2			
Daphne										5						
Ephedra										1						
Ericaceae										5						
Euphorbia										1						
Fabaceae		7		1	12	5		3		10	15	1	2		1	
Jasminum		0				1				2						
Lamiaceae		1		5	4	2		3		4	4	1			1	
Olea			1							5						
Phillyrea			1							5						
Pinus			88	53			63	36	6			1				
Plumbaginaceae					2						2				1	
Poaceae	9	7	51	6	14	17	5	7	13	12	15	5	9	1	2	
Potentilla					1											
Decidious *Quercus* t.	3						5		55				3			
Evergreen *Quercus* t.			1	14		37				30	2					
Rhamnus						1				1						
Rosaceae	4			1						1	3	1	4			
Rubiaceae			2													
Salix									1							
Sanguisorba												1	1			
Saxifraga								1								
Smilax										1						
Styrax			3				11									
Verbascum										1						

2.5. ERV Model Runs

In this study, we applied the ERV model using ERV-Analysis software version 2.5.4, a program developed by Sugita (unpublished), to determine the RPPs for different plant taxa. Each sub-model calculates the RPP and background pollen content by comparing pollen and vegetation datasets gathered from various pollen sampling sites. Besides the pollen and vegetation data, the ERV model required additional input including the FSP rates and wind speed (taken as 3 m s^{-1}) to run properly. There are three ERV sub-models: ERV models 1 and 2 estimate a species' constant background in pollen proportion, whereas ERV model 3 estimates a constant background pollen loading instead of pollen proportion [18,43]. We applied the ERV model to three different distance-weighting functions: the inverse distance (1/d), Prentice's model (uses a Gaussian plume diffusion model (GPM)) [44], and the Lagrangian stochastic dispersal model (LSM) [45].

To identify the most dependable estimates for the RPP, various combinations of ERV sub-models and distance-weighting methods were employed, and the outcomes were subsequently compared. In conducting the ERV model, we selected specific plant/pollen taxa for RPP estimation, focusing on species present both in the vegetation and the pollen samples. For initial analysis, we selected eleven pollen types comprising *Pinus*, *Cedrus*, *Juniperus*, evergreen *Quercus* t., deciduous *Quercus* t., *Olea*, *Phillyrea*, Asteraceae, Fabaceae, Chenopodiaceae, and Poaceae (Table 3). We selected FSP estimates from the Mediterranean studies except *Olea* [23,25]. The *Cedrus* estimate is from Borrel (2012) [46]. The *Olea* FSP was calculated for this study from the reference taxon collection presented by Istanbul University, Institute of Marine Sciences and Management (Table 3). A minimum of 30 grains of *Olea* pollen were measured for both their long and short axes on reference slides. These measurements were used to calculate the fall speed of pollen (FSP) based on Stokes' Law of particle settling velocity [47] (Table 3). Relative Source Area of Pollen (RSAP) was estimated statistically using a moving window regression approach and the moving window was 200 m. A reference taxon with an RPP value of 1 was used for calculating RPPs for other taxa.

Table 3. The plant species included in the vegetation survey were matched to pollen morphological categories and the fall speedestimates. The *Olea* FSP estimates was calculated from the reference taxon collection presented by Istanbul University for this study, the *Cedrus* estimate is from Borrel (2012) [46], and the other values are from Githumbi et al. (2022) [23].

Pollen Morphological Type	Corresponding Plant Taxa in Vegetation	Fall Speed (m/s)
Asteraceae	*Centaurea*, *Anthemis*, *Carduus*,	0.051
Amaranthaceae/Chenopodiaceae	*Atriplex*	0.019
Cedrus	*Cedrus libani*	0.097
Juniperus	*Juniperus excelsa*, *J. foetidissima*, *J. oxycedrus*	0.016
Fabaceae	*Astragalus*, *Calicotome*, *Dorycnium*, *Trifolium*	0.021
Olea	*Olea europaea*	0.011
Phillyrea	*Phillyrea latifolia*	0.015
Pinus	*Pinus brutia*, *Pinus nigra*	0.031
Poaceae	Poaceae	0.035
Deciduous *Quercus* t	*Quercus cerris*, *Q. ithaburensis*, *Q. pubescens*	0.035
Evergreen *Quercus* t.	*Quercus coccifera*	0.016

Typically, the most common reference taxon for ERV models is Poaceae, given its wide distribution which includes many plant species with differing ecologies [29,48–50]. This variety may lead to variations in pollen production among regions [29]. Our study region did not provide an adequate abundance of Poaceae for ERV modelling. Therefore, we chose a single-species reference taxon, *Quercus coccifera*, as the reference taxon, given its abundance in both pollen and vegetation data.

During this process, we identified taxa that exhibited the most linear relationships between pollen and vegetation data. The procedure was repeated, gradually reducing the number of taxa, until the log-likelihood and RSAP curve assumed the theoretically optimal shape which reached an asymptote at a certain distance.

3. Results

3.1. Pollen Assemblages

A total of 48 pollen types were identified in 21 moss samples. The pollen types such as Geraniaceae, Ericaceae, Cerealia t., *Abies*, *Artemisia*, *Potentilla*, *Xanthium*, *Juglans*, *Urtica*, *Polygonum*, *Plantago*, *Corylus*, *Convolvulus*, *Alnus*, *Pistacia*, and *Cannabis* were only observed in the pollen slides and were not encountered in the vegetation survey. *Pinus* (79%), evergreen *Quercus* t. (6%), and *Cedrus* (5%) were the main taxa encountered in pollen. Although *Juniperus* species were observed in high numbers within the vegetation, their pollen counts did not reflect a similar abundance. *Pinus* pollen was abundant across all sites, yet its abundance was significantly lower in Site 23 compared to the other sites (Figure 4). The vegetation at Site 23 was composed of a *Cedrus-Juniperus* forest, which explains the higher abundance of *Cedrus* pollen and the relatively lower presence of *Pinus* in this sample (Figures 4 and 5). The *Platanus* pollen was found only in Site 45, as the site constituted a mixed forest of *Pinus* and *Platanus*. Although the deciduous *Quercus* type was represented in almost all samples, its actual representation in the local vegetation was relatively low. *Olea* and *Phillyrea* were recorded only at one location, a red pine (*Pinus brutia*) forest at a low altitude (Site 13), although they were present in many of the pollen samples. The most common taxon among herbaceous plants was Poaceae, especially in the steppe sites 22, 49, 34 (Figures 4 and 5). Although Fabaceae, Brassicaceae, Caryophyllaceae, and Asteraceae (Cichorioideae, Leucanthemum (*Anthemis*) t., *Artemisia*, *Centaurea*) had higher vegetation abundances, their representation in the pollen samples was low.

3.2. Vegetation Data

At the local scale, our field survey revealed a great prevalence of *Pinus* spp. in the vegetation composition. Among the 21 sampled points, 7 were representative of coniferous forests, another 7 of mixed forests where *Pinus* spp. was the dominant species, 4 of *Quercus coccifera* maquis, and 3 of steppe vegetation. In the field survey, 34 plant families and 90 genera were identified. The primary arboreal species in coniferous forests typically included *Pinus* spp., *Juniperus* spp., and *Cedrus libani*. However, it is important to note that only a single site had a *Cedrus libani* community. Land cover types in a 5 km zone (Figure 5) show that arable land is a common land cover type among all sites. Pine (*Pinus* spp.) forest land cover type is abundant across all sites; however, it is observed in notably lower percentages in the steppe sites (22, 34, 49), the *Cedrus libani-Juniperus* spp. forest type (Site 23), and the *Q. coccifera* shrubland type (Site 33). *Pinus brutia* forest (Site 13) is the only forest located at a lower elevation exhibiting a nearly homogenous vegetation community within a 5 km radius. Similarly, Sites 22, 34, and 49 are situated in the steppe area and exhibit a homogenous vegetation community. Maquis vegetation is present only at Site 50 due to its proximity to the southern coastal area and the corresponding decrease in elevation. Deciduous *Quercus* forest-type abundance is lower and also seen mixed with pine forest in Sites 41 and 50.

3.3. Relevant Source Area of Pollen

For the first runs of ERV models, we assessed the log-likelihood curve and identified the RSAP, then plotted the pollen/vegetation relationships from the three sub-models at the RSAP distance and evaluated these relationships. Eleven pollen types comprising *Pinus*, *Cedrus*, *Juniperus*, evergreen *Quercus* t., deciduous *Quercus* t., *Olea*, *Phillyrea*, Chenopodiaceae, Asteraceae, Fabaceae, and Poaceae were selected for the first analysis. However, weak correlations were detected between six of these taxa due to the low vegetation abundances. Hence, five taxa, *Q. coccifera*, *Juniperus*, Fabaceae, *Pinus*, *and* Poaceae (listed in Table 4) were selected for the final ERV analysis.

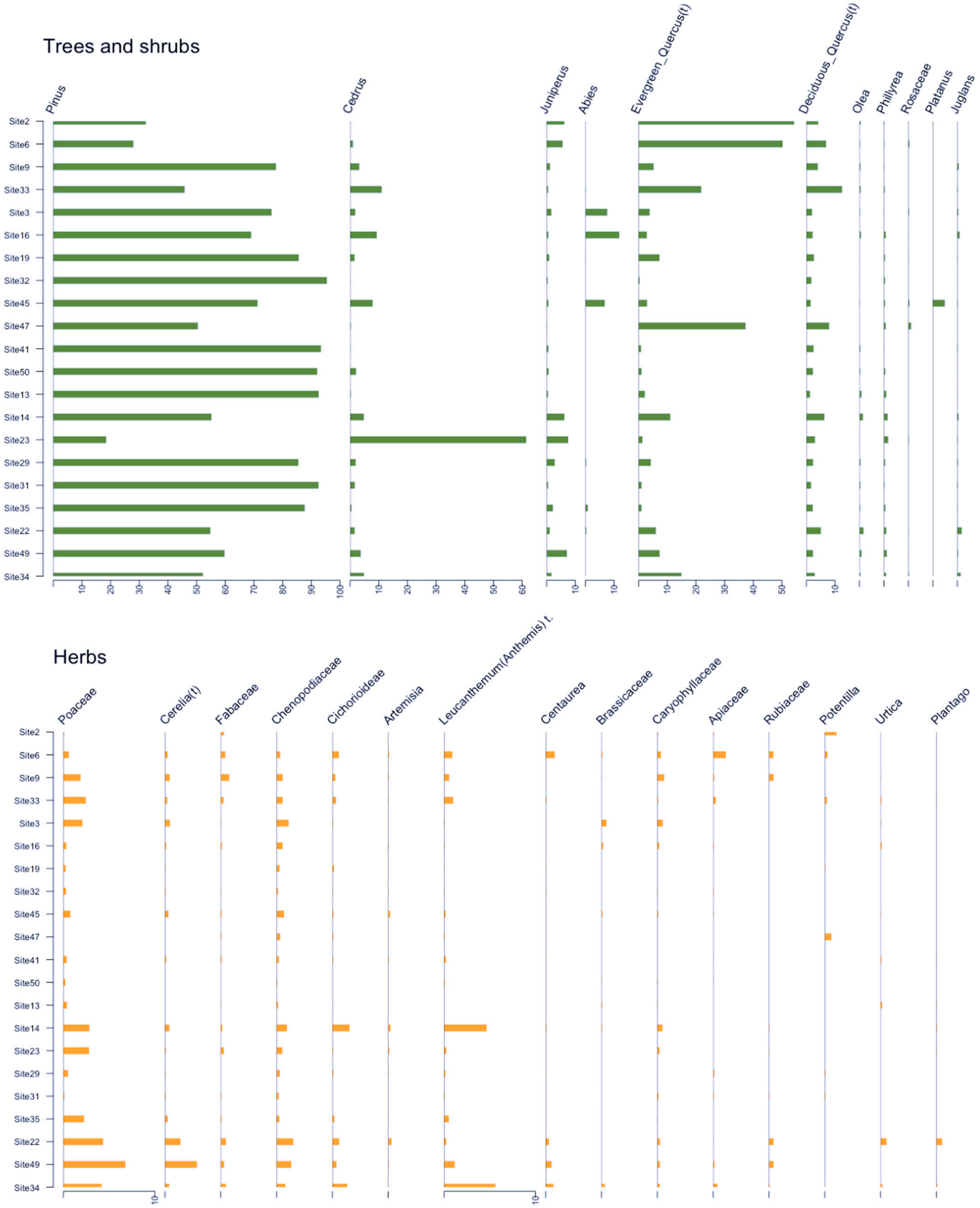


Figure 4. Pollen percentage diagram of the major pollen taxa found in the 21 moss pollster samples.

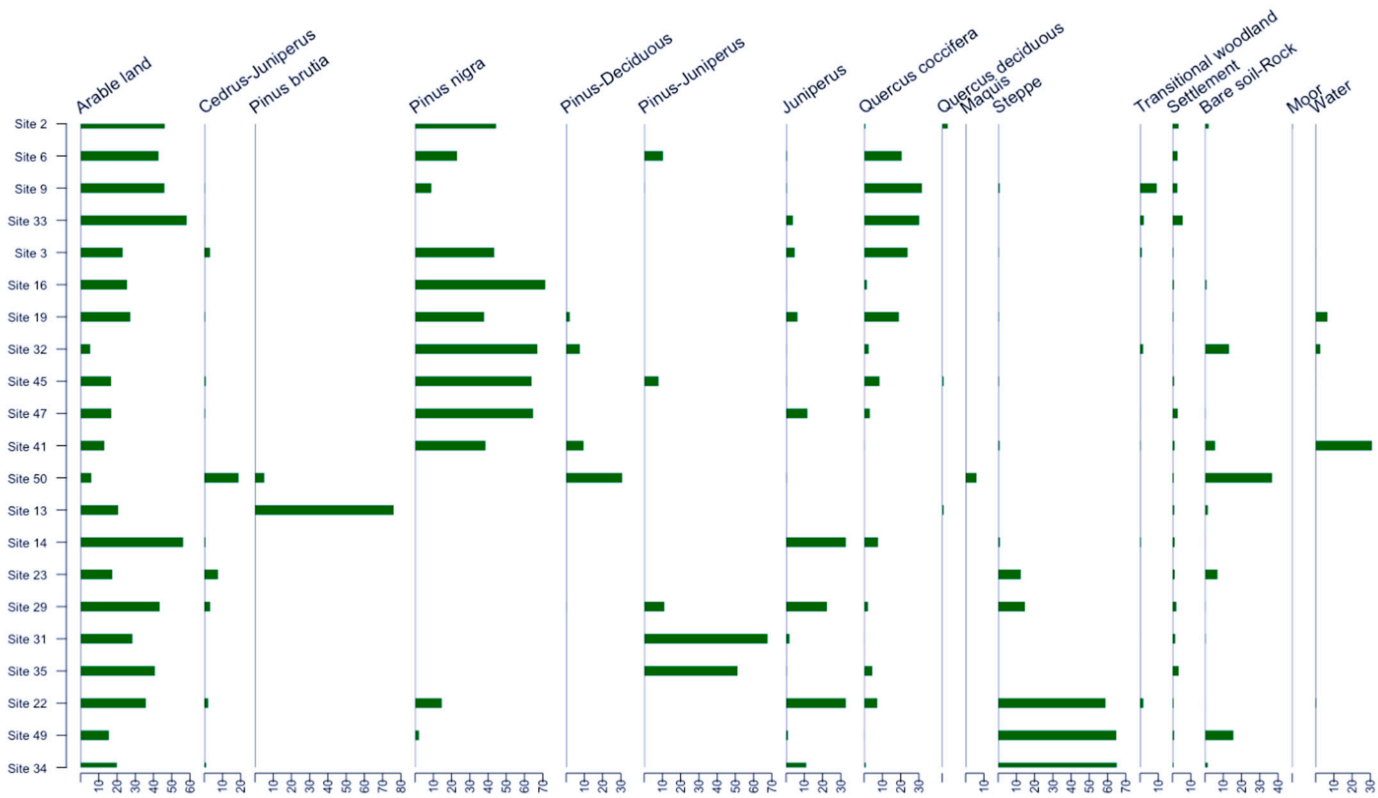
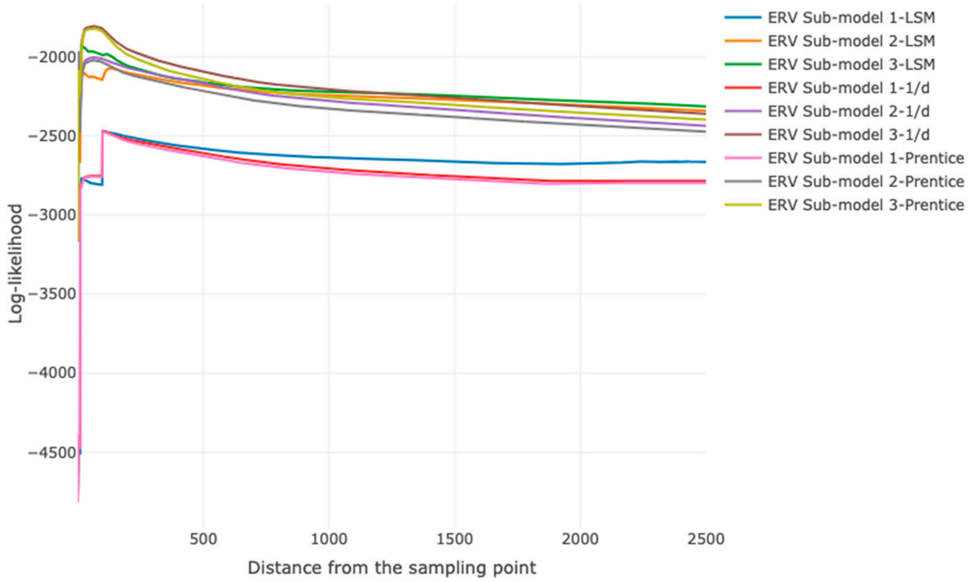


Figure 5. Land cover type categories percentages within a 5 km radius diagram in the 21 sampling sites.

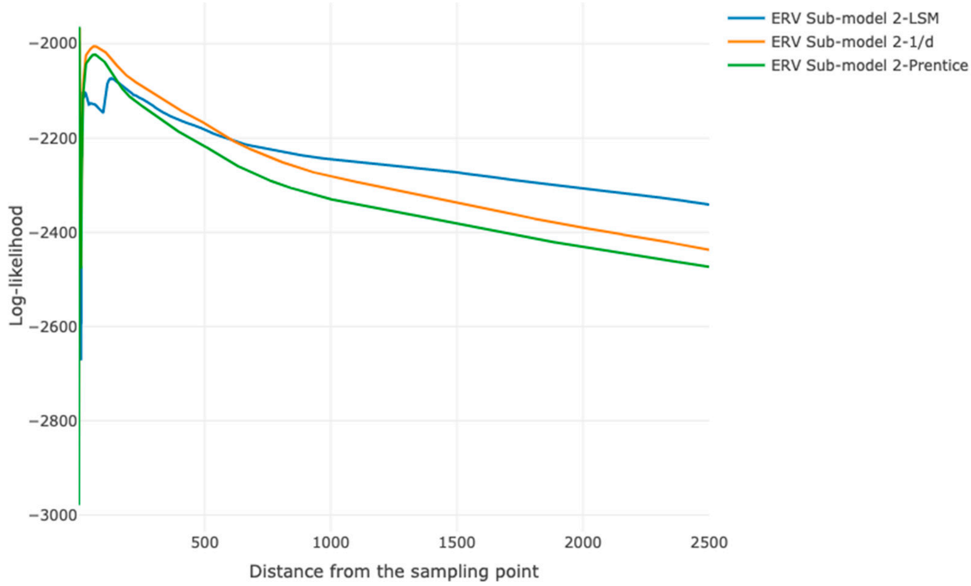
Table 4. Predictions of the RPP estimates with standard error and relevant source area of pollen (RSAP) in meters. These predictions are derived by exploring different combinations of ERV sub-models and distance-weighting methodologies, i.e., GPM (Prentice's taxon-specific model), the inverse distance (1/d), and the Lagrangian stochastic model (LSM).

	Sub-Model 1		**Sub-Model 2**		**Sub-Model 3**		**Sub-Model 1**		**Sub-Model 2**		**Sub-Model 3**		**Sub-Model 1**		**Sub-Model 2**		**Sub-Model 3**	
Dispersal Model	GPM (Prentice)		GPM (Prentice)		GPM (Prentice)		1D		1D		1D		LSM		LSM		LSM	
RSAP	182		102		66		184		106		67		145		59		57	
Taxon	alpha	s.d.	alpha	s.d.	alpha	s.d.	alpha	s.d.	alpha	s.d.	alpha	s.d.	alpha	s.d.	alpha	s.d.	alpha	s.d.
Q.coccifera	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0
Juniperus	0.112	0.000	0.279	0.001	0.253	0.001	0.120	0.000	0.301	0.001	0.275	0.001	0.095	3302.44	0.257	7695.08	0.239	0.001
Fabaceae	0.005	0.000	0.008	0.000	0.004	0.000	0.005	0.000	0.008	0.000	0.004	0.000	0.007	0.000	0.010	0.000	0.006	0.000
Pinus	1.424	0.001	5.782	0.011	5.589	0.007	1.438	0.001	5.919	0.013	5.782	0.007	1.450	0.000	6.066	0.003	6.255	0.009
Poaceae	0.060	0.000	0.112	0.001	0.057	0.000	0.059	0.000	0.116	0.001	0.061	0.000	0.059	0.000	0.119	0.000	0.084	0.000

The RSAP estimates were obtained from three ERV sub-models and three distance-weighting models, along with the corresponding log-likelihood function curves for nine combinations of ERV sub-models and distance-weighting methods, as shown in Figure 6 and Table 4. Within a given distance-weighting method, ERV sub-model 1 consistently exhibited the weakest performance, characterized by the lowest log-likelihood values among the three ERV sub-models and a log-likelihood curve that deviated from the expected pattern. On the other hand, ERV sub-models 2 and 3 employed similar equations to linearize the pollen–vegetation relationship but differed in RSAP values (Figure 6a, Table 4). The combinations of ERV sub-model 2 with Prentice's and 1/d vegetation distance-weighting methods produced highly similar log-likelihood values and trends (Figure 6a).



(**a**)



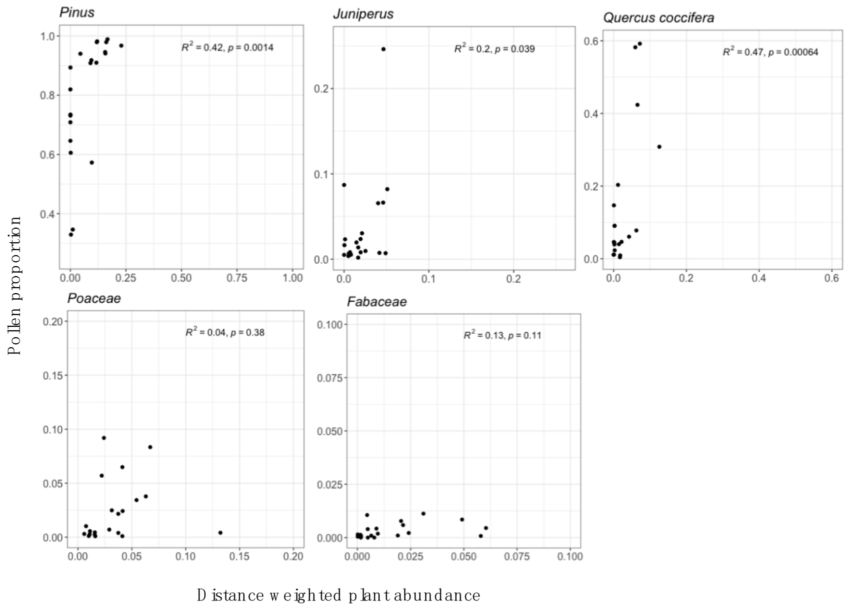
(**b**)

Figure 6. Plots displaying log-likelihood values as a function of distance are shown for a total of nine combinations, which involve three ERV sub-models and three distinct distance-weighting methods. These graphs are based on the analysis of pollen data obtained from moss samples collected at 21 randomly selected sites, coupled with the corresponding vegetation data encompassing a radius of 5000 m around each sampling point: (**a**) represents all nine model combinations, (**b**) illustrates the outcomes when ERV sub-model 2 is applied with the three available distance-weighting methods.

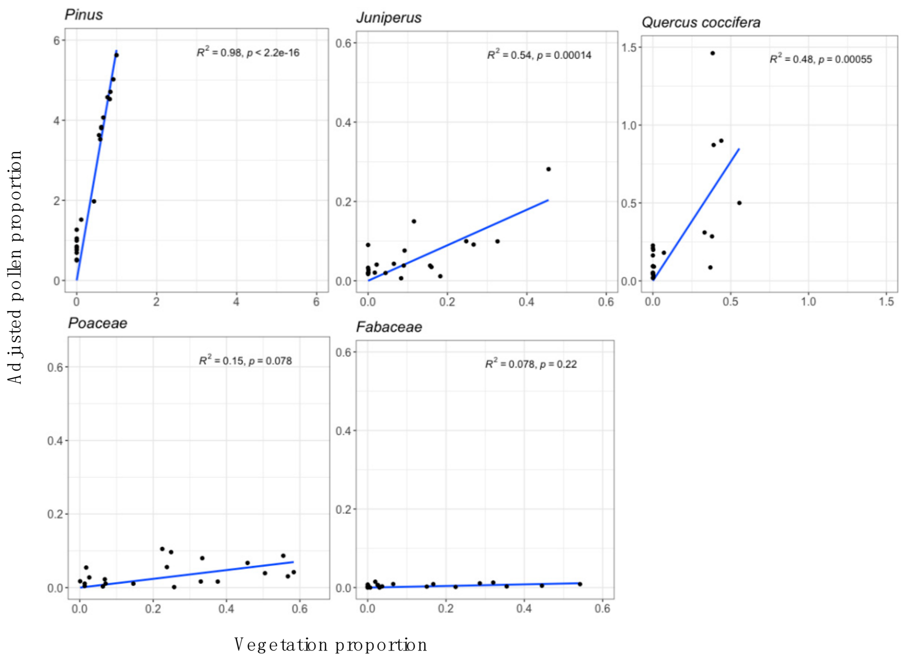
Meanwhile, the combination of ERV sub-model 2 with LSM distance-weighting produced similar log-likelihood values yet exhibited significant variation and produced low RSAP values. The ERV sub-model 2 paired with Prentice's and 1/d vegetation distance-weighting method produced log-likelihood curves that aligned most closely with expectations, characterized by a gradual increase towards an asymptote, and thus, was deemed the most favorable outcome. In the optimal model combination (ERV sub-model 2 with Prentice's vegetation distance-weighting method), the log-likelihood curve stabilized and maintained consistent values after approximately 100 m (Figure 6b). Consequently, we defined the RSAP as 102 m in this study

3.4. Pollen–Vegetation Relationships

The scatter plots illustrating the original (percentage-based) and ERV-adjusted pollen and vegetation values, as calculated with sub-model 2 and Prentice's model, are depicted in Figure 7. Among the taxa examined, *Quercus coccifera* demonstrates the relationship that most closely resembles an ideal linear correlation, with *Juniperus* coming in as the second closest (see Figure 7). In contrast, Fabaceae and Poaceae exhibit a broad range of values, where high plant cover tends to coincide with low pollen values. And finally, *Pinus* presents a notably elevated background pollen loading.



(**a**)



(**b**)

Figure 7. Scatter plots of the pollen–vegetation relationships at the distance of the relevant source area of pollen (RSAP = 102 m) as estimated using the ERV sub-model 2 and Prentice's vegetation distance–weighting method: (**a**) original pollen proportion and vegetation absolute abundance, (**b**) relative pollen loading and absolute distance-weighted vegetation abundance.

We obtained the RPP value of Fabaceae, despite the nonlinear relationship between its vegetation proportion and adjusted pollen proportion. The Fabaceae family is the second most common among the top three families in Turkey [34]. One of its most prevalent genera, *Astragalus*, is widely distributed in Turkey, with 440 species [34], as frequently recorded during our fieldwork. Therefore, we decided to include it for future comparison in similar studies conducted in Turkey.

3.5. Relative Pollen Productivity Estimates

RPP estimates, their corresponding alpha values, and standard deviation values (SD) for five taxa are illustrated in Figure 8 and Table 4. These estimates were computed by applying three different ERV sub-models and employing three alternative distance-weighting methods.

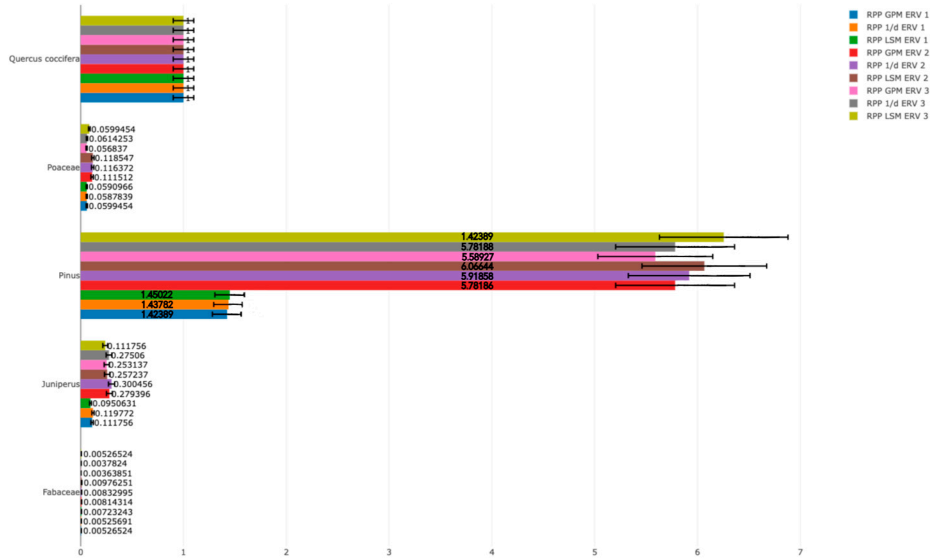


Figure 8. Relative pollen productivity estimates (RPPEs) along with their standard deviations are provided for five taxa found in the Mediterranean woodland ecosystem. *Quercus coccifera* is used as the reference with an RPP value set to 1. The RPP values for the other taxa are expressed in relation to *Quercus coccifera*. These RPP estimates are derived using ERV sub-models 1, 2, and 3, employing Prentice's model, LSM, and the inverse distance (1/d) distance-weighting function.

In this study, the values obtained using ERV sub-model 1 consistently exhibited lower RPP values for Poaceae, *Pinus* and *Juniperus*, ERV sub-model 3 exhibited lower RPPs for Poaceae, *Juniperus* and Fabaceae, while ERV sub-model 2 yielded higher values for Poaceae, *Juniperus* and Fabaceae, than the other two sub-models regardless of the distance-weighting method used. According to the results, *Pinus* (1.42–6.06) is the highest pollen producer while Poaceae, *Juniperus*, and Fabaceae exhibited lower values among the three ERV sub-models. Therefore, we focused on ERV sub-model 2 and distance-weighting methods (Prentice's (GPM), 1/d, and LSM) which tended to produce similar RPP values except *Pinus* (5.91–5.78–6.06). Consequently, we obtained the most accurate results, with lower RPP values for *Pinus* (5.78) and higher for the other taxa, from the ERV sub-model 2 and Prentice's taxon-specific method.

4. Discussion

This study provides the first RPP estimates for Turkey, in a region characterized by Oro-Mediterranean vegetation. This new set of RPP opens the door for quantitative Holocene vegetation reconstructions in the Mediterranean. The RPP results obtained in this study can help us to understand historical landscape changes in the Southwestern part of Turkey, through an analysis of fossil pollen assemblages obtained from lake or marsh sediments. This approach enables the assessment of various processes related to vegetation patterns, thereby enhancing our understanding of human-induced landscape changes and biodiversity.

4.1. Challenges of Fieldwork in the Mediterranean Region

The fieldwork was carried out in September when pandemic restrictions were lifted, and permissions for field access were regranted. Despite September being late in the season for assessing plant diversity in the Mediterranean region, there were no problems in identifying trees and perennial herbaceous plants. Additionally, various annual herbaceous plants were identified, owing to the beginning of autumn precipitation. It is important to note that conducting the fieldwork during the spring season has the potential to substantially enhance the quality of the study and the RPP estimates through the facilitation of a more comprehensive collection of vegetation data, particularly for taxa such as Poaceae and other herbaceous species [39,51]. Studies show that the timing is crucial for vegetation surveys, especially for grassland communities, that exhibit variation throughout the fieldwork season, while synchronization is less critical for woodlands [38,39]. Out of the initially selected 50 random sites, 24 sites were visited; however, the moss samples were collected from 21 sites. No moss samples were encountered at three of the sites, as these sites were sparsely vegetated, mostly covered with rocks, and located in steppe vegetation formation. The moss samples were typically found in forest areas and *Quercus coccifera* shrublands among sampling sites. Finding moss samples in the southern part of Turkey poses certain challenges. The study area's geographical structure with elevations of 1000 m and above poses physical challenges in accessing the sampling points. Finally, to generate reliable RPP values that will encompass the main Mediterranean taxa (*Cedrus libani*, *Abies cilicica*, *Olea europea*, *Phillyrea*, deciduous *Quercus* t., etc.) within all this diversity, the boundaries of the study area should be expanded and the number of randomly selected points increased.

4.2. Reliable RPPs for Southwestern Turkey

In the first run of the ERV model, we were unable to produce RPP values for *Cedrus*, *Olea*, and *Phillyrea* species due to the low vegetation abundance of these plants, according to the distance-weighted model results, especially because only one cedar forest (Site 23) and one red pine forest (Site 13) could be visited. Similarly, there were only two deciduous *Quercus* forests (Site 41 and Site 50) visited and deciduous *Quercus* t. was excluded from the ERV model analysis due to its low abundance in the vegetation and the distance-weighted model results. As a result, we were unable to calculate RPP values for the deciduous *Quercus* type, *Cedrus*, *Olea*, and *Phillyrea.*

In the second run of the ERV model, we have selected six pollen types, including *Pinus*, *Juniperus*, evergreen *Quercus* t., Fabaceae, Asteraceae, and Poaceae which are well represented in both vegetation and pollen records. With the initial results, we observed that the SD for Asteraceae exceeded the RPP value, so we opted to exclude the Asteraceae from the final run. Consequently, we ran the ERV model with five taxa, *Pinus*, *Juniperus*, evergreen *Quercus* t., Fabaceae, and Poaceae.

Quercus coccifera was selected as the reference taxon as it is appeared well represented in both vegetation and pollen records. We observed that every sampling site with evergreen *Quercus* t. pollen was also abundant as a vegetation type (i.e., *Quercus* shrublands) within a 5 km radius, as depicted in Figure 5.

According to the results of our fieldwork, there is a clear dominance of *Pinus* pollen abundance (79%) in the data obtained from moss samples (Figure 4). In a study conducted in southwestern Turkey at the end of the 1990s, a comparison was made between moss and trap samples [52]. This *Pinus* dominance was also observed in the BNP (Blackdown Hills Natural Futures Project), where the comparison of moss samples and Tauber traps (averaging 2-year pollen data) indicated that *Pinus* proportions in moss pollsters were, on average, twice as high [53]. These variations are typically attributed to the unique structures of moss cushions, which result in differential efficiency in trapping and preserving pollen of varying sizes and shapes [54,55]. Additionally, pollen deposition in mosses may be influenced by occasional extreme meteorological events or pollen addition by insects [50,56].

The Fabaceae recorded in the vegetation survey were generally in the form of perennial low shrubs. Particularly, cushion-form species belonging to the *Astragalus* genus have been commonly observed. Similarly, although in smaller quantities, shrubby forms of *Dorycnium*, *Spartium junceum*, *Calicatome*, and *Cytisus* species were also recorded. While Fabaceae's actual representation in the vegetation yielded a higher value, it presented low pollen abundance, as well as a very low RPP value. Fabaceae are primarily insect-pollinated, thereby influencing their pollen abundance and resulting in low pollen production.

Although Poaceae were recorded during the fieldwork, they exhibited low pollen abundance. This could be attributed to the fact that the fieldwork was conducted in the autumn or the possibility that they were not well preserved in the moss samples.

There is still a need to have RPP estimates for *Cedrus*, *Olea*, deciduous *Quercus* t.and *Phillyrea*, among othere for the Mediterranean area. Therefore, it may be beneficial to consider increasing the number of randomly selected points to overcome the accessibility challenges arising from elevation variations and to prevent points from overlapping with agricultural areas. Additionally, it would be beneficial to expand the study area to encompass lower elevations in order to generate RPP values for taxa such as *Pistacia*, Ericaceae, and other maquis plant taxa.

4.3. Relevant Source Area of Pollen (RSAP)

RSAP is influenced by several factors, including the size and type of sediment basin, as well as the spatial distribution of taxa and vegetation patches within the studied landscape [18,57,58]. Furthermore, the boundary separating vegetation surveying strategies within zones of 10–100 m and beyond 100 m can influence RSAP outcomes in pollen modelling research [36]. Our research area displays a diverse landscape comprising various elements, including forests, semi-open landscapes, high mountain steppes, and *Quercus coccifera* maquis. In our study, the RSAP value is 102, while in similar studies, 100 m in the forest steppe landscape of southeastern Romania [25], and 145 m in cultural landscapes in central eastern China were calculated [48]. Although the study area exhibits diverse habitat types, the sites where vegetation surveys were conducted generally contain homogeneous plant covers. This could explain the low RSAP values found in our study. The data pertaining to vegetation units beyond 100 m were obtained from the forest management plans of the General Directorate of Forestry of Turkey. Plant abundances based on these data are relatively coarse. This could be another possible reason explaining the low RSAP values. It is therefore, recommended that the vegetation data beyond 100 m should be further examined and assessed.

4.4. Relative Pollen Productivity (RPP) Estimates

In determining the RPP values, we assessed both the log-likelihood scores for each model and the RPP values associated with each taxon, ultimately concluding that submodel 2 was the most appropriate choice. Estimates of RPP and SDs from the three ERV sub-models for five pollen taxa and comparisons are shown in Table 4.

The research carried out in southern France [23] has generated new FSP and RPP values specifically for seven taxa found in the sub-Mediterranean and Mediterranean regions. These taxa include *Buxus sempervirens*, *Carpinus orientalis*, *Castanea sativa*, Ericaceae (Mediterranean species), *Phillyrea*, *Pistacia*, and the evergreen *Quercus* type t. [23]. When we compare our RPP values with those reported in previous research conducted in the Mediterranean region, we observe both similarities and differences. While we used *Quercus coccifera* as the reference taxon in our study, Poaceae was often used as a reference taxon in other studies. In this study, we determined the average RPP values for the Mediterranean region using software developed by Sugita (unpublished), to calculate Standard Errors based on the Delta Method.

To facilitate comparison, we recalculated our RPP values to use Poaceae as the reference taxon, as shown in Table 5. Our RPP values for evergreen *Quercus* t. (8.97) and *Juniperus* (2.52) are relatively similar to the values found in France (11.04 and 1.61). However, our estimate for Fabaceae (0.07) is lower than that reported in Romania (0.4). One of explanations could be that in the Romanian study, the Fabaceae predominantly constituted herbaceous plants, whereas, in our study, they were predominantly composed of perennial Fabaceae species in the form of cushions or bushes. In addition, Fabaceae species are primarily insect-pollinated, thereby influencing their pollen abundance and resulting in low RPP. Wind-pollinated (anemophilous) plants tend to produce a high amount of pollen compared with insect-pollinated (entomophilous) plants [59]. Insect-pollinated plant's pollen is not carried by the wind as well and tends to be under-represented in the pollen records [59].

Table 5. The RPP values were recalibrated using Poaceae as a reference taxon to enable comparison with previous studies. The Mediterranean region is a combination of the results obtained by the three local studies in the region. The average RPP values for the Mediterranean region used software developed by Sugita (unpublished), to calculate Standard Errors based on the Delta Method.

Region	**France, Medit. (ERV3)**			**Romania (ERV3)**			**Turkey, Medit. (ERV2)**			**Mediterranean Region**		
Study reference	Githumbi et al. (2022) [23]			Grindean et al. (2019) [25]			This paper			This paper		
	RPP	SD	FSP	RPP	SD	FSP	RPP	SD	FSP	RPP	SD	FSP
Herb taxa												
Poaceae (reference taxon)	1	0	0.035	1	0	0.035	1.00	0.00	0.04	1.00	0	0.035
Apiaceae				5.91	1.23	0.042				5.91	1.23	0.042
Artemisia				5.89	3.16	0.014				5.89	3.16	0.014
Compositae (Asteroideae + Cichorioideae)				0.16	0.1	0.029				0.16	0.1	0.029
Comp. SF Cichorioideae	1.162	0.675	0.061							1.162	0.675	0.061
Cerealia (Cerealia t. + *Triticum* t. + Secale + Zea)				0.22	0.12	0.06				0.22	0.12	0.06
Fabaceae				0.4	0.07	0.021	0.073	0.00	0.021	0.16	0.023	0.021
Plantago lanceolata				0.58	0.32	0.029				0.58	0.32	0.029
Ranunculaceae	2.038	0.335	0.02							2.038	0.335	0.02
Rosaceae *(Filipendula, Potentilla t., Sanguisorba)*				0.29	0.12	0.018				0.29	0.12	0.018
Rubiaceae				0.4	0.07	0.019				0.4	0.07	0.019
Tree/shrub taxa												
Buxus sempervirens	1.89	0.068	0.032							1.89	0.068	0.032
Carpinus orientalis				0.24	0.07	0.042				0.24	0.07	0.042
Castanea sativa	3.258	0.059	0.01							3.258	0.059	0.01
Corylus avellana	3.44	0.89	0.025							3.44	0.89	0.025
Cupressaceae *(Juniperus communis, J. phoenicea, J. oxycedrus)*	1.618	0.161	0.02				2.52	0.00	0.02	1.37	0.054	0.02
Ericaceae *(Arbutus unedo, Erica arborea, E. cinerea, E. multiflora)*	4.265	0.094	0.051							4.265	0.094	0.051
Fraxinus (F. excelsior, F. ornus)				2.99	0.88	0.022				2.99	0.88	0.022
Phillyrea	0.512	0.076	0.015							0.512	0.076	0.015
Pistacia	0.755	0.201	0.03							0.755	0.201	0.03
Evergreen *Quercus* t. *(Q. ilex, Q. coccifera)*	11.043	0.261	0.015				8.97	0.00	0.015	6.67	0.087	0.015
Deciduous *Quercus* t. *(Q. spp., Q. peduncularis dominant)*				1.1	0.35	0.035				1.1	0.35	0.035
Pinus (P. sylvestris, P. brutia, P. nigra)	6.058	0.237	0.031				51.85	0.01	0.031	19.3	0.079	0.031

The RPP estimates for *Pinus* in Europe generally tend to be lower than our estimates. Our estimation for *Pinus* (51.85) is notably higher than findings from forested regions in northern China [60] and northern Europe [61], although it is similar to the value reported in Poland (51.38) [53]. In our study area, *Pinus brutia* and *Pinus nigra* species are prevalent and pollen production can vary depending on factors such as plant taxa, pollen type, anthropogenic impact, geography, and climate [45,60,61] which can further affect the RPPs.

Fossil pollen studies conducted in southwestern Anatolia [2,14,62] reveal that the most common taxa observed include *Cedrus*, *Olea*, deciduous *Quercus* t., *Phillyrea*, Asteraceae, *Centaurea*, *Artemisia*, Cichoridae, Anthemideae, Brassicaceae, Chenopodiaceae, Cyperaceae, Apiaceae, *Polygonum*, *Plantago*, and Chenopodiaceae. Thus, there is still a need for new RPP values for those taxa.

5. Conclusions

We have estimated the first values of RSAP and RPP for the main plant taxa in the Mediterranean area of southwestern Turkey, based on ERV sub-model 2 and Prentice's dispersal model. *Pinus*, evergreen *Quercus* t., *Juniperus*, Poaceae, and Fabaceae are the main pollen types in the study area. The results of ERV analysis suggest that RSAP in surface samples is ca. 102 m. The inconsistencies in RSAP results across different Mediterranean regions may be caused by the size of the vegetation patch and landscape openness. The RPP estimates obtained using ERV sub-model 2 analysis show that the highest producer among arboreal pollen taxa is *Pinus* (5.782) a wind-pollinated plant, and the lowest is Fabaceae (0.008), an insect-pollinated plants. The variations in RPP values can be explained by different sample materials, variations in vegetation composition, and vegetation landscape openness. The RPP values from the current study area are comparable to those with similar vegetation composition and structure, and climate settings from other Mediterranean regions. The differences observed might be attributed to various factors including landscape patchiness, species composition, climate., and land use. Methodological approaches such as vegetation surveys and sampling strategies may have also contributed to differences in RPPs between our study area and other regions in the Mediterranean.

The RPP results obtained in this study can help us to understand historical landscape changes in the southwestern part of Turkey, based on fossil pollen assemblages and pollen-based modelling.

Author Contributions: Conceptualization, E.E. and H.N.D.; methodology and analysis, E.E., L.M. and F.M.; writing—original draft preparation, E.E., L.M. and F.M.; writing—review and editing, E.E., L.M., F.M. and H.N.D.; visualization, E.E. and U.B. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: All data used in this study are open access except for the forest management plans. The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

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