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ORIGINAL ARTICLE

# Correlation between spatial distributions of pollen data, archaeological records and physical parameters from north-western France: a GIS and numerical analysis approach

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**Abstract** New methodologies using Geographical Information Systems (GIS) and statistical tools were developed to provide new elements to the interpretation of fossil pollen records on the large spatial scale of north-western France. The originality of these methods lies in the analysis of the spatial distribution of the archaeobotanical data in order to identify correlations with other spatial parameters such as geological, climatic, pedological, topographical and archaeological characteristics. 218 pollen analyses from north-western France and a series of thematic maps (geological, archaeological, climatic, etc.) were used. The application of numerical analyses makes it possible to describe the spatial distribution of pollen data at a regional scale, and to identify spatial correlations between pollen data and other environmental parameters, and between archaeobotanical groups, archaeological and abiotic parameters simultaneously. Two examples are presented and discussed: (A) The spatial distributions of the predominance of hazel over oak between 6700 and 5700 cal B.P. and of modern precipitation are shown to be positively correlated, i.e. hazel is dominant in the most humid areas of the region. (B) The pollen data from the Bronze Age show associations of (1) pollen groups ascribed to meadows, shrubland, and forests with cooler temperatures, higher altitudes and northern latitudes, and (2) pollen groups ascribed to moor environments and anthropogenic vegetation with warmer temperatures, southern latitudes and lower altitudes. The latter implies that the agricultural landscapes of the Bronze Age were mainly confined to southern latitudes and low altitudes of the region, while the areas characterised by high altitudes and low temperatures were characterised by extensive activities such as grazing by cattle.

**Keywords** Holocene pollen data · Spatial analysis · Geo-statistics · Explanatory models · North-western France

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## Introduction

Archaeobotanical analyses (pollen, charcoal, plant macrofossil and dendrology) are common in studies of past palaeoenvironments. In north-western France, such studies have been carried out for the last 50 years. A compilation of all data available shows that ca. 500 archaeobotanical analyses have been completed, including 218 pollen studies and 109 plant macrofossil or charcoal investigations (Gaudin 2004). These studies were carried out as research for theses (Morzadec-Kerfourn 1974; Visset 1979; Marguerie 1992; Barbier 1999; Cyprien 2002; Gaudin 2004), or within specific investigations at archaeological sites.

However, in spite of the great number of studies available, the interpretation of the pollen results was never undertaken using the totality of the pollen records.

Comparisons between results often had the aim of examining a particular characteristic recorded in several studies (e.g. sea level changes in Morzadec-Kerfourn 1974 and Visset et al. 1995). Such comparisons generally use only a small part of the records available.

The first step in the method proposed here consists of the development of a geo-referenced database in order to describe palaeo-vegetation on regional spatial scales. In a second step, the method aims to describe the spatial distribution of the archaeobotanical data (pollen, plant macroremains, charcoal etc.) and to explain the results on the basis of other parameters. If the various palaeo-environmental and archaeological data record the same palaeo-landscapes, it should be possible to identify spatial correlations between the data from different disciplines (e.g. palynology, archaeology, geology etc.).

In this paper, we illustrate the proposed methodology with two examples:

- The first example aims to explain the spatial distribution of a pollen dataset in relation to an abiotic parameter (use of a non-parametric test).
- The second example aims at identifying landscape characteristics using the entire pollen dataset. We then attempt to correlate the spatial distribution of these characteristics with the spatial distributions of other parameters (e.g. altitude, climate, soils, geology, distance to the sea etc.) using multivariate analyses.

## Methods

### The pollen descriptors

Pollen results are generally presented in pollen diagrams in which the information is expressed in pollen percentages. In the method that we propose, we chose to record pollen data using qualitative descriptors (presence/absence). In addition to the occurrence of some taxon 'markers' of well-known landscape/land-use characteristics (e.g. pollen of Cerealia, *Fagopyrum* and *Linum* as indicators of agriculture), we also used the occurrence of associations of archaeobotanical taxa. These archaeobotanical groups have the purpose of aiding the interpretation of the data in terms of landscape at local to regional spatial scales. These groups can often characterise the same vegetation/landscape type in different studies, e.g. the 'moor group' can be identified simultaneously by charcoal studies, plant macrofossil and pollen analyses. The archaeobotanical groups are pollen, plant macrofossil and charcoal groups.

The choice of the descriptor types depends on the questions addressed in each case study.

### The abiotic and archaeological descriptors

The environmental parameters were extracted from various thematic charts. The pedological data were compiled from the geographical soil database of Europe (or Soil Information System of Europe: SISE) and the national soil test database at the canton scale (Walter et al. 1998). The climate descriptors (temperatures and precipitation) were obtained from meteorological maps (Météofrance 1998), and the geological data from the Geological Map of France (BRGM 1996). The wetland areas were extracted from the CORINE Land Cover database (1995). In order to take into account differences in continentality, we included an estimation of the coastline position for each period. To achieve this, we used curves of sea-level changes produced by Larsonneur (1977) and Bard (1996), in combination with the bathymetric map produced by Bonnet (1998). Finally, the topographical data came from the world data base GTOPO30 (1996), known as the data base DTED (Digital Terrain Elevation Data). The spatial data were recorded in the form of a grid or 'raster' with a pixel size of about 1 km (918 m).

With regard to the archaeological maps, the documents provided by the Regional Archaeology Services could not be used directly because of questions related to taphonomy and sedimentology and/or because of the very uneven quality of the surveys. Therefore, the archaeological maps had to be carefully controlled before use. In the example presented in this paper, we used the map of metal deposits dated to the Bronze Age. The chronological, geographical and archaeological data of this map were checked by Gabillot et al. (2007).

### The spatial distribution of the pollen analyses

Once an inventory of the archaeobotanical analyses was produced and geo-referenced, it was necessary to identify the type of spatial distribution of the studies. This is an essential step in order to be able to choose the relevant statistical tests. We used the quadrate test to identify the type of spatial distribution. This test consists in generating a great number of circles with a random spatial distribution, and the number of pollen records located within each circle is recorded. It is then possible to calculate the average and the variance of the number of records in the circles. The test can be repeated as many times as required by randomly generating new circles. The dispersion index ($I$ = Variance/Average) indicates the type of spatial distribution of the records, i.e. regular ($I < 1$), random ($I = 1$), or heterogeneous spatial distribution ($I > 1$). We also tested the spatial correlation between pollen sites and the occurrence of wetlands using the same method i.e. by randomly distributing one hundred circles

(30 km in radius) in the region. The number of pollen sites and areas of wetland in each circle were then recorded and the coefficient of correlation between the two was calculated.

Correlation between the spatial distribution of pollen records and the spatial distribution of an environmental parameter

The aim of this analysis is to show the existence of a relationship between the spatial distributions of an archaeobotanical characteristic and an environmental parameter. The first step consisted of the selection of two series of pollen data related to a particular archaeobotanical characteristic (e.g. two pollen datasets, one characterised by the presence of a particular taxon, the other by the absence of the same taxon in a chosen time period). In the second step, the values of the environmental parameter were assigned to each pollen record/site selected in the first step, according to their location. In the last step, we used a parametric test (e.g. Chi-square test) and a non-parametric test (e.g. Mann and Whitney *U* test) (Sokal and Rohlf 2000) to assess the significance of the difference between the two datasets of pollen records (i.e. (1) presence, and (2) absence of the selected archaeobotanical characteristic) in terms of the chosen environmental parameter.

*Example: spatial correlation between precipitation and the pollen analyses characterised by pollen percentages of Corylus (hazel) higher than those of Quercus (oak) between 6700 and 5700 cal B.P.*

A Chi-square test was carried out on the distribution of the precipitation values of 66 pollen sites and the distribution of the modern precipitation values observed at a regional scale using a grid of 22,723 pixels. The results showed a significant difference (see Results section). Therefore we attempted to weight the relative frequencies of the observed precipitation values at pollen sites in order to obtain the relative frequencies of the precipitation values that would be expected in the case of random sampling. The transformation consisted in calculating the ratios between the relative frequency of the precipitation value observed at the 66 pollen sites and those observed on the regional scale (grid of 22,723 pixels), and dividing the number of pollen records by these ratios. It was then possible to compare the two sets of pollen records (i.e. Set 1—*Quercus* dominant, Set 2—*Corylus* dominant in the example presented here). Two types of tests were applied; a Chi-square test (Sokal and Rohlf 2000) where the data used were the precipitation frequencies at each pollen site, and the Mann and Whitney *U* test in which the calculation was carried out using the precipitation values observed in each set.

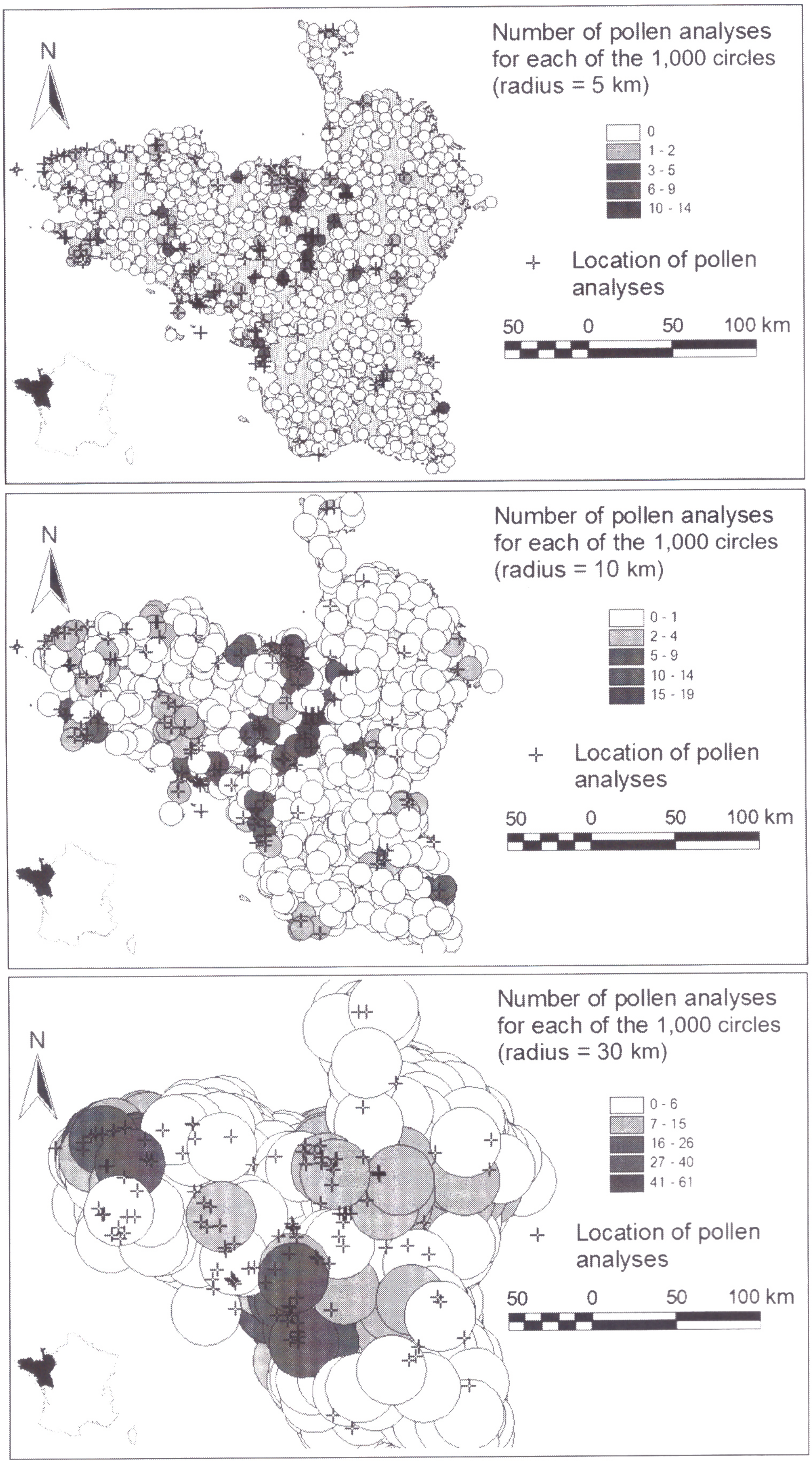
Correlation between archaeobotanical descriptors, archaeological characteristics and abiotic parameters

Each pollen study recorded in the database is characterised by archaeobotanical data and by environmental information (e.g. distance to the sea, altitudes, soils, climate, archaeological density etc.). In this type of analysis the first step consists in identifying archaeobotanical characteristics on the basis of all records available in the region. The second step aims at explaining the identified archaeobotanical characteristics by environmental parameters associated with each pollen analysis.

This analysis requires the use of multivariate analyses. We chose to use analysis by Co-inertia (ADE-4 Software™, Thioulouse et al. 1997). The method is described in detail in Dolédec et al. (1997). Application of this method has become more common within landscape ecology to study trends in biological and environmental datasets simultaneously (e.g. Dolédec and Chessel 1994; Millan de la Pena et al. 2003). Canonical analyses have perhaps been used more often for the same purpose but seem to be more demanding in terms of data input, i.e. a ratio of at least ten objects to one descriptor is required (Lebreton et al. 1988), which is not fulfilled in the case of our database. In addition, the Co-inertia analysis is performed in three steps, which makes it simpler to understand and interpret.

The first step consisted of the 'classification' of the pollen records in terms of pollen groups. This was done using a Correspondence Analysis (CA). The results of the CA provided groups of pollen records defined by the same archaeobotanical characters. The second step classified the same pollen records according to abiotic and archaeological parameters. Because the descriptors are expressed in quantitative terms and are characterised by different units, we used a Principal Component Analysis (PCA). The third step compared the two multi-dimensional spaces using an analysis by Co-inertia, in order to obtain a correspondence between the archaeobotanical results and abiotical parameters. The latter produces a simultaneous projection, on the same scale, of the projections of pollen scores obtained in the two multivariate analyses, CA and PCA. It is a method that combines two matrices based on the calculation of a covariance matrix (biotical data × abiotical data). The analysis by Co-inertia searches for axes that maximize the covariance of the projection coordinates. The relevance of the Co-inertia plots is tested using a Monte-Carlo test which consists of comparing the observations with the results obtained using random permutations of the data

Fig. 1 Three maps showing the quadrate test carried out with circles of 5, 10 and 30 km radius



(in this case, 1,000 random permutations carried out on the values of the two tables).

*Example: spatial correlations between the pollen data, archaeological and abiotic parameters during the Bronze Age (2500 to 750 cal B.C.)*

The Bronze Age period was selected as a good example because it is well documented in north-western France in terms of human activities thanks to the acquisition of abundant and verified archaeological data (Gabillot et al. 2007). In this study, we use 63 pollen records dated to the Bronze Age (ESM Table 4).

The archaeobotanical descriptors used in the CA were taxa and pollen groups characteristic of well drained soils. The parameters taken into account in the PCA were for each pollen site, (1) annual average temperature, (2) average of the lowest soil pH per canton, (3) distance between the pollen sites and the −5 m sea level contour, (4) average altitude, (5) average annual rainfall, (6) longitudinal co-ordinate, (7) latitudinal co-ordinate, and (8) density of occurrences of metallic objects of the Bronze Age in a radius of 10 km around each pollen site. Some studies were withdrawn from this analysis because of the absence of data for one or more environmental factors.

## Results

### The spatial distribution of the pollen analyses

Results from the quadrate test (three calculations) show that the variance is always higher than the average (Fig. 1; Table 1). It implies that the spatial distribution of the pollen analyses/sites is heterogeneous. A similar test confirmed that the pollen sites are strongly correlated to the occurrence of wetlands (correlation coefficient = 0.73) (Figs. 2, 3).

### Spatial correlation between precipitation and those pollen analyses which recorded pollen percentages of hazel higher than those of oak between 6700 and 5700 cal B.P.

A comparison between the selected pollen analyses and the map of precipitation suggests that there is a positive relationship between the amount of precipitation and high pollen percentages of hazel compared to oak percentages (Fig. 4). The modern ecology of hazel (more hygrophilous than the majority of oak species) also supports this assumption (Rameau et al. 1996). However, because of the heterogeneous spatial distribution of the 66 pollen analyses, it was necessary to test the significance of the relationship. A Chi-square test showed a significant difference between the distribution of the precipitation values at the 66 pollen sites and the distribution of precipitation values observed on the regional scale (Fig. 5; Table 2a). In other words, the distribution of the precipitation values obtained using the location of the 66 pollen analyses did not correspond to the distribution of the precipitation values observed on the regional scale. The Chi-square test carried out on weighted (Table 3) and non-weighted data showed significant differences in each case (see Methods section; Table 2b, c). The Mann and Whitney *U* tests (non-parametric tests) also exhibited significant differences (Table 2d, e). The relationship between the spatial distribution of the precipitation and the two sets of pollen analyses was thus confirmed—according to the Chi-square and the Mann and Whitney *U* tests, the pollen studies with pollen percentages of *Corylus* higher than *Quercus* are prevalent in the most humid areas.

### Spatial correlations between pollen records, archaeological and abiotic parameters during the Bronze Age (2500 to 750 cal B.C.)

*Correspondance analysis*

The first axis of the CA analysis (21.7% of total inertia) (Fig. 6) contrasts two sets of pollen records, one set comprising pollen groups interpreted as shrubland, forests and meadows, i.e. natural landscapes or landscapes characterised by extensive agriculture, and a second set including pollen groups that are characteristic of agricultural landscapes. Fallow lands (AB_L2 in Fig. 6) were recorded in the majority of the pollen analyses; therefore, the score of this descriptor is located in the middle of the first axis. *Cannabis-Humulus* pollen is often associated with pollen groups interpreted as typical of natural landscapes. Thus, in this case, the *Cannabis-Humulus* pollen probably originates from wild *Humulus lupulus* growing on wet, nutrient-rich soils in alder carrs, along lakes and rivers, and in wet woods.

*Principal correspondance analysis*

The second axis of the PCA (Fig. 7) separates sites along continentality gradients expressed by gradients in longitude and distance to the −5 m sea level contour (DIST_5 M in Fig. 7). Moreover, there is a negative relationship between the number of archaeological sites (NBSITE_10 K in Fig. 7) and DIST_5 M, which indicates that pollen data from archaeological sites are more numerous near the sea.

**Table 1** Dispersion index calculated for the spatial distribution of pollen sites

The quadrate test and the distribution index were calculated for circles of 5, 10 and 30 km radius

| | Quadrat test carried out with 1,000 circles of 5 km radius | Quadrat test carried out with 1,000 circles of 10 km radius | Quadrat test carried out with 1,000 circles of 30 km radius |
|---|---|---|---|
| Average | 0.126 | 0.58 | 5.313 |
| Variance | 0.378 | 2.6 | 43.54 |
| Dispersion index (Var/Av) | 3.003 | 4.49 | 8.195 |

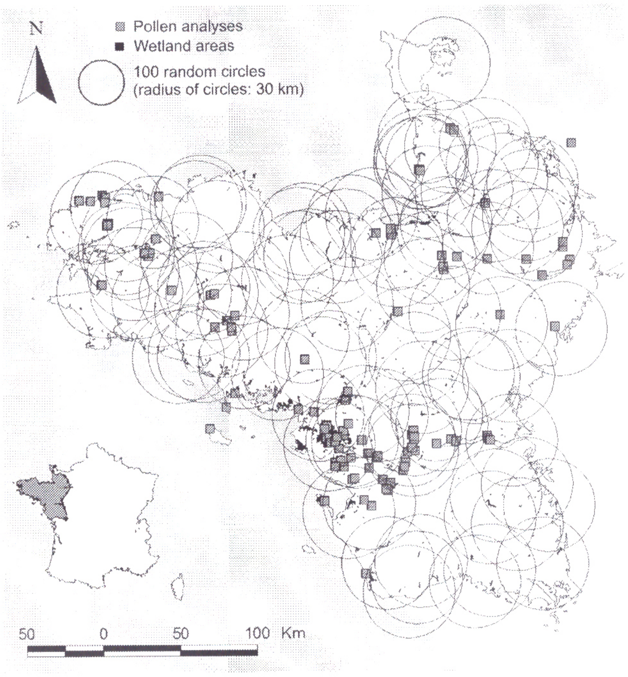



**Fig. 2** Spatial distributions of the wetland areas (data extracted from the CORINE Land Cover database, v 1.3) and of the pollen records. One-hundred randomly distributed circles were created to test the correlation between the two spatial distributions

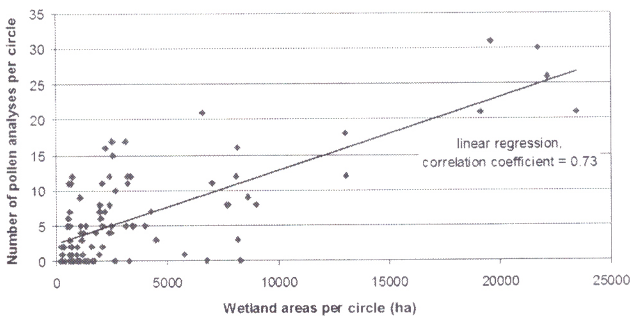



**Fig. 3** Correlation between the wetland areas and the number of pollen records per circle, see text for further explanation

*Co-inertia analysis*

A Monte Carlo test showed that 71.4% of the relationships obtained by the Co-inertia analysis were not random. The position of the pollen groups in the Co-inertia analysis plot (Fig. 8) makes it possible to

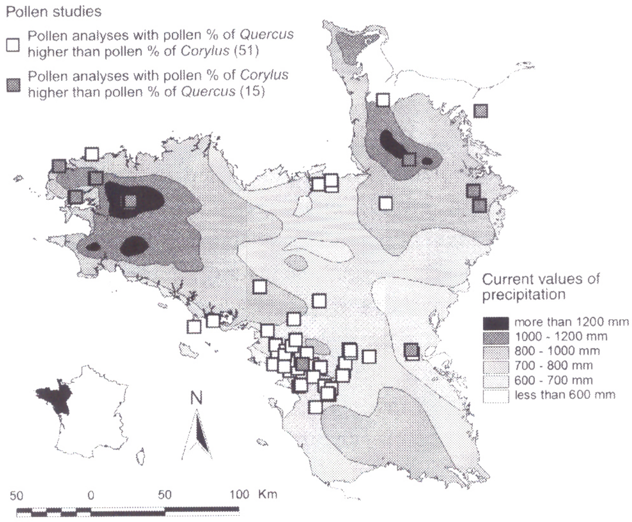



**Fig. 4** Two sets of pollen records with contrasting *Corylus-Quercus* relationships between 6700 and 5700 cal B.P. A precipitation map makes it possible to compare the spatial distribution of the pollen data sets with the spatial distribution of rainfalls. See text for further explanation

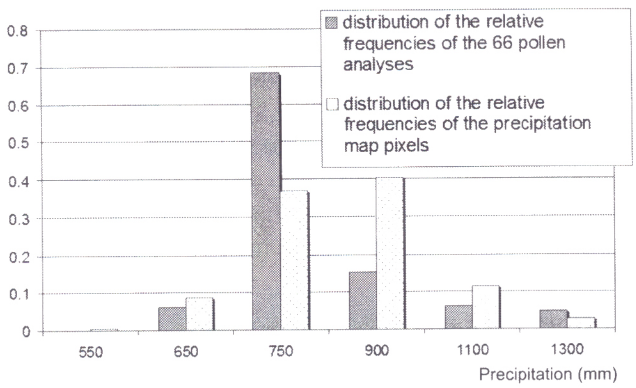



**Fig. 5** Distributions of the relative frequencies of the 66 pollen records and the relative frequencies of the precipitation map pixels, according to rainfall groups. See text for further explanation

recognise the principal PCA axes (Fig. 7). The first axis is associated with temperature, altitude, rainfall and latitude, while the second axis is related to longitude, distance to the sea and density of archaeological sites. The general orientation of the vectors is almost vertical i.e. they more often cross the first axis than the second. This suggests that the relationship between the

**Table 2** Results of the Chi-square and Mann and Whitney *U* tests

| | Tests and data compared | Results |
|---|---|---|
| a | Chi-square test between the rainfall group distributions of the 66 pollen analyses and those of the rainfall map pixels (22,723) (data not transformed) | $\chi^2 = 31.13$; theoretical $\chi^2 = 11.07$ at 5%. The difference is significant because of the heterogeneous spatial distribution of the 66 pollen analyse sampling |
| b | Chi-square test between the distributions of the two archaeobotanical sets: pollen analyses with oak pollen rates higher than those of hazel and inversely (series of data not transformed) | $\chi^2 = 36.61$; theoretical $\chi^2 = 11.07$ at 5%. The difference is significant |
| c | Chi-square test between the distributions of the two archaeobotanical sets after weighting | $\chi^2 = 28.6$; theoretical $\chi^2 = 11.07$ at 5%. The difference is significant |
| d | Mann and Whitney *U* test carried out between the precipitation value series of the two archaeobotanical sets (data not transformed) | $z = 4.745$; variance = 2547.4; critical value = 1.96; the difference is significant<br>Pollen analysis set with hazel pollen rates higher than those of oak; average = 997 mm; standard error = 53.77; number of pollen analyses = 15<br>Pollen analysis set with oak pollen rates higher than those of hazel; average = 758.82 mm; standard error = 7.37; number of pollen analyses = 51 |
| e | Mann and Whitney *U* test carried out between the precipitation value series of the two archaeobotanical sets after weighting | $z = 5.403$; variance = 4525; critical value = 1.96; the difference is significant<br>Pollen analysis set with hazel pollen rates higher than those of oak; average = 980 mm; standard error = 30.78; number of pollen analyses = 25<br>Pollen analysis set with oak pollen rates higher than those of hazel; average = 791.5 mm; standard error = 13.17; number of pollen analyses = 41<br>after weighting of the data, the Mann and Whitney *U* test confirms a significant difference between the two series of precipitation values |

See text for further explanation

**Table 3** Weighting indexes according to rainfall groups

| Rainfall groups (mm) | 500–600 | 600–700 | 700–800 | 800–1,000 | 1,000–1,200 | 1,200–1,300 |
|---|---|---|---|---|---|---|
| Ratios between relative frequencies of pollen analyses and relative frequencies of the rainfall map pixels | 0 | 0.711 | 1.84 | 0.38 | 0.54 | 1.76 |

See text for further explanation

archaeobotanical classification (the factorial plot of the CA) and the contextual classification (the factorial plot of the PCA) is more stable along the first than along the second axis. Thus, only weak relationships can be interpreted from the second axis. The pollen occurrences of *Vitis* and *Cannabis-Humulus* were mostly recorded at eastern continental sites (e.g. sites nos. 74, 76 and 77), whereas the moor vegetation (AB_L4), meadows (AB_L3), shrubland and vegetation linked to human activities (AB_L5 and AB_L7) were found primarily in the western sites and were located closer both to the littoral and high densities of archaeological sites (e.g. sites 61 and 69).

The first axis of the analysis by Co-inertia (Fig. 8) presents more systematic relationships between abiotic, archaeological and archaeobotanical parameters. The meadows (AB_L3), shrubland (AB_L6), and forests (AB_L5) are associated with cooler temperatures, higher altitudes and northern latitudes (e.g. sites 132, 133, 144, 145, 8 and 7), while the moor vegetation (AB_L4), the anthropogenic vegetation (AB_L7), and pollen occurrences of Cerealia and *Vitis* are related to warmer temperatures, southern latitudes and lower altitudes (e.g. sites 18, 16, 24 and 22). Moreover, the two descriptors 'distance to the sea' and 'number of archaeological sites' also have a positive relationship with the first axis.

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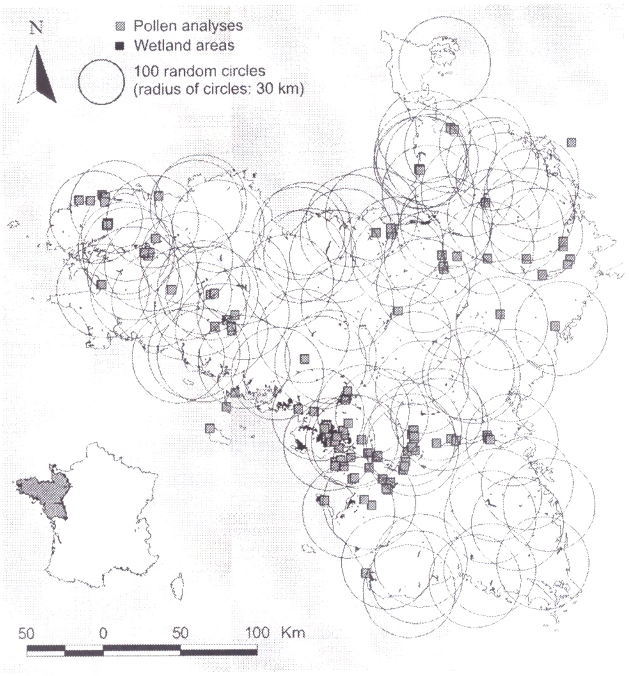


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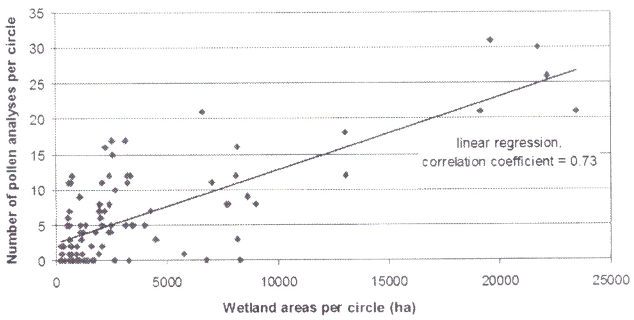


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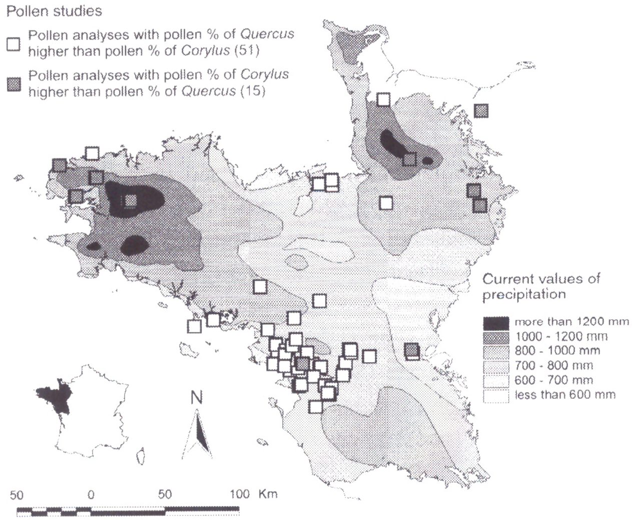


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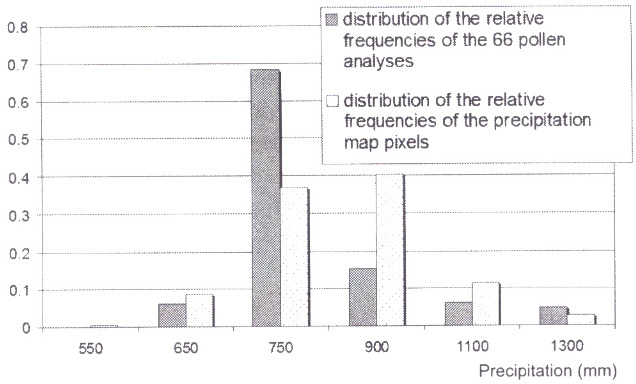


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The first axis of the analysis by Co-inertia (Fig. 8) presents more systematic relationships between abiotic, archaeological and archaeobotanical parameters. The meadows (AB_L3), shrubland (AB_L6), and forests (AB_L5) are associated with cooler temperatures, higher altitudes and northern latitudes (e.g. sites 132, 133, 144, 145, 8 and 7), while the moor vegetation (AB_L4), the anthropogenic vegetation (AB_L7), and pollen occurrences of Cerealia and *Vitis* are related to warmer temperatures, southern latitudes and lower altitudes (e.g. sites 18, 16, 24 and 22). Moreover, the two descriptors 'distance to the sea' and 'number of archaeological sites' also have a positive relationship with the first axis.

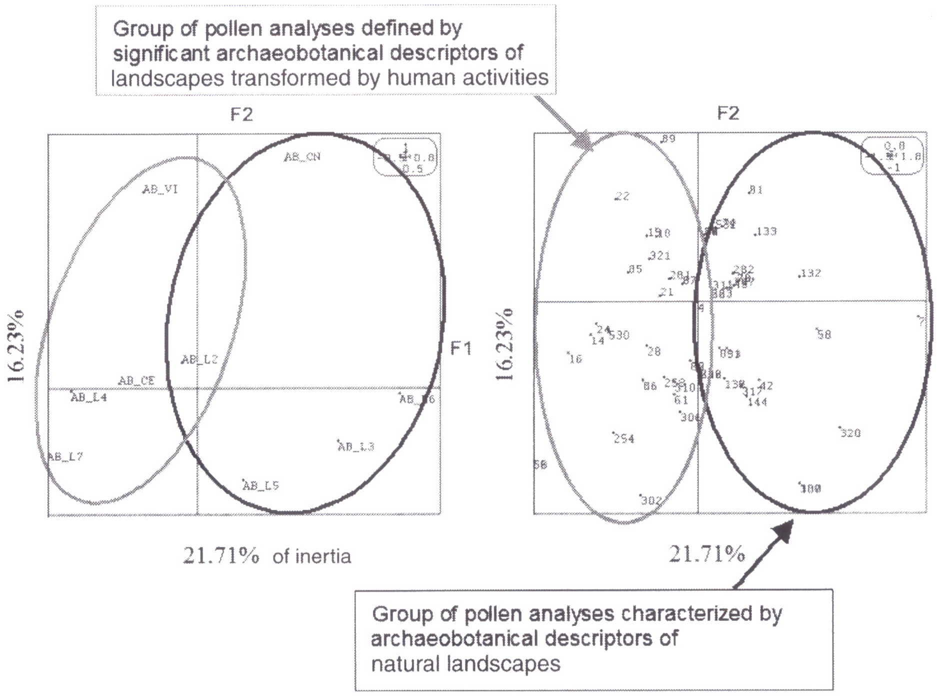


**Fig. 6** Correspondence Analysis of pollen records according to pollen descriptors for the Bronze Age. The scores of the archaeobotanical descriptors are presented in the *left-hand factorial plot*. The scores of the pollen records on the principal components 1 and 2 are presented in the *right-hand factorial plot*. *AB_CE* Cerealia pollen occurrences; *AB_VI Vitis* pollen occurrences; *AB_CN Cannabis-Humulus* pollen occurrences; *AB_L2* fallow land pollen groups; *AB_L3* hygrophilous and mesophilous meadow pollen groups; *AB_L4* moor pollen groups; *AB_L5* shrubland pollen groups. *AB_L6* forest edge pollen groups; *AB_L7* pollen groups from roads, tracks and byways etc. (ruderal plants), pasturelands and inhabited areas

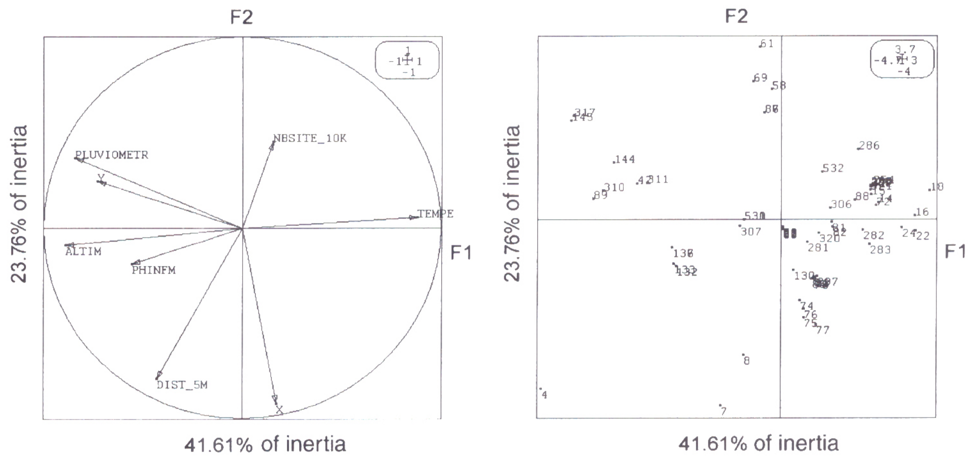


**Fig. 7** Principal Component Analysis of pollen records according to pollen descriptors for the Bronze Age. The scores of the abiotic and archaeological descriptors are presented in the *left-hand factorial plot*. The scores of the pollen records on the principal components 1 and 2 are shown in the *right-hand factorial plot*. Abiotic and archaeological descriptors at each pollen site: *TEMPE* annual average temperature; *PHINFM* average of the lower pH of the soils by township of each pollen site; *DIST_5 M* distance between the pollen sites and the sea level −5 m contour; *ALTIM* average altitude; *PLUVIOMETR* average annual rainfall; *X* longitudinal co-ordinate; *Y* latitudinal co-ordinate; *NBSITE_10 K* density of occurrences of metallic objects dated to the Bronze Age in a radius of 10 km around each pollen site

## Discussion

### Spatial distribution of the pollen analyses

Because of the lack of strategy in the spatial selection of sites, the distribution of the pollen sites appears to be heterogeneous ($I > 1$), which was expected. There are several possible explanations for such a distribution. The most probable explanation resides in the fact that pollen sites often correspond to wetlands, which was confirmed by a correlation analysis. The Loire estuary region is a good example of such correlation. The area is characterised by numerous wetlands that were studied for pollen by Visset (1979), Voeltzel (1987), Ouguerram (2002) and Cyprien (2002). These investigations contribute largely to the correlation. However, some studies weaken the correlation because pollen analysis was performed in other deposits, as is the case of the work performed by Barbier (1999).

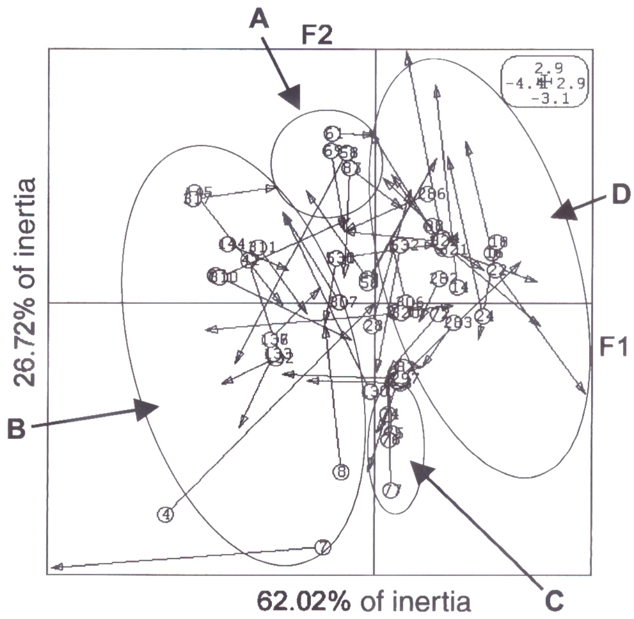


**Fig. 8** Co-inertia analysis performed on the pollen records of the Bronze Age, comparing the Correspondence Analysis of pollen descriptors and the Principal Component Analysis of abiotic and archaeological parameters. *A* pollen records located in the western part of the study region and close to the coastline. The number of archaeological sites is high around these sites. The pollen groups 'moor vegetation' (AB_L4), 'meadows' (AB_L3), 'shrubland' and 'anthropogenic vegetation' (AB-L5 and AB_L7) are recorded in most analyses. *B* Pollen sites located in the northern part of the study region characterised by cooler temperatures, higher altitudes and precipitation. These parameters are associated with the pollen groups 'meadows' (AB_L3), 'shrubland' and 'forests' (AB_L5, AB_L6). *C* Pollen sites located in the eastern part of the study region. The pollen occurrences of *Vitis* and *Cannabis-Humulus* are characteristic of these pollen records. *D* Pollen sites located in the southern part of the study region characterised by higher temperatures and lower precipitation. These pollen records are characterised mainly by the pollen groups 'anthropogenic vegetation' (AB_L7) 'moor vegetation' (AB_L4), and by the pollen occurrences of Cerealia (AB_CE) and *Vitis* (AB_VI)

### Spatial correlation between precipitation and the pollen analyses which recorded pollen percentages of hazel higher than those of oak between 6700 and 5700 cal B.P.

Even though precipitation might have been different during the studied period (6700–5700 cal B.P.) from today, one can assume that the spatial distribution of rainfall was roughly the same as today as it depends partly on the topography, i.e. the spatial distribution of altitudes. In north-western France, the selected time period is generally characterised by the dominance of oak pollen over hazel pollen, which is used as a chronozone characteristic by Bernard (1996). However, when all pollen records in the region are considered, hazel pollen is dominant over oak pollen in 15 records out of 66, i.e. in 22% of the cases. Therefore, dominance of oak is not the rule, and the tests performed indicate that high values of hazel characterise sites located in the most humid areas of the region, which does make sense ecologically.

### Spatial correlations between pollen records, archaeological and abiotic parameters during the Bronze Age (2500 to 750 cal B.C.)

The interpretation of the analysis by Co-inertia to produce explanative models of palaeobotanical/pollen data may be difficult because of the complexity of past landscapes. There are often many exceptions to the few relationships that are identified. Therefore, although multivariate analyses are useful to identify tendencies in the spatial distributions of landscape parameters that can be correlated to palaeobotanical groups, they can never provide unequivocal relationships between spatial distributions of pollen groups/palaeo-vegetation and spatial distributions of environmental or archaeological parameters. In the example presented in this paper, although the archaeobotanical groups 'shrubland' and 'meadows' are mostly characteristic of the northern pollen sites, they are also present in some sites in the southern part of the region.

Problems of interpretation may also arise from the different spatial scales at which the various descriptors are recorded. For example, even if it is possible to identify the major tendencies in the densities of archaeological findings at regional spatial scales from the archaeological maps, the local disparities are much more complex to take into account and may blur the results of the numerical analyses.

## Conclusion

The originality of the methods presented in this paper lies in the analysis of the spatial distributions of the archaeobotanical data along with the spatial distributions of other parameters (geology, climate, ground types, topography, archaeology etc.) in order to identify possible correlations between them. Despite the absence of spatial strategies in the selection of pollen sites, the large number of pollen studies in north-western France and the diversity of the contexts in which they were carried out, made it possible to identify correlations between the spatial distributions of the archaeobotanical records and other parameters. When the spatial disparities of the palaeo-vegetation are sufficiently important to be recorded by several types of archaeobotanical data (e.g. pollen, plant macrofossil, charcoal etc.), it is possible as a first step to attempt to identify and map the principal types of palaeo-vegetation. In a second step, one can attempt to explain the archaeobotanical maps by correlating them with other thematic maps using different tests and numerical analyses. Significant correlations may provide new, valuable elements of interpretation of the archaeobotanical data. Explanatory models of the pollen/palaeobotanical data can be obtained in several ways depending on the objectives and the data available. In each case, particular attention must be given to the choice of descriptors and statistical tools.

In our case, the heterogeneous spatial distribution of the pollen records required that we tested the significance of the sampling in relation to the regional distribution of a particular parameter (e.g. precipitation in the example presented in this paper). If the difference is significant, one can weight the values of the parameter in order to obtain values that one would expect from random sampling. In our example, we then compared two series of precipitation values selected according to archaeobotanical data and tested the significance of the correlation with the Mann and Whitney *U* (non-parametric test) and Chi-square tests.

The Co-inertia analysis makes it possible to search for relationships between the archaeobotanical data and the contextual parameters by taking into account several descriptors at once. Thus, it is possible to integrate the complexity of the palaeo-landscapes. In order to apply this method, each pollen site needs to include two types of record: a record of pollen per time window studied, and a record of abiotic parameters and archaeological properties. In our case, the pollen records could be sorted in two different ways, on the one hand according to their pollen descriptors, which makes it possible to identify the main associations of palaeo-vegetation for each selected period and on the other hand according to the abiotic and archaeological parameters. It is then possible to search for relationships between the sets of pollen records described independently according to (1) the archaeobotanical data and (2) the contextual parameters (abiotic and archaeological).

The proposed methodology could be used in many regions of Europe and the world where palaeobotanical records are available from a large number of sites within regions characterised by significant differences in abiotic parameters, as is the case of many areas in Europe and northern America. It allows the exploration of all sorts of questions related to the causes behind vegetation changes through time and differences in vegetation development between sites/areas within a region. Alternative methodologies using the potentials of GIS have been proposed by other authors, however often with another type of objective. For instance, Fyfe (2006) uses GIS and the application of a model of pollen deposition and dispersal to test landscape hypotheses and Bunting et al. (2007, 2008) apply GIS and pollen deposition and dispersal in the Multiple Scenario Approach (MSA) in order to produce spatial quantitative reconstructions of past vegetation in the form of vegetation/landscape maps.

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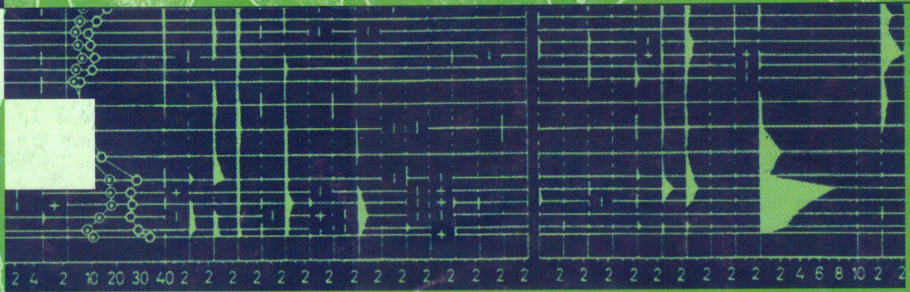

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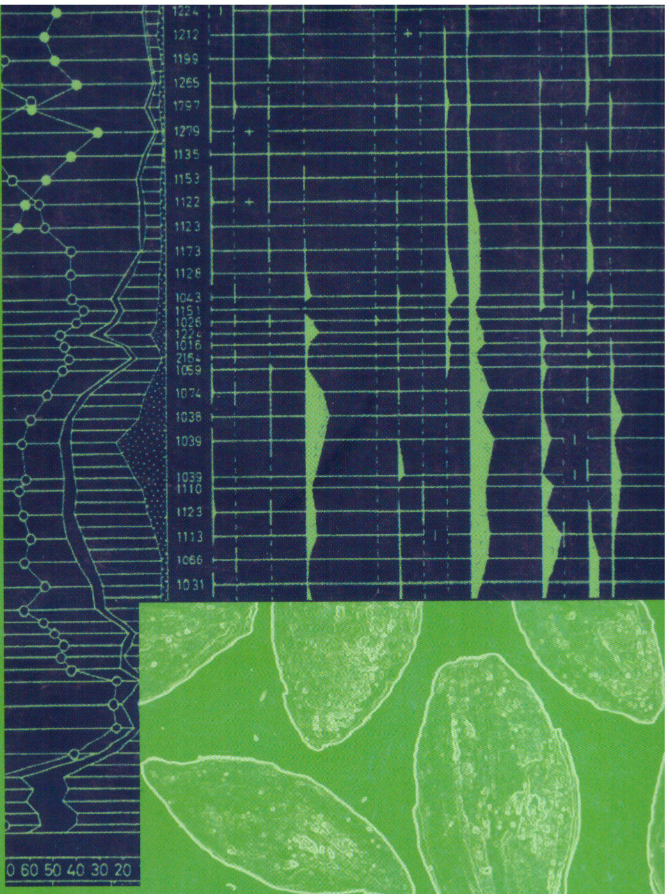

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