Palaeoecological transition in southwestern New South Wales: ecosystem changes in pollen assemblages revealed by fuzzy analysis

by Matt Cupper[1] and Bill Ward[2].

[1]School of Earth Sciences,
The University of Melbourne
Victoria 3010
m.cupper@pgrad.unimelb.edu.au

[2]Faculty of Environmental Sciences,
Griffith University, Nathan
Queensland 4111
billward@webtime.com.au

Abstract

Fuzzy analysis, a numerical analytical technique, was used to elucidate vegetation changes expressed in pollen proxy data from Warrananga salt lake, southwestern New South Wales. Significant modifications of the structure and composition of plant communities occurred in this region during the Holocene. These included the development of casuarinaceous woodlands in the mid-Holocene and subsequent woodland-decline with the expansion of chenopod shrublands during the late Holocene. Eucalypts became more prominent and Casuarinaceae recovered prior to the European settlement phase. Significantly, fuzzy analysis also revealed phases of grassy open-woodlands between the woodland-shrubland transitions, suggesting a complex sequence of ecological succession. This study highlights the considerable potential of fuzzy analysis in interpreting fossil assemblages.

Introduction

Counts of fossil pollen in sediment sequences usually generate large multivariate data sets and are often difficult to interpret objectively. Numerical analysis is often enlisted. Many palynologists, for instance, use techniques such as CONstrained Incremental Sum-of-Squares [CONISS] (Grimm, 1987, 1988), Non-metric Multi-Dimensional Scaling [NMDS] (Kruskal, 1964), and Detrended Correspondence Analysis [DCA] (Hill, 1979). Principal Component Analysis [PCA] (Pearson, 1901) is also common. Analyses usually represent the relationships of the pollen assemblages at each sampled depth as cluster dendrograms, or as spatial ordination diagrams. These techniques are merely tools to simplify large data sets. They facilitate interpretation of the data, but do not offer solutions.

The different numerical procedures elucidate particular aspects of a multivariate data set. CONISS, for example, constrains the sample depths stratigraphically, to facilitate the selection of phases of change through a sequence (e.g. Horrocks and Ogden, 2000). Spatial arrangements of samples, generated by NMDS, PCA or DCA ordinations, can be useful for comparing samples within sequences, or from different sites, and help identify patterns, or trends (e.g. Waller, 1988; Dodson and Wright, 1989; Rull, 1999). Moreover, they can match fossil pollen assemblages with modern analogues (e.g. Caseldine and Pardoe, 1994; Gaillard *et al*., 1994). An iterative partitioning method of cluster analysis, namely fuzzy analysis (Bezdek, 1981; Alt, 1990), is able to group similar entities in multivariate data sets. It can also identify situations where the groups replace one another in either space or time, or both. For these reasons, it is worth applying fuzzy techniques to pollen data, because pollen counts, which record changes in frequency of plant species over time, can be regarded as parameters of distinct plant communities. To test the method, we applied fuzzy analysis to a pollen assemblage from Warrananga salt lake in southwestern New South Wales.

Warrananga salt lake is about 20 km east of Lake Victoria, near the Murray and Darling Rivers (Figure 1), a semiarid region with a mean annual rainfall of 265 mm (Bureau of Meteorology, 2000). Bluebush and saltbush (*Maireana* and *Atriplex* spp.) shrublands dominate the surrounding landscape, with belah-rosewood (*Casuarina pauper-Alectryon oleifolius*) low open-woodlands and mallee (*Eucalyptus* spp.) tall shrublands on nearby linear dunes. Lithostratigraphic correlation of a 139 cm core taken from the lake with a dated core indicates the sequence probably represents the full Holocene (Cupper, 1998).

Methods

Field and laboratory analyses

The first author (M.C.) extracted pollen from the Warrananga core using heavy liquid separation (Hart, 1988). At least two hundred pollen grains (on average, 238 pollen grains) were counted for each 1 cm wide sample, at 3 cm intervals.

Numerical analyses

Counts for each pollen taxon were converted to percentages of the total sum of identified pollen grains. Pollen percentages for individual taxa were accepted as attributes that describe real plant communities. Fuzzy analysis was used to discover what plant communities might exist in the entire data set.

The numerical program for fuzzy analysis (Ward *et al*., 1992) takes all samples and assigns them randomly to groups. The groups are then progressively refined, by altering the sample membership values until the differences between the groups are maximized. Standardized Euclidean distances are used to measure dissimilarity. Major groups are separated satisfactorily when the same optimal result is given by repeated analysis. Objective function values are calculated for each analysis and the smallest objective function value indicates the optimal solution.

In fuzzy analysis the objects being placed in groups are regarded as having a potential membership, to a greater or lesser degree, in every group that is formed. The extent of membership in a group can range from zero to one. A zero membership shows that the object is not a member of a group, whereas a membership score of one indicates membership in one group only. Shared group memberships (or transitions between groups) are indicated by intermediate values. The scores for group membership and the averages for each group are outcomes of the analysis.

The overall averages for the measured attributes describe the final groups. These are weighted averages and are termed centroids, the means being weighted by the group membership scores. They describe the general features of the groups. As at least two groups are given by a fuzzy analysis, it can be that the groupings are forced on a uniform population. Outcomes have to be examined, therefore, to check whether no subdivision might be the best solution. The results of a series of fuzzy analyses that examine an increasing number of groups can help with this problem. Expert judgment and perhaps other data may also be required.

Results

The Warrananga data set consisted of forty-six sample depths each with thirty-four variables (taxa). Pollen percentages of the main taxa are summarized in an area graph (Figure 2a). We decided to treat the thirty-four taxa as being equally significant in defining a group, standardizing their ranges on a scale of zero to one. Different settings of the fuzzy parameter were explored, as recommended by Ward *et al*. (1992). The value of 1.10 was selected as being appropriate for the data set, as settings of 1.00 did not yield a fuzzy result and settings greater than 1.20 had outcomes that failed to separate groups. Three optimal groups were regularly identified (objective function value of 1258.42). The numerical analyses were repeated several times to check this result and in the re-runs it became clear that one of these three groups was composed of two smaller groups close by one another in multivariate space. The four groups that appeared in these re-runs gave an improved objective function value (1182.18).

The three-group analyses identified thirteen taxa as major components: *Leptospermum*, *Eucalyptus*, Casuarinaceae (<28 μm diameter), Casuarinaceae (>28 μm diameter), *Callitris*, Myoporaceae, Sapindaceae, Chenopodiaceae, Pittosporaceae, Asteraceae (Liguliflorae), Fabaceae, Poaceae and Cyperaceae. An examination of a subset of the data that consisted only of these thirteen variables gave substantially the same result as before. It was evident, however, that the less abundant taxa were contributing to the group definitions and for this reason subsequent analyses were based on the full data set.

The four-group membership scores for each sampled depth are given in Table 1 and plotted against depth in Figure 2b. Centroid values are given in Table 2.

Depth (cm)	Group 4a	Group 4b	Group 4c	Group 4d
0	0.011	0.032	0.003	0.953
3	0.000	0.046	0.000	0.954
6	0.001	0.187	0.000	0.813
9	0.012	0.005	0.000	0.983
12	0.003	0.024	0.000	0.973
15	0.000	0.000	0.000	1.000
18	0.995	0.001	0.000	0.004
21	0.935	0.019	0.021	0.025
24	1.000	0.000	0.000	0.000
27	0.997	0.001	0.000	0.001
30	0.959	0.004	0.000	0.037
33	0.946	0.022	0.009	0.023
36	0.006	0.016	0.002	0.977
39	0.008	0.002	0.000	0.990
42	0.000	0.000	0.000	1.000
45	0.001	0.068	0.000	0.931
48	0.000	0.006	0.000	0.994
51	0.021	0.083	0.003	0.893
54	0.000	0.977	0.000	0.023
57	0.001	0.972	0.000	0.027
60	0.000	0.000	0.000	1.000
63	0.000	0.978	0.000	0.022
66	0.001	0.996	0.000	0.003
69	0.005	0.091	0.064	0.840
72	0.000	0.001	0.000	0.999
75	0.000	0.690	0.000	0.310
78	0.715	0.189	0.013	0.083
81	0.006	0.019	0.968	0.007
84	0.000	0.998	0.000	0.002
87	0.000	1.000	0.000	0.000
90	0.882	0.081	0.010	0.027
93	0.006	0.959	0.033	0.002
96	0.004	0.004	0.987	0.005
99	0.002	0.018	0.977	0.003
102	0.001	0.000	0.998	0.000
105	0.000	0.016	0.978	0.005
108	0.000	1.000	0.000	0.000
111	0.000	0.000	0.000	1.000
114	0.000	0.998	0.000	0.002
117	0.000	0.001	0.000	0.999
120	0.001	0.002	0.000	0.997
123	0.000	0.026	0.000	0.974
126	0.000	0.004	0.000	0.996
129	0.009	0.024	0.003	0.965
132	0.002	0.003	0.000	0.995
135	0.000	0.000	0.000	0.999

Table 1. Membership scores for each sampled depth as reported by fuzzy analysis.

Pollen taxon	Group 4a	Group 4b	Group 4c	Group 4d
Leptospermum	0.3011	0.9842	1.2280	0.3260
Eucalyptus	5.7597	2.0927	3.5560	3.1763
Other Myrtaceae	0.4257	0.0673	0.3337	0.1571
Casuarinaceae (<28 µm)	13.9561	4.1698	4.8903	2.6576
Casuarinaceae (>28 µm)	1.5528	3.3035	9.3057	1.1980
Callitris	2.5213	7.2262	4.0324	2.7177
Pinus	0.0018	0.0070	0.0007	0.1136
Myoporaceae	0.6043	0.3200	0.4523	0.3815
Sapindaceae	9.5198	5.5069	9.9068	2.7051
Acacia	0.0609	0.3376	0.1518	0.0411
Cassia	0.0542	0.0034	0.0006	0.0363
Hakea	0.1051	0.1405	0.2546	0.0027
Other Proteaceae	0.0536	0.1479	0.0028	0.0335
Pittosporaceae	0.5194	0.2435	0.1806	0.1967
Exocarpus	0.0612	0.0029	0.3220	0.0738
Santalum	0.0001	0.0001	0.0846	0.0000
Gyrostemaceae	0.0020	0.0891	0.2561	0.1275
Chenopodiaceae	34.8550	42.7323	39.0602	51.8637
Rhamnaceae	0.0003	0.0012	0.0001	0.0412
Malvaceae	0.3725	0.0002	0.0000	0.0203
Zygophyllaceae	0.1046	0.0486	0.0022	0.0018
Asteraceae (Tubuliflorae)	19.2272	18.2156	11.8913	26.8024
Asteraceae (Liguliflorae)	0.0533	0.0012	0.1586	0.0004
Fabaceae	0.4126	0.2112	1.0165	0.3642
Epacridaceae	0.0003	0.0008	0.0001	0.0204
Scrophulariaceae	0.1723	0.0848	0.4057	0.2170
Haloragaceae	0.3280	0.0859	0.1726	0.2000
Sterculiaceae	0.1021	0.0074	0.0008	0.0014
Violaceae	0.0002	0.0948	0.0000	0.0375
Plantaginaceae	0.3680	0.0537	0.0008	0.0210
Poaceae	7.3214	11.4372	7.9735	5.0402
Cyperaceae	0.0464	0.8112	1.4274	0.3898
Cyatheaceae	0.0003	0.0041	0.2468	0.0140
Other Pteridophyta	0.1638	0.0817	0.1516	0.0774

Table 2. Centroid values of the Warrananga pollen taxa for the four groups. Centroids are averages of the pollen percentage for each taxon that occur within the four groups, weighted by the group membership scores. They describe the general features of the groups.

Discussion

When analyzing the pollen data, we were aware that percentages are interdependent, that is, all taxa are susceptible to changes in the absolute abundance of any one taxon (Yarranton and Ritchie, 1972). However, percentages reflect the relative importance of the pollen taxa (Birks and Gordon, 1985) and are a reliable quantitative measure of vegetation. Prentice (1988) has shown that pollen percentages are subject to less irrelevant variability within and between sampling sites than absolute values.

Our fuzzy analysis detected acceptable groups in the pollen assemblage and helped to identify phases where they replaced one another through time. The four fuzzy groups represent distinct ecological phases.

Groups 4a and 4c are dominated by two types of woodland, distinguished mainly by the Casuarinaceae. Casuarinaceae pollen with a diameter greater than 28 µm are dominant in Group 4c, but very much reduced in Group 4a. Larger grain size (>28 µm) Casuarinaceae pollen may belong to *Allocasuarina luehmannii*, with pollen less than 28 µm in diameter probably derived from *Casuarina pauper*. *Casuarina pauper* is the more xeromorphic of the two, and the only representative of the Casuarinaceae in the modern flora of the region. It survives with less than 150 mm annual rainfall, whereas *A. luehmannii* is common to the 380-630 mm rainfall band (Doran and Hall, 1983, Ladd, 1989). Group 4a also has a low representation of tall shrubs such as *Leptospermum*, *Hakea*, *Exocarpus* and Gyrostemaceae. These factors, along with the prominence of mallee eucalypts in Group 4a, are indicative of a drier-climate woodland than Group 4c.

Group 4b has a casuarinaceous element, but is distinguished by native pine (*Callitris* spp.) and Poaceae. This suggests an opening-up of the vegetation from woodland to open-woodland. Abundant native pine and grasses indicates relatively moist climatic conditions compared to today, although conditions were possibly drier than at the height of the Group 4c woodland phase.

Group 4d is shrubland and herbfield dominated by members of the Chenopodiaceae and Asteraceae. It predominates in the early part of the record prior to the establishment of woodland and also expands with the decline of tree cover in the late Holocene.

The graphed results in Figure 2b display a sensible sequence. The occurrence of grassy native pine and casuarinaceous open-woodland (Group 4b) both above and below casuarinaceous woodland (Group 4c) suggests ecological succession. Native pine was displaced by Casuarinaceae during the mid-Holocene, when the tree cover thickened. As conditions became drier, the structure of the community opened up, and native pine regained some of its ecological advantage.

Conclusion

Fuzzy analysis assisted in elucidating vegetation changes expressed in the Warrananga core. After the development of woodland in the mid-Holocene, representation of Casuarinaceae declined and chenopod shrubland expanded. Casuarinaceae recovered prior to European settlement, but the woodland composition altered, with mallee eucalypts and less tall shrubs. The analysis also revealed transitional phases of grassy open-woodlands, suggesting ecological succession. This study indicates the considerable potential of fuzzy analysis in interpreting fossil assemblages and we believe that it merits further testing on other pollen data sets.

Acknowledgements

Thanks are due to Rod Baird (Tooperoopna Station), Bob Duncan (Dunedin Park Station) and Greg Pollard (Warrananga Station) for providing access to their properties.

References

Alt, M., 1990. *Exploring Hyperspace - a non-mathematical explanation of multivariate analysis*. McGraw-Hill, London.

Bezdek, J.C., 1981. *Pattern Recognition with Fuzzy Objective Function Algorithms*. Plenum Press, N.Y.

Birks, H.J.B. and Gordon, A.D., 1985. *Numerical Methods in Quaternary Pollen Analysis*. Academic Press, London.

Brown, C.M. and Stephenson, A.E., 1991*. Geology of the Murray Basin, southeastern Australia*. BMR, Canberra.

Bureau of Meteorology, 2000. Climatic averages - Lake Victoria, New South Wales. Bureau of Meteorology, Commonwealth of Australia (online).
http://www.bom.gov.au/climae/averages/tables/cw_047016.shtml

Caseldine, C., and Pardoe, H., 1994. Surface pollen studies from alpine/sub-alpine southern Norway: applications to Holocene data. *Review of Palaeobotany and Palynology*, 82, 1-15.

Cupper, M., 1998. Casuarinaceae:Chenopodiaceae pollen ratios and soil salinization in the Murray-Daring Basin. *Quaternary Australasia*, 16, 28-34.

Dodson, J.R. and Wright, R.V.S., 1989. Humid to arid to subhumid vegetation shift on Pilliga Sandstone, Ulungra Springs, New South Wales. *Quaternary Research*, 32, 182-192.

Doran, J. and Hall, N., 1983. Notes on fifteen Australian *Casuarina* species. In S.J. Midgley, J.W. Turnbull and R.D. Johnston (editors). *Casuarina Ecology, Management and Utilization*. CSIRO, Melbourne. 19-52.

Gaillard, M.-J., Birks, H.J.B., Emanuelsson, U., Karlsson, S., Lagerås, P. and Olausson, D., 1994. Applications of modern pollen/land-use relationships to the interpretation of pollen diagrams-reconstructions of land-use history in south Sweden, 3000-0 BP. *Review of Palaeobotany and Palynology*, 82, 47-73.

Grimm, E.C., 1987. CONISS: A FORTRAN 77 program for stratigraphically constrained cluster analysis by the method of incremental sum of squares. *Computers and Geosciences*, 13, 13-35.

Grimm, E.C., 1988. Data analysis and display. In B. Huntley and T. Webb (editors). *Vegetation History*. Kluwer Academic, Dordrecht. 43-76.

Hart, D.M., 1988. A safe method for the extraction of plant opal from sediments. *Search*, 19, 293-294.

Hill, M.O., 1979. *DECORANA - a Fortran program for detrended correspondence analysis and reciprocal averaging*. Cornell University, Ithaca, N.Y.

Horrocks, M. and Ogden, J., 2000. Evidence for Lateglacial and Holocene tree-line fluctuations from pollen diagrams from the subalpine zone on Mt Hauhungatahi, Tongariro National Park, New Zealand. *The Holocene*, 10, 61-73.

Kruskal, J.B., 1964. Nonmetric multidimensional scaling: a numerical method. *Psychometrika*, 29, 115-129.

Ladd, P.G., 1989. The status of Casuarinaceae in Australian forests. In K.J. Frawley and N. Semple (editors). *Australia's Ever Changing Forests*. Department of Geography and Oceanography, Australian Defence Force Academy, Campbell, ACT. 63-85.

Pearson, K., 1901. On lines and planes of closest fit to systems of points in space. *Philosophical Magazine, Series VI*, 2, 559-572.

Prentice, I.C., 1988. Records of vegetation in time and space: the principles of pollen analysis. In B. Huntley and T. Webb (editors). *Vegetation History*. Kluwer Academic, Dordrecht. 17-42.

Rull, V., 1999. A palynological record of a secondary succession after fire in the Gran Sabana, Venezuela. *Journal of Quaternary Science*, 14, 137-152.

Waller, M.P., 1988. An investigation into the palynological properties of fen peat through multiple pollen profiles. *Journal of Archaeological Science*, 25, 631-642.

Ward, A.W., Ward, W.T., McBratney, A.B. and de Gruijter, J.J., 1992. MacFuzzy - a program for data analysis by generalised fuzzy k-means on the Macintosh. *CSIRO, Division of Soils, Divisional Report*, 116.

Yarranton, G.A. and Ritchie, J.C., 1972. Sequential correlations as an aid in placing pollen zone boundaries. *Pollen et Spores*, 14, 213-223.

Figures and Tables

Figure 1. Map of southwestern New South Wales and northwestern Victoria showing the location of Warranaga salt lake. (Adapted Brown and Stephenson 1991).

Figure 2a. Pollen counts for the main taxa expressed as percentages of the total pollen sum.

Figure 2b. Graph of membership scores for four groups plotted against depth.

Table 1. Membership scores for each sampled depth as reported by fuzzy analysis.

Table 2. Centroid values of each pollen taxon for the four groups. Centroid values of the Warrananga pollen taxa for the four groups. Centroids are averages of the pollen percentage for each taxon that occur within the four groups, weighted by the group membership scores. They describe the general features of the groups.