



Multiscale analysis of palynological records: new possibilities

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Abstract. Palynological records helped to illuminate the past, but we show the take can be made much sharper when statistical analysis recognises the records' scale dependence. The latter is an unavoidable consequence of site selection, sediment sampling, and the samples' arrangement into time series by dating. To make provision for this in statistical analysis, scale has to be incorporated as one of the intrinsic variables. But by incorporating scale, the analysis will render the outcome not to be a single conclusion, the usual case in conventional statistics, but a multitude of conclusions each regarding the same set of response and forcing variables and each as valid at its own scale as any of the other conclusions at theirs. Thus, the central question for a usable Statistics is this: how to incorporate scale into the analysis and still have a unique conclusion. We address the methodological aspects and illustrate them by worked examples. We use 14 sites scattered across the globe. Interestingly, the analysis of these brought forth hitherto hidden aspects of the temporal synchronicity of change in palynological composition and concomitant atmospheric temperature oscillations that should greatly interest Ecology, as one critique put it, in the age of Global Change. The examples testify to a conceptual advance in laying open a very basic principle: the synchronicity's statistically strong formation specificity, dominantly positive (in frequency terms) for climate warming at sites in the currently humid, micro- and mesothermal zones, and negative in the currently arid and semi-arid zones. Our paper begins with an introduction to the terminology of multiscale analysis in Ecology, followed by data sources, the method we call *canonical serial scaling*, and objectives. A detailed discussion of data properties with special attention to error sources in palynology is provided. The method components discussed include the scalars of compositional transition and synchronicity, error dampening, stabilisation of the synchronicity scalar and its sign distribution, analysis of time shifted series, the use of deviation graphs, and pointers to help detect hotspots and other characteristic points of change on the time axis.

*One of the greatest pains to human nature is the
pain of a new idea.*
Walter Bagehot (1969)

Introduction

We present a methodology that we call *canonical serial scaling*. We do not blame the reader for thinking that "canonical" is a misnomer, after an unsuccessful search through dictionaries for a meaningful entry in the statistical context. Yet, the term "canonical" has the right connotation. It indicates the presence of groups (canons, categories) of variables to be subjected to analysis as groups simultaneously and correlatively. Uniquely in what we do, one group contains the response variables (pollen,

spore, or cell counts) and the other the forcing (environmental) variables. Again uniquely, both groups have associated intrinsic variables specific to "scale". In the most generic sense we are dealing with scales of pattern and process. In the commonest case the scale is spatial or temporal. It is intuitive to regard the perception of pattern and process as a scale dependent variable, specific to the mode in which these phenomena are observed. This implies accepting as a fact of common experience that the observer sees pattern and process one way on one scale and another way on other scales. The experience conditioning interests has lead early to adoption of a multiscale view of pattern in Ecology. The seminal work of Greig-Smith (1952, 1983) with multiscale ground patterns of vegetation is an

éclat example. As a most general outcome, Greig-Smith defines the ecological paradigm in which "... the causes of patterns of distributions, patterns of all scales ..." are the central objects of inquiry. The essence of the point would not change if we substituted time for space in pattern analysis.

The minimum outcome of Greig-Smith's pattern analysis is a series of scale related intensity values (inferences, conclusions) generated by varying the ground scale (block size) at which pattern is observed. The technique thus incorporates "scale" as an intrinsic variable. As a consequence, Greig-Smith's inferences about species pattern and the linkages of species pattern to environmental forcing are scale dependent. So in the analysis the inference itself becomes a scale dependent variable. What is the advantage of making inference a variable? Simply stated, the analysis will allow the practitioner to identify scale points at which pattern or process reach maximum sharpness or the linkage to concomitant environmental forcing attains maximum strength. This way of measuring pattern fits Schneider's (1994) broader definition of "scaling".

The emphasis in vegetation ecology has shifted over the decades from the micro patterns edaphically forced and ruled by competition, which so much interested Greig-Smith, to the mega patterns that challenge current global change research. Reynolds and Wu (1999) dissertate on the latter and its implications. Raising the scale interests us not just out of curiosity, but directly as a context for the objectives that we set, namely, to find regularities in temporal transitions of palynological composition and their synchronicity with changes in high-level environmental forcing. It is on this scale that our work has contact points with current global change research, concerning the climate (Walther et al. 2002; IPCC, 2001) and its destabilizing effects on the vegetation (Samuel et al. 1999).

In short, we subject temporal palynological data to multiscale analysis. There is an entire science about the analysis of this kind of data as time series. Rayner (1971) gives a relatively simple introduction. The most noted of the variants run under such names as harmonic analysis (Wiener 1930), spectral analysis (Wonnacott 1961), time series analysis (Hannan 1960), and spatial analysis (Ripley 1977, 1981). These all have their unique and also shared constraints, the regularity conditions under which their application can be sanctioned. As far as the present

case of *canonical serial scaling* is concerned, there is but a single requirement: identifiable common points on the temporal axis. We will discuss or point to specifics in the sequel.

Our primary objective with *canonical serial scaling* is to examine the long-term vegetation process as it unfolded in the past that shaped the current global vegetation pattern. The time scale in our examples reaches back to at least 20 k yr BP, and in one case to almost 200 k yr BP. The palynological records of that era of the late Quaternary were interpreted by palynologists who collected the sediment samples and recorded their contents. There are many facts already known about the broad historic shifts in the global vegetation cover and their timing vis-à-vis the forcing climatic cycles. What then could we offer anew to what is already known? The questions we pose are not about the fact of global shifts, but rather about how closely synchronous were the shifts in palynological composition in the sediment profiles and the peaks and lows in atmospheric temperature oscillations. Our questions touch two major problem areas in quantitative ecology: data acquisition and statistical inference.

Considering data acquisition, we had no control over sampling design or techniques of measurement. All data sets were received from recognised sources¹. The methodology of data analysis is another matter. With this we could rely on our own results (Orlóci et al. 2002).

The paleoecological record

Before we discuss the records general characteristics, we introduce the sites from which we obtained palynological spectra. The location details, contact person, and other site information are laid out in Table 1. Deuterium based temperature estimates are given in Fig. 1, following Petit et al. (1999).

The palynological record will allow effective targetting of the vegetation process only in the limited terms of compositional transitions. The limits are set by the population level of the identified taxa and the inherent noise-like oscillations in the data. Regarding these, the population level is ill-defined in systematic terms, since the taxa amount to no more in the analysis than paleopollen, spore, or other tissue types. These could correspond to any systematic level, and they do mainly higher than species or genera. The consequence of this is a potentially low ecological resolving power of the analysis.

¹ Palynological records were downloaded from the Global Pollen Database (<http://www.ncdc.noaa.gov/paleo/ftp-pollen.html>) in 2000. One of the record sets is H. Behling's (see Behling et al. 2004). The temperature records were downloaded from the World Data Center for Paleoclimatology (<http://www.ngdc.noaa.gov/paleo/icecore/antarctica/vostok>) in 2002.

Table 1. Description of palynological spectra used in the case examples. Vegetation classification and precipitation records follow Kühler (1990) and Trewartha (1990). Potential evapotranspiration records follow Trewartha (2001). Legend to symbols: T – Tundra; TR – Tropical rainforest; LSC – Lowland shrub conifer; TA – Taiga; AT – Alpine tundra; TDF – Temperate deciduous forest; ARA – Araucaria forest; TG – Tropical grassland; G – other grassland; XF – Xerophytic forest; TH – Thorn shrub; EAS – Eucalyptus, acacia shrub; EASC – EAS plus Conifer; MDSC – Montane desert shrub conifer; DS – Desert shrub. See addresses to contact persons and data sources in Footnote 1.

Location and contact person	Latitude Longitude Altitude m	Number of taxa Number of time steps	Period covered yr BP	Regional vegetation formation Annual precipitation (cm) Potential evapo- transpiration (cm)
1. Lagoa das Patas, Amazonas – P. E. Oliveira (Colinvaux et al. 1996)	00.16.00N 66.41.00W 300	179 49	0 - 44569	TR >200 120-160
2. Joe Lake, Alaska – P. M. Anderson (1988)	66.46.00N 157.13.00W 183	90 87	0 - 43804	T,TA 25-50 <40
3. Camel Lake, Florida – E.C. Grimm (Watts et al. 1992)	30.16.00N 85.01.00W 20	147 116	0 - 36658	LSC 100-150 80-120
4. Hanging Lake, Yukon Territory – L. C. Cwynar (1982)	68.28N 138.23W 500m	89 133	0 - 41134	T 25-50 <40
5. Jack London Lake, Magadan Oblast, Russia – P. M. Anderson (Lozhkin et al. 1993)	62.10.00N 149.30.00E 820	72 60	221 - 29876	AT,TA 25-50 <40
6. Jackson Pond, Kentucky – G. R. Wilkins (Wilkins et al. 1991)	37.27.00N 85.43.00W 212	71 58	0 - 20477	TDF 100-150 80-120
7. Cambará, Rio Grande do Sul, Brazil – H. Behling (Behling et al. 2004)	29.03.09S 50.06.04W 1046	164 190	0 - 42784	ARA,G 150-200 80-120
8. Lake Patzcuaro, Michoacán de Ocampo, Mexico – W. A. Watts (Watts and Bradbury 1982)	19.35.00N 101.35.00W 2044	53 64	20 - 44100	XF 50-100 120-160
9. Rusaka Swamp, Burundi – R. Bonnefille (Bonnefille et al. 1995)	03.26.00S 29.37.00E 2070	179 141	796 - 11910 (46666)	TG,TH 50-150 120-160
10. Lynch's Crater, Queensland, Australia – A. P. Kershaw (1994)	17.22.00S 145.42.00E 760	22 44 (234)	868 – 40000 (-192649)	EAS 50-150 120-160
11. Harberton, Tierra del Fuego – V. Markgraph (no reference given).	54.53.00S 67.10.00W 20	33 81	0 - 13360	DS 25-50 80-120
12. Lake George, NSW – G. S. Hope (Singh and Geissler 1985)	35.05.00S 149.25.00E 673	93 30 (68)	1 – 40000 (116711)	EASC 25-100 80-120
13. Potato Lake, Arizona – R. S. Anderson (1993)	34.27.43N 111.20.43W 2205	77 61	1389 - 35271	MDSC 25-50 80-160
14. Hay Lake, Arizona – B. F. Jacobs (1985)	34.00.00N 109.25.30W 2780	44 46	106 - 44692	MDSC 25-50 80-160

The noise-like data oscillations can come from a multiplicity of sources (Orlóci et al. 2002). We mention the main ones:

(1) *Broad geographic base.* Pollen, spore, and algal cells can originate outside the site or even beyond the immediate region. What is adding further to the problem is the

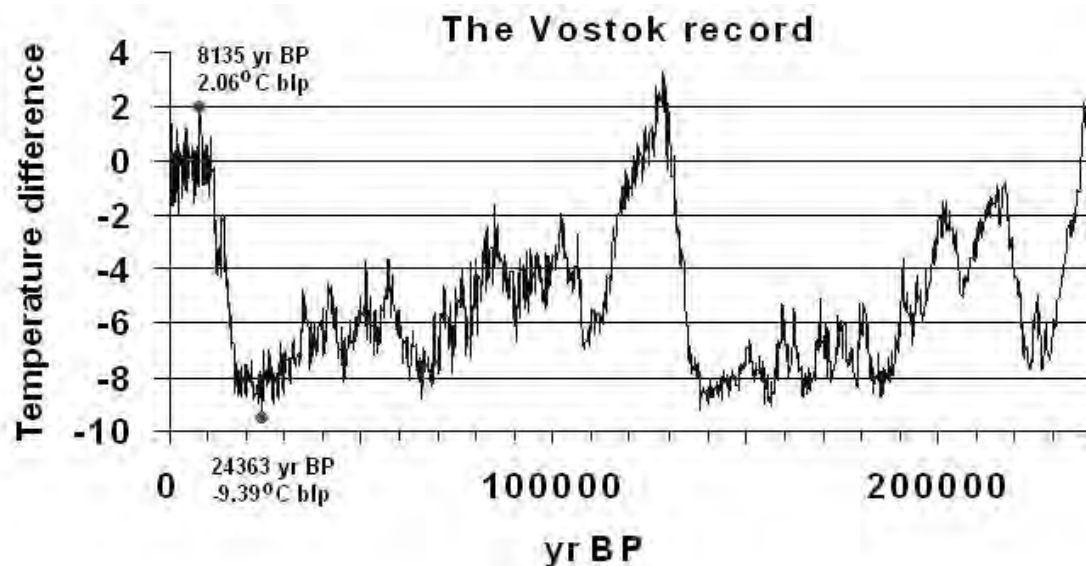


Figure 1. Inversion layer temperature oscillations expressed as differences from present, following Petit et al. (1999). Temperature values are deuterium based from ice core at Vostok, Eastern Antarctic (78° S, 106° E). Zero point on the temperature scale corresponds to the current state of deuterium in the higher atmosphere. See the text, for further details.

common presence of exogenous materials that cannot be separated from the materials originated in the site. These all but rule out inferences of a local nature that will not apply also in the broader geographic area. Charcoal macro particles and other plant remains are the exceptions that may have more definitely local origin.

(2) *Plant type identification.* Pollen, spore, cell, or other plant tissue is identifiable with only limited taxonomic accuracy in most cases. An inevitable consequence of this is the mixing of taxa from different systematic levels in the same sample. This blurs the specificity of statistical inference.

(3) *Site selection, sediment sampling, extraction of organic remains, dating.* Each of these is an error source in itself specific to the technique used and also to the implementation of the techniques. We discuss some implications in the present paper and refer to work by others for additional details and references (Libby 1955, Lowe and Walker 1997, and Orlóci et al. 2002). The reader is referred to the original web files (see footnote 1) regarding the dating method used. The approach is far from being uniform. It involves mostly linear and low order polynomial interpolation between the radiocarbon dates. Linear extrapolation is common, and occasionally the extrapolation is based (dubiously) on polynomials. In at least one case (Cambará) calibration of the radiocarbon dates is available (see Appendix 5, for details). We assumed that in all other cases uncalibrated dates were given, since no

“calibration” is mentioned. We used uncalibrated dates in the Cambará sample.

We make a distinction between two main sources for noise-like data oscillations. One includes *chance events* and the other includes *bias*. The chance events have to do with pollen and spore production, transport, sedimentation, preservation, and like events. *Bias* comes as part and parcel of personal choices made when siting sediment cores and locating sediment samples, committing mistakes of a systematic nature in taxon identification, erroneously logging measurements. The chance related noise can be handled as part of the symmetric error terms of variation and controlled by the usual tools of statistical design and analysis. Bias cannot be handled this way. It should be avoided with foresight. We present in this paper a technique for noise dampening when the noise is chance related. The user should keep it in mind that for a whole spectrum of sources the errors may intensify by non-linear feedback in system components’ behaviour, the case of the fractal (Orlóci 2001) and accumulate to produce extreme chaotic dynamics (Anand 2000). We do not deal with the problem of measuring that kind of feedback in this paper, but we are confident that the ‘scaling’ method we present can be extended to handle the problem reasonably well (Orlóci et al. 2002).

Regarding our source for atmospheric temperature records we mention that the choice of Vostok is forced upon us by circumstance. Why did we choose Vostok? The first

thing to be observed about this is the non-existence of other sources to our knowledge for long-term temperature records in the range we specified anywhere in the sites. The choice is thus reduced to one source out of two: Greenland or Vostok. When we tested Vostok, we obtained sensible results. The Greenland record appeared ill-conditioned and did not produce an interpretable outcome. We mention further in support of Vostok, findings in two paleoclimatic and deep ocean studies of Stocker (2000) and Clark et al. (2002). According to these studies, changes in the Polar climates have wide rippling effects in the global atmosphere, possibly with a millennial scale asynchrony for abrupt and delayed warming events in Greenland compared to the Antarctic (Blunier and Brook 2001). We interpret this as being supportive of the global synchronicity hypothesis regarding atmospheric oscillations across the globe, even though the magnitude of oscillations can be different at different sites. Other impressive aspects offering further support to our use of Vostok include the long sampling period and relatively high sampling intensity; the known geographic correlation of deuterium content and temperature in the high atmosphere where precipitation forms (Schweingruber 1996); and the reasonably close reproducibility of Vostok temperature patterns by records taken elsewhere from glacial ice, terrestrial sediments and deep-sea deposits (Petit et al. 1999,

Stocker 2000). For further details regarding temperature inferences from the isotopic content of ice, and the determination of ice age by the combined ice-flow ice-accumulation model, we refer to Petit et al. (1999) and Lorius et al. (1985).

Method components and numerical examples

With constraints as given, it may appear hopelessly risky to expect much from statistical analysis, if it requires “clean data” that the mathematically “neat” classical statistical techniques stipulate (Orlóci 1993). Fortunately, there are effective ways to ease the constraints and to find answers to such pointed questions as we will phrase concerning the synchronicity of change in palynological composition and in environmental forcing, formation specificity of synchronicity, and the siting of hot spots of change. But, before we can precisely pose these questions, we need to describe the essentials of the methodology.

Compositional transition scalars

$V = \frac{d}{\Delta t}$: average compositional transition velocity over time period Δt ; always positive; interpretable as average instability in the site’s palynological composition.

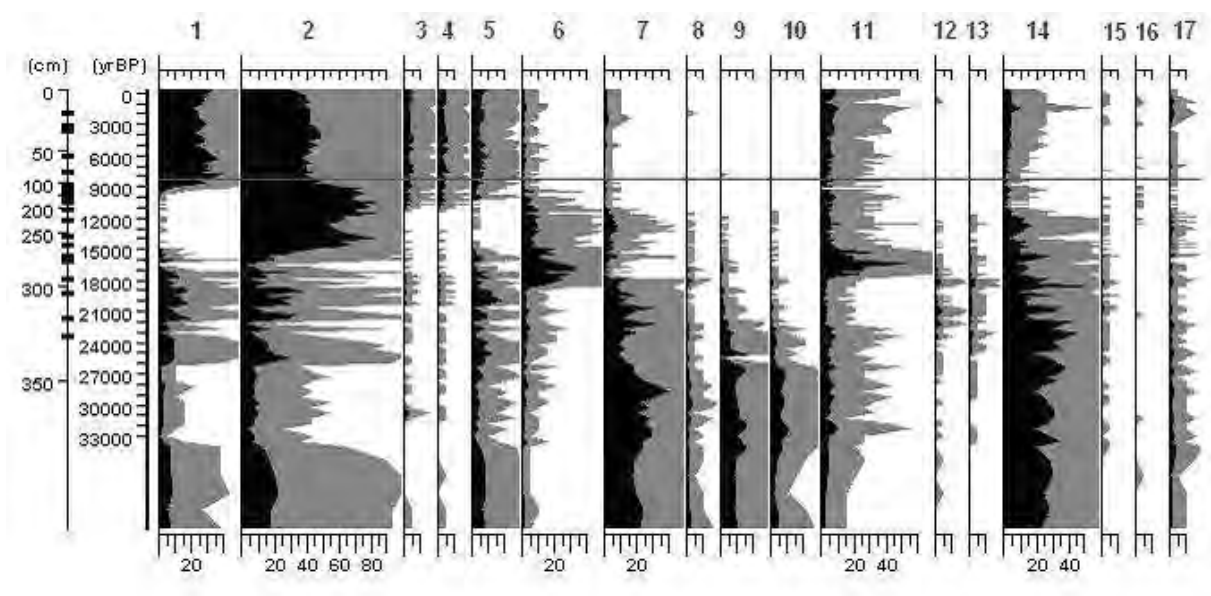
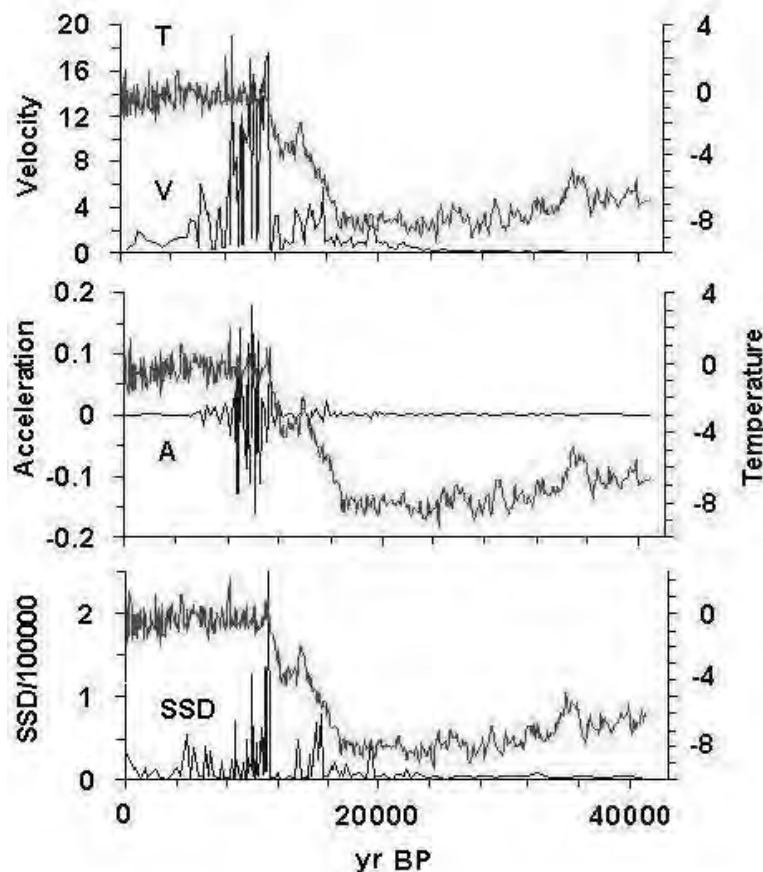


Figure 2. Cwynar’s (1982) palynological records from Hanging Lake, Yukon Territory. Sample and location are described in Table 1. Graph and accompanied data were downloaded from the Global Pollen Database (see the main text for web address). Short listed taxa after L.C. Cwynar: 1 *Alnus*, 2 *Betula*, 3 Ericaceae, 4 Ericales, 5 *Picea*, 6 *Salix*, 7 *Artemisia*, 8 Asteraceae-Asteroidae, 9 Brassicaceae, 10 Chenopodiaceae/Amaranthaceae, 11 Cyperaceae, 12 Fabaceae, 13 *Plantago canescens*, 14 Poaceae, 15 Rosaceae, 16 Other trees and shrubs, 17 Other herbs. Bottom scale: pollen counts %. Dark shading: original scale. Light shading: 5× exaggerated scale. Black markings on depth scale: dated horizons. Horizontal line inside graph demarks a record set called *paleorelevé*. This is the virtual equivalent of the regional vegetation community 8200 years BP.

Figure 3. Vostok temperature differences (T), compositional transition velocity (V), acceleration (A), and squared compositional deviation (SSD) from random expectation over time (yr BP) for L.C. Cwynar's Hanging Lake record sequence (Fig. 1). Appendix 1 contains the graphs for all sites. Horizontal axis: time before present. Time begins at top sediment horizon. Some details and references are given in the main text. Petit et al. (1999, 2000, 2001) describe details of the temperature records.



d : Euclidean distance of two paleorelevés time units apart. The “paleorelevé” is an ecologist’s term for the palynological record-set for a given horizon of the sediment core (horizontal line inside Fig. 2).

$A = \frac{V_{t+\Delta t} - V_t}{\Delta t}$: average compositional transition acceleration (when positive) or deceleration (when negative); interpretable as the amount of change in compositional stability over time period Δt .

Extreme peaks in the A graphs of Fig. 3 and Appendix 1 identify time points of dramatic change in palynological composition. We refer to the extreme peaks as *hotspots of change*.

Synchronicity scalar

$$r(V, T) = \frac{\sum_i (V_i - \bar{V})(T_i - \bar{T})}{\sqrt{\sum_i (V_i - \bar{V})^2 \sum_i (T_i - \bar{T})^2}} :$$

as written, a product moment correlation of compositional transition velocity V and atmospheric temperature oscillations T .

\bar{V}, \bar{T} : averages of the entire V, T sequence.

The product moment has its advantages/disadvantages (Orlóci 1978), but if users prefer other synchronicity measures in the -1 to 1 range the analysis can accommodate them. Whatever the case, the $r(V, T)$ values are best not to be calculated directly from the original V and T records of the graphs, but from the adjusted values after error dampening. Our method of error dampening is based on moving averages. The technique is best explained by example as in Table 2.

F^+, F^- : the synchronicity scalar’s sign frequency distribution; interpreted as the tendency of $r(V, T)$ to be negative or positive under chance ruled sampling of the same V, T sequence. For this, the $n-BS+1$ valued time series of running averages is re-sampled by way of randomly laid sub series of random length (minimum 5 and maximum $n-BS+1$ units); a new value of $r(V, T)$ is computed for each sub series; and by repeating the process a large number of times the frequencies of negative (F^-) and positive (F^+) $r(V, T)$ are found.

The magnitude of $r(V, T)$ and the nature of its sign frequency distribution are key characteristic of the palynological process. Strong positive synchronicity is indicated when $r(V, T)$ is positive and numerically large.

Table 2. Calculation of moving averages. Block size starts at step size 1, incremented in units of one (on time axis). In general terms, there are $BS = 1, 2, 3, \dots, M < n$ block sizes and for each block size $n - BS + 1$ moving averages. We chose not to have an M value larger than 40 in long series. In the example above, $n = 10$ and $M = 4$. The extreme right column in the table contains the values of the synchronicity scalar.

Block size (BS)	Variable	Values of V and T at time points before present										$r(V, T)$
		1	2	3	4	5	6	7	8	9	10	
1	V	3	3	5	6	6	1	4	8	3	9	0.963
1	T	-1	-2	3	4	4	-3	1	5	0	6	
2	V	3	4	5.5	6	3.5	2.5	6	5.5	6	0.963	
2	T	-1.5	0.5	3.5	4	0.5	-1	3	2.5	3		
3	V	3.7	4.7	5.7	4.3	3.7	4.3	5	6.7	0.996		
3	T	0	1.7	3.7	1.7	0.7	1	2	3.7			
4	V	4.3	5	4.5	4.3	4.8	4	6	0.934			
4	T	1	2.2	2	1.5	1.8	0.8	3				

Table 3. Regression estimates and related statistics read off Fig. 4 and Appendix 2. See method and data details in the text. Symbols $V, T, r(V, T), \rho(V, T), R^2, \phi^+, \phi^-$, and BS are same as in Figs 3-4. Additional symbols: LL and UL – lower and upper limits of the 95% confidence interval about the regression estimate (normally distributed statistical errors are assumed); Thi – Thornthwaite index (precipitation per potential evapotranspiration); $CRVF$ – current regional vegetation formation; T – Tundra; TR – Tropical rainforest; LSC – Lowland shrub conifer; TA – Taiga; AT – Alpine tundra; TDF – Temperate deciduous forest; ARA – Araucaria forest; G – temperate grassland; TG – Tropical grassland; XF – Xerophytic forest; TH – Thorn shrub; EAS – Eucalyptus, acacia shrub; $EASC$ – EAS plus conifer; $MDSC$ – Montane desert shrub conifer; DS – Desert shrub.

Locality	$\rho(V, T)$	LL	UL	R^2	ϕ^+	ϕ^-	CRVT	Thi
Lagoa das Patas 00.16N 6.41W	0.12	-0.01	0.28	0.73	80.96	16.30	TR	>1.43
Joe Lake 66.46N 157.13W	0.35	0.30	0.40	0.98	80.90	16.76	T	1.88
Camel Lake 30.16N 85.01W	0.31	0.27	0.35	0.98	75.84	20.68	LSC	1.25
Hanging Lake 68.28N 138.23W	0.63	0.56	0.71	0.91	68.68	30.22	T TA	1.88
Jack London L. 62.10N 149.30E	0.11	0.02	0.20	0.98	65.08	29.16	AT TA	1.88
Jackson Pond 37.27N 85.43W	0.30	0.28	0.32	0.98	57.31	38.39	TDF	1.25
Cambará 29.03S 50.06W	0.53	0.50	0.56	0.95	56.63	32.77	ARA G	1.75
Lake Patzcuaro 19.35N 101.35W	0.60	0.50	0.70	0.78	52.79	41.25	XF G	0.54
Rusaka Swamp 3.25S 29.37E	0.23	0.17	0.24	0.86	46.84	39.99	TG TH	0.71
Lynch's Crater* 17.22S 145.42E	-0.66	-0.70	-0.62	0.74	42.62	55.08	EAS	0.71
Tierra del Fuego 54.53S 67.10W	-0.25	-0.37	-0.15	0.55	33.64	63.71	DS	0.36
Lake George* 35.05S 149.25E	-0.48	-0.99	-0.28	0.57	15.12	84.32	EASC	0.63
Potato Lake 37.27N 111.20W	-0.31	-0.42	-0.19	0.86	11.15	84.91	MDSC	0.31
Hay Lake 34.00N 109.25W	-0.23	-0.34	-0.12	0.85	4.74	93.91	MDSC	0.31
<i>Mean (positive)</i>	0.35	0.29	0.42	0.91	65.00	29.50		1.39
<i>Mean (negative)</i>	-0.39	-0.56	-0.27	0.71	21.45	76.39		0.46
<i>Grand mean</i>	0.09	-0.02	0.17	0.84	49.45	46.25		1.04

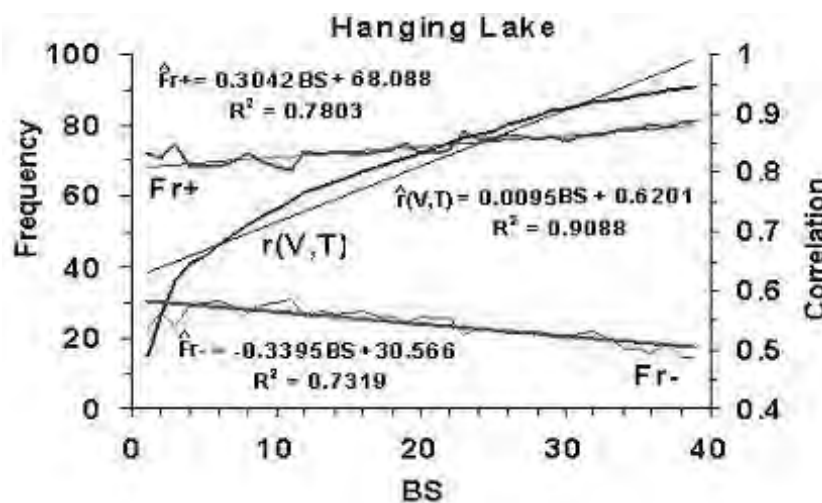
Correlation values: $\rho(V, T) \times Thi = 0.621$; $\phi^+ \times Thi = 0.821$; $\phi^- \times Thi = -0.804$.

* Current 40 k yr period analysed.

Table 4. Calculations at $Lag = 0, 1, 2, 3$. The basic data come from rows $BS = 1$ in Table 2.

Block size (BS)	Lag	Variable	Values of V and T at time points before present										$r(V,T)$
			1	2	3	4	5	6	7	8	9	10	
1	0	V	3	3	5	6	6	1	4	8	3	9	0.963
1		T	-1	-2	3	4	4	-3	1	5	0	6	
1	1	V	3	3	5	6	6	1	4	8	3		-0.186
1		T	-2	3	4	4	-3	1	5	0	6		
1	2	V	3	3	5	6	6	1	4	8			-0.174
1		T	3	4	4	-3	1	5	0	6			
1	3	V	3	3	5	6	6	1	4				0.028
1		T	4	4	-3	1	5	0	6				

Figure 4. Graphical outline of the regression method for estimation of stable synchronicity and frequency values. Symbols: V - compositional transition velocity; T - Vostok temperature; BS - block size for averages; F^+ and F^- - sign frequencies; $r(V,T)$ - synchronicity; R^2 - coefficient of determination; $\rho(V,T) = 0.63$, $\phi^+ = 68$; $\phi^- = 30$ - stable estimates at $BS = 1$ based on the regression equations; heavy lines - values derived from moving averages; light lines - fitted regression lines for the equations. See explanations and references in the main text. The numerical results are summarised in Table 3.



Formation specificity is indicated when one of F^+ , F^- is dominant (see following explanations).

Stabilisation of the synchronicity scalar and its sign frequencies

A new $r(V,T)$ value is calculated from moving averages at each BS . There are M new $r(V,T)$ values to which we fit line $\hat{r}(V,T)$ (see Fig. 4 and Appendix 2). We take $b+a$, the regression estimate of the current synchronicity value at $BS=1$, as the “stable” synchronicity estimate $\rho(V,T)$. We do similar calculations with the sign frequencies to obtain the stable estimates ϕ^+ and ϕ^- . The sample values are summarised in Table 3.

Determination of ϕ^+ and ϕ^- in the time shifted V and T series

Until this point we retained a time equivalent pairing of the V and T values. Now we pose the question: what

will happen to ϕ^+ and ϕ^- if we shifted the T series forward in time (left in the V,T graphs) so that the time lag of the V and T values paired widens from 0 to 1 then to 2, 3, and so forth in millennial steps. To illustrate this, we take the example of Table 2 and define $Lag = 0, 1, 2, 3$ for $BS = 1$ in Table 4. This is done in the same manner to each of the remaining $BS = 2, 3, 4$. At each Lag , we re-compute the $\rho(V,T)$, ϕ^+ and ϕ^- estimates for $BS=1$ in the same manner as already described. The basic graphs that result in the Hanging Lake case are in Fig. 5 and all the graphs in Appendix 3. The dominant stable sign frequencies are identified in Table 5.

Deviations from random expectation

$$D_{ij} = X_{ij} - e_{ij}, \text{SSD}_j = \sum_i D_{ij}^2, e_{ij} = \frac{X_{i.} X_{.j}}{X_{..}}$$

e_{ij} - random expectation, a compositional state that would occur if a chance ruled process were generating pa-

Table 5. Identification of dominant stable sign frequencies at $BS = 1$ of the synchronicity scalar at different *Lag* (thousand year units). See the method description in the text. Dominant ϕ^+ is indicated by + and dominant ϕ^- by -. Lag code is $Lag/1000$. Symbols in bold face identify points at which the dominant sign frequency or correlation change direction considerably (hotspots). Note the robust adherence of the sites to their value at $Lag = 0$ up until about $Lag = 10$ k yr or even longer, except for the transitional cases 8, 9, and unexpectedly 6. Legend to columns: 1 - Lagoa das Patas, 2 - Joe Lake, 3 - Camel Lake, 4 - Hanging Lake, 5 - Jack London L., 6 - Jackson Pond, 7 - Cambará, 8 - Lake Patzcuaro, 9 - Rusaka Swamp, 10 - Lynches' Crater, 11 - Tierra del Fuego, 12 - Lake George, 13 - Potato Lake, 14 - Hay Lake.

Lag code	Location 1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	+	+	+	+	+	+	+	+	-	-	-	-	-	-
2	+	+	+	+	+	-	+	+	-	-	-	-	-	-
3	+	+	+	+	+	-	+	+	-	-	-	-	-	-
4	+	+	+	+	+	-	+	+	-	-	-	-	-	-
5	+	+	+	+	+	-	+	-	-	-	-	-	-	-
6	+	+	+	+	+	-	+	-	-	-	-	-	-	-
7	+	+	+	+	+	-	+	-	+	-	-	-	-	-
8	+	+	+	+	+	-	+	-	-	-	-	-	-	-
9	+	+	+	+	+	-	+	-	-	-	-	-	-	-
10	+	+	+	+	+	-	+	-	-	-	-	-	-	-
11	+	+	+	-	+	-	+	-	-	-	-	-	-	-
12	+	+	-	-	+	+	+	-	-	-	+	-	-	-
13	+	0	-	-	-	+	+	-	-	-	-	-	-	-
14	+	0	-	-	-	+	+	-	-	-	-	-	-	-
15	+	0	+	-	-	+	+	-	-	-	-	-	-	-
16	+	0	+	-	-	+	+	-	-	-	-	-	-	-
17	+	0	+	-	-	+	+	-	-	-	-	-	-	-
18	+	0	+	-	-	+	+	-	+	-	-	-	-	-
19	-	0	+	-	-	+	-	-	-	-	-	-	-	-
20	-	0	+	-	+	+	-	-	-	-	-	-	-	-
21	-	0	+	-	+	+	-	-	-	-	-	-	-	-
22	-	0	+	-	-	+	-	-	-	-	-	-	-	-
23	-	0	+	-	-	+	-	-	-	-	-	-	-	-
24	-	0	+	-	-	+	-	-	-	-	-	-	-	+
25	-	0	+	-	-	+	+	-	-	-	-	-	-	+
26	-	0	+	-	-	+	+	-	-	-	-	-	-	+
27	-	-	+	-	-	+	+	-	-	-	-	-	-	+
28	-	-	+	-	-	+	+	-	-	-	-	-	-	-
29	-	-	+	+	-	+	+	-	-	-	-	-	-	+
30	-	-	-	+	-	+	+	-	-	-	-	-	-	+
31	-	-	-	-	-	+	+	-	-	-	-	-	-	-
32	-	-	-	-	-	+	+	-	-	-	-	-	-	-
33	-	-	+	-	-	-	+	-	-	-	-	-	-	-
34	-	-	-	-	-	-	+	-	-	-	-	-	-	-
35	-	-	-	-	-	-	-	-	-	-	-	-	-	-
36	-	-	-	-	-	-	-	-	-	-	-	-	-	-
37	-	-	-	-	-	-	-	-	-	-	-	-	-	-
38	-	-	-	-	-	-	-	-	-	-	-	-	-	-
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40	-	-	-	-	-	-	-	-	-	-	-	-	-	-

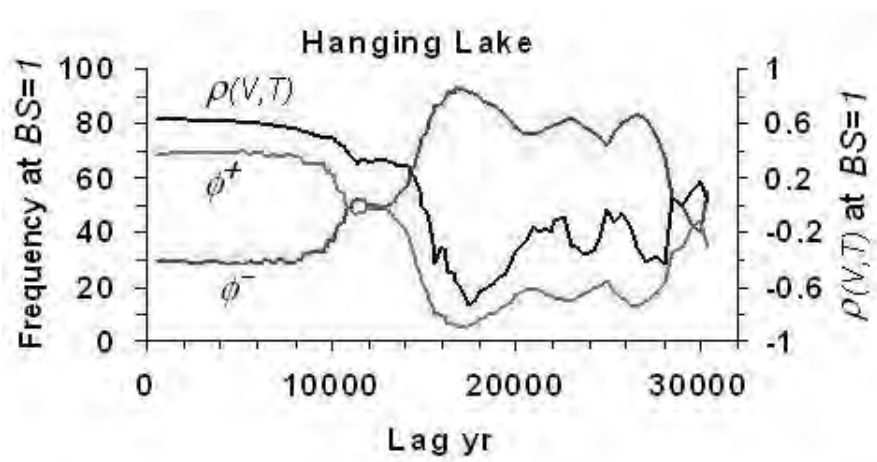


Figure 5. Lag dependent values of $\rho(V,T)$, ϕ^+ and ϕ^- graphed for the entire period in the Hanging Lake site. *Lag yr* indicated the number of years the temperature series is shifted to the left in Fig. 1 before repairing the T and V values. $\rho(V,T)$, ϕ^+ and ϕ^- are estimates at $BS = 1$. See main text, for method and comments.

Table 6. Hotspots detection based on peaks in compositional transition acceleration (A graphs) and extreme deviation from random expectation (SSD). Time points at which the extreme peaks occur are in $yr BP$ columns. See definitions and discussion in the text.

Palynological sequence	Extreme A	$yr BP$	Extreme SSD	$yr BP$
Lagoa das Patas	0.00168	16380	35788; 23468	5523; 12122
Joe Lake	0.0211	10730	503291	10570
Camel Lake	0.511	11143	3617503	13040
Hanging Lake	0.179	9998	2592547	11287
Jack London L.	0.721; 1.908	9040; 11980	5.8×10^8	12074
Jackson Pond	0.407; 0.373 ; 0.0276	58; 135; 10673	87218	10857
Cambará	0.1; 0.1; 0.262; 0.182; 0.00376	33; 673; 783; 928; 19852	335173	12368
Lake Patzcuaro	0.00555; 0.00633	21476; 42759	20972	15396
Rusaka Swamp	0.0354; 0.0179; 1.208; 0.0217	1040; 7088; 9140; 10280	492284; 294125	45513; 28210
Lynches Crater*	0.000154; 0.000114; 0.00142	14112; 118868; 164821	792587; 629056	900; 32732
Tierra del Fuego	0.394	9568	515049; 340976	12849; 10947
Lake George*	0.0261; 0.265	8470; 47411	47901238	34379
Potato Lake	0.0105; 0.00685	1471; 17641	1845477	17236
Hay Lake	0.159; 0.428; 0.169	2235; 19154; 42511	73725; 50529	42511; 10003

*Current 40 k yr.

lynological composition; X_{ij} - a quantity of taxon i (pollen, spore, algal cell count) at time step j . A dot subscript indicates summation over the subscript that it replaces. We should mention that a zero X_{ij} will always have an associated D_{ij} value less than zero. We used SSD in the graphs of Fig. 3 and in Appendix 1. We construct the taxon specific graphs of D_{ij} (Fig. 6 and in Appendix 4). We are now ready to address the detection of hotspots and other characteristic points on the time axis.

Detection of hotspots and other characteristic points on the time axis

The indicator value of extreme peaks in the A graphs was mentioned, and the potential of the SSD graphs is obvious. The details are given in Table 6. Clearly, hotspot dating by locating extreme peaks on the A and SSD graphs is an analogue of edge detection (Orlóci and Orlóci 1990), in search of boundaries that separate qualitatively different segments within long ordered series.

We continue with considerations of specific aspects of the V , A , SSD and D^2 graphs in Fig. 6 and Appendix 4.

Hanging Lake. Observing the great age of the sediments, clearly, the site remained essentially unperturbed by glacial ice for at least forty millennia. The V , A , and SSD graphs (Fig. 3) remain flat and low close to the zero level during the period of dominant climate cooling. Low and flat graphs testify to a low intensity, highly stable palynological process. Then sharp oscillations begin to ap-

pear, heralding the advent of a period of intense dynamics, i.e., high instability. The changeover occurs in the wake of climate warming (sharp ascent of the T graph) and culminates around 11 k yr BP. Considering the A and SSD graph peaks, maximum compositional dynamics is registered after rapid temperature increase, ending more than 20,000 years of high stability. The sharp deviation peaks (Figure 6 and Appendix 4) of asco (Fu) and goniidium spore types (Pe) is an indication of the lichen element reaching maxima in the middle period. Earlier Fu and Pe do not deviate much from random expectation in stark contrast with the performance of cold steppe elements such as the Poaceae (Po), *Artemisia* (Ar), *Chenopodium* (Ch), and Brassicaceae (Br), the taxa that very much outperformed random expectation during the early period. The advent of the Holocene saw higher temperatures accompanied by increasing humidity. A most remarkable indicator of this episode is the peaking *Sphagnum* (Sp) around 5000 BP. By that time peat bog formation must have reached maximum extent in the region. The extreme peaks allow delimitation of the vegetation formations that moved through the Hanging Lake site over the millennia. The following identify the principal ecological indicator taxa and corresponding community habitat type for per time period:

- Up to 19400 – Poaceae, *Artemisia*, *Brassicaceae*, *Chenopodium*; shrub steppe on windswept dry uplands.

- 19,400 to 11,300 – *Pediastrum* (alga, lichen component), *Betula*, *Botrychium*, Fungi (lichen component), *Poaceae*, *Salix*, *Cyperaceae*, *Picea*, *Equisetum*; lichen dominated taiga, swamps expanding.
- 11,300 to 5,000 – *Alnus incana*, *Picea*, *Ericales*, *Vaccinium*; taiga uplands. *Sphagnum*, azonal peat bogs.
- After 5,000 – *Betula*, *Alnus*, Fungi, *Cyperaceae*, *Picea*, *Ericales*, *Vaccinium*; the taiga.

Cambará. We consider next the events that occurred during the same period at the *Cambará* site on the Atlantic rim of the Highlands in Rio Grande do Sul. We observe the major SSD peaks (Appendix 1) subdividing the vegetation process into 4 temporal phases. The densely arranged peaks indicate a period of intense dynamics, beginning around year 21500 BP just before the Vostok graph starts its steep ascent. Considering the taxon graphs in Appendix 4, deviation peaks of the hydrophytes, such as *Isoetes*, *Botryococcus*, and *Sphagnum* indicate increased regional humidity. Interesting to note the increased representation of *Isoetes* around 26000 BP, concomitant in time with the sustained decline of grasses

(*Poaceae*). It is also interesting to note that *Isoetes* and the *Poaceae* reach bottom in negative deviation around 13000 yr BP when *Botryococcus* attains maximum deviation. The *Sphagnum* peak around 759 BP indicates maximum peat bog formation in the site. *Araucaria* (Pinophyta) comes into considerable prominence around 759 BP in the wake of forest expansion over grassland, which was likely consequence of a more humid regional climate (Behling et al. 2004) coupled with the spatial process of expansion itself related to availability of dispersal agents and proximity of the site to forest seed sources (Duarte et al. 2006). *Araucaria* is seen reaching maximum deviation around 560 BP by which time the representation of *Poaceae* has fallen off considerably. *Araucaria* continuously outperforms random expectation until about 100 years ago from which point on its representation rapidly declines under the loggers' axe. The concurrent anthropogenic effect is tantamount to a complete redoing of the Highlands vegetation landscape. We refer to Behling et al. (2004) for other details. The Late Quaternary paleoecological history of *Cambará* can be read as the temporal march of life-zones over the site. The following identifies the principal eco-

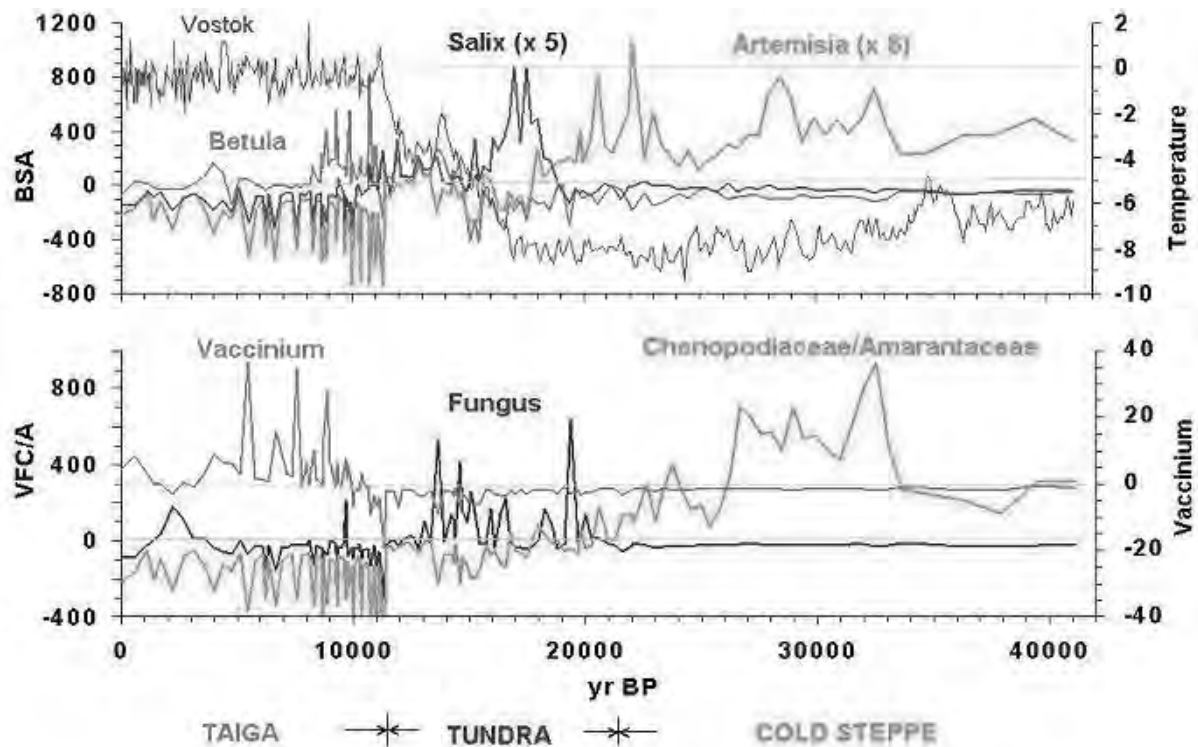


Figure 6. Vostok temperature (*T*) and deviation graphs for taxa as identified in Cwynar’s Hanging Lake data set. Horizontal line across the graphs at zero is the base line for random expectation on the taxon scales and for temperature corresponding to current deuterium content on the Vostok scale. Deviations of taxa above or below the zero line indicate over or under-representation of those taxa in palynological collection, relative to expectation. *TBP* is time before present. The following percentages indicate proportions of the total sum of squared deviation (*SSD*) accounted for by the individual taxa in the total sample: *Betula* 19.1%, Fungus (ascospores) 8.5%; *Artemisia* 2.2%; *Sphagnum* 1.5%; *Salix* 0.9%; *Chenopodiaceae/Amaranthaceae* 0.1%; *Vaccinium* 0.01%. See method and references in the text.

logical indicator taxa and the community habitat type per time period:

- Up to 26,000 – Poaceae (zonal upland treeless Campos); *Myriophyllum* and *Isoetes*; azonal, shallow permanent ponds, mud flats.
- 26,000 to 11,500 – *Eryngium* (Apiaceae, a perennial semi-shrub), *Blechnum* (Blechnaceae) and *Poaceae*; zonal upland treeless Campos. *Botryococcus*; azonal mudflats; *Myriophyllum* and *Isoetes*; azonal, shallow permanent ponds.
- 11,500 to 758 – Poaceae, *Eryngium*; zonal upland Campos). *Sphagnum*, *Blechnum*; azonal peat bog. *Araucaria* increases and Poaceae decreases below expectation after 2000 BP.
- 758 to 100 – *Araucaria*; zonal treed upland. *Sphagnum*; blanket bog, peat bog.
- After 100 – Anthropogenic parkland, much of it under grazing. Reduced Poaceae and *Araucaria*; increased *Mimosa* and *Eryngium*; reduced *Sphagnum*.

The synchronicity results for V with the time shifted temperature series T can be used to find significant points at which a type of linkage to the past fades or changes direction considerably. These are the points where the serial lag-dependent (time shifted) graphs reach extreme points (Fig. 5, Appendix 3, Table 5) and the associated ϕ^+ and ϕ^- graphs come close together or even cross paths. We note that in the case of truncated cores, such as at Russaka Swamp, the Table 5 records should be referred back to the graphs in Fig. 5 and Appendix 3 for clarification.

Discussion

We begin by revisiting our reasons of the choices that determined the outcome. The decisions involve statistical technicalities and data aspects. We agree with those who warned us that the condition of the data, in the acquisition of which we had no control, could cast doubt on the paleoecological conclusions. But the methodology we introduce is different. It stands on its own internal logic and its suitability for the stated objectives.

Regarding the choice of palynological data, we preferred cases with long period length and rich lists of low-level taxa. Since the number of qualifying spectra is rather limited, the representation of the major vegetation formations is disproportionately heavier in the America's than on the other continents. This fact noted, we believe the 14 sites satisfy amply the requirement for a successful exposition of the power of our analytical approach. We mentioned reliability. In statistical analysis this will be eroded

in proportion of the peculiar error properties of the data. We assume that sampling and measurement errors in the course of the original data acquisition do not exceed usual scientific standards. The choice to reach for a proxy model of long term atmospheric oscillations could not be avoided. We opted for the Vostok temperature records, relying on arguments put forward by us and others. Regarding the analysis, we can add to the arguments yet another point. This is our success to show linkages that certainly meet common sense expectation, which we consider as positive reflection back upon the suitability of the Vostok temperature oscillogram as a proxy for atmospheric temperature oscillations at the sites. The choice of transition scalars requires further comments:

1. Compositional transition velocity is proven, through the measurement of synchronicity, to be a reliable indicator of process sensitivity to environmental forcing. Ideally the synchronicity scalar should be partitioned according to the main effects, conditional effects, and interaction of several factors. But where should the data come from for this? We found long term records only for temperature.
2. Regularities found in velocity oscillations with regard to temperature oscillations indicate that global governing principles exist. But they do not indicate that these are exclusively climate related.
3. The significant departure of our results from random expectation on all levels almost in all the cases is an important, albeit not unexpected finding. Stated in other words, compositional transitions have levels of determinism and for that reason predictability, but never free of chance effects.

The general picture drawn about linkages of change in palynological composition and environment is a portrayal of tendencies played out in the past. The numerical results present interesting facts about these tendencies. Considering synchronicity and synchronicity scaling based estimation, and considering the determination of sign frequency distributions, the numerical results provide clarification of an important tendency: increasing atmospheric aridity (decreasing Thornthwaite index based on current evapotranspiration and precipitation rates) in tandem with decreasing values of ϕ^+ . The statistical linkage shown could appear coincidental if it were not for the fact that the amplitude of environmental change at sites did not attain opposite extremes in aridity during the last 40 k yr. When the analysis is performed over a much longer period, such as in the case of Lynches' Crater, a different picture emerges. The 0 to 40 k yr BP period is dominated by ϕ^- and the 129 k to 190 k yr BP period is dominated by ϕ^+ as if a moister climate had existed earlier in that part of

Australia. To emphasize the climatic connection, it is interesting to mention the compositional change in the palynological spectrum after 129 k yr BP, highlighted by reduction in pollen counts of the Cunoniaceae (tropical trees), the lowland forest trees, the montane forest trees, the Cyatheae (tree ferns), and epiphytic Polypodiophyta, in contrast with the noted increase of *Agathis* (broad leaf conifer), Arecaceae (palms), dry forest trees and shrubs, and Poaceae which we found named in original records (Kershaw 1994). There are volumes of discussion about climate change in Australia during the last 200 k yr (Kershaw et al. 2002, Bowman 1998), but the details in that regard are outside the intended contents of this paper.

Compositional change, a permanent feature in the palynological spectra, at some points in time becomes extreme. The extreme points are indicated by spikes of acceleration (*A*) and deviations (*D*) from random expectation. We used Hanging Lake and Cambará as examples to illustrate this. The spikes clearly show extreme vegetation instability at the beginning of the current Interglacial from about 11 k yr BP until about 8 k yr BP. Maximum is reached around 10 k yr BP. The instabilities are climate related, but not necessarily uniquely climate defined.

Beyond local specificity, there is high-level coincidence in hotspots timing among the sites. Maxima around 10 k yr BP just after a steep millennial ascent of the Vostok temperature gradient, and again around 15 k yr BP and 20 k yr BP under similar settings is seen clearly in the graphs. Well defined hotspots occur in the immediate past at Jackson Pond (<200 yr BP), Cambará (<800 yr BP), and with one order of magnitude less intensity at Rusaka Swamp (<100 yr BP) and Potato Lake (<1500 yr BP). Increased frequency of fire and range wide cattle grazing have been shown specifically as major forcing events at Cambará (Behling et al. 2004). The extreme *A* and *SSD* peaks testify to the extraordinary destabilising effects of events since 800, most clearly human occupation in the last 100 years.

Hotspots occur within a roughly 3 k yr interval from 12 k yr BP at Jack London Lake, Camel Lake, and Harberton (Tierra del Fuego), and less intensely at Joe Lake and Hanging Lake. At Lynches Crater hotspots are most prominent during an earlier Ice Age cycle before 130 k yr BP. Based on period segments bounded by hot spots, we can trace the march of vegetation formations in the sites. We did this for Hanging Lake and Cambará. What can we read from these? The formations become destabilised after even short periods of warming. How long lasting is the effect? This and other specific questions are addressed in the final section.

Formation specificity of the processes associated with indicators ϕ^+ and ϕ^- are not well understood. One could point to water and temperature as limiting factors, assuming globally synchronous cooling and warming periods over the timeframe used and the resolution scale variable (*BS*). One of the suggestions is that warming in humid zones speeds up the ecosystem processes and hence promotes vegetation change, while in atmospherically arid zones it does the opposite by aggravating water stress. Another suggestion is that changes in precipitation are inherently linked to changes in temperature (Wang et al. 2004), with opposite tendencies in the humid and arid zones: increasing the precipitation in the currently humid zones and decreasing it in the currently arid zones. It is true that fire history cannot be dismissed in arid zones as an influential factor, but as seen by Kershaw et al. (2002) it is difficult if not impossible to separate fire from climate. It makes sense to assume that climate change determines changes in fire regime. But anthropogenic ignition sources are important. The proposition that the time of the arrival of humans in a continent or island may be detected from aberrations in the ϕ^+ graphs appears confirmable.

Closing remarks

We return to our objectives and the objects of the core analysis: the *V* and *A* graphs; the synchronicity graphs computed from moving averages over *BS*; deviations graphs specific to *BS*; the graphs of $\rho(V,T)$, ϕ^+ and ϕ^- at *BS* = 1 either as single values or as graphs. Now we will use what we so far presented to answer in brief specific questions we put about the palynological process:

Can the synchronicity of V and T be considered significant? Observe the 95% confidence limits in Table 3. Consider also that any estimate is deemed significant when the confidence limits do not enclose zero. Based on these conclude that compositional transitions have significant synchronicity with atmospheric temperature oscillation in all cases except one.

Are $\rho(V,T)$, ϕ^+ and ϕ^- sensitively linked to the Thornthwaite Index? Observe $\rho(V,T) \times ThI = 0.621$, $\phi^+ \times ThI = 0.821$, $\phi^- \times ThI = -0.804$ in Table 3 and conclude the presence of highly sensitive linkages.

Is synchronicity a current formation specific property of historic compositional transitions? Observe the distributions of ϕ^+ and ϕ^- in Tables 3 and 5 and the strong tendencies: dominance of ϕ^+ in the currently humid formations and same of ϕ^- in the currently arid formations. Conclude current formation specificity and conclude further a tendency of resistance against formation disintegra-

tion at levels of climate forcing characteristic in the Late Quaternary.

What about destabilisation? We interpret the previous tendencies as an indication that climate warming destabilises vegetation composition more readily in sites within the current climatically humid regions than in sites within the current climatically arid regions.

What about the temporal hotspots of change? The *A*, *SSD*, and *D* graphs presented reveal maximal transition dynamics in the wake of dramatic change in the environment. Climate warming and human activities figure as important triggers.

Does atmospheric temperature change have lasting effects on synchronicity? The evidence presented helps the reader to trace the serial correlation pattern of the *V* curve fixed in position and the *T* curve moved forward in time steps. Up to 10 k yr BP lag and in some cases much longer, there appears to be no change in frequency dominance relative to current formation type, except in the transitional cases which we already identified. How to interpret this? Dominance is a robust property of compositional change. To alter it, substantial forcing has to occur in the formation's climate. Our use of a minimum lag of 1 k yr should be considered further. At this minimum lag the observed stability in forward synchronicity is related to climate changes within the glacial cycle. For detecting whether synchronicity is stable at finer time scales, the minimum lag used in the analysis should be shorter, but then we would be limited by the time resolution constraint of the available data.

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Appendices

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Appendix EA7-1. Vostok temperature differences, compositional transition velocity, acceleration, and sums of squared compositional deviation from random expectation over time.

Appendix EA7-2. Graphical outline of the regression method for estimation of stable synchronicity and frequency values.

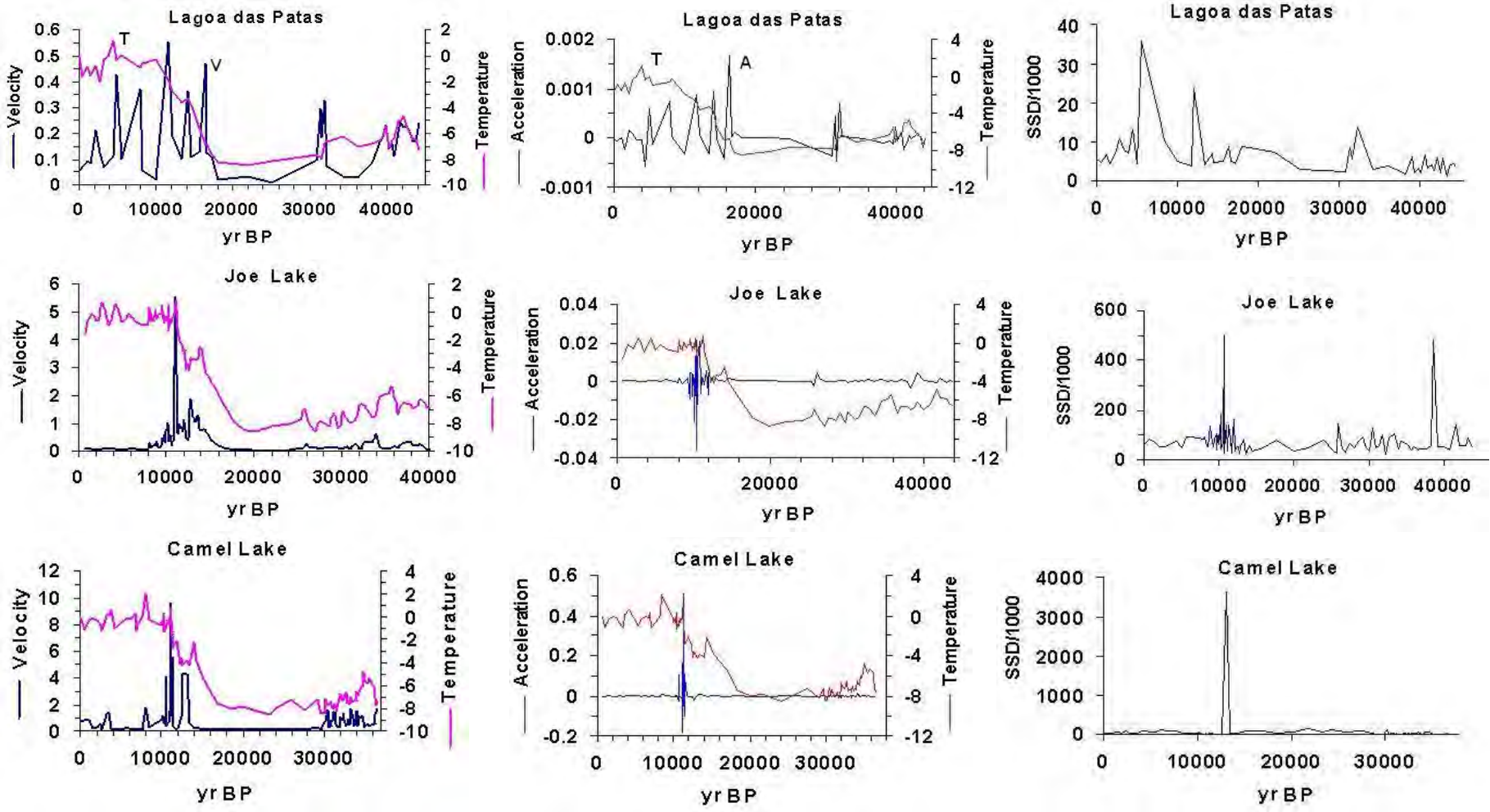
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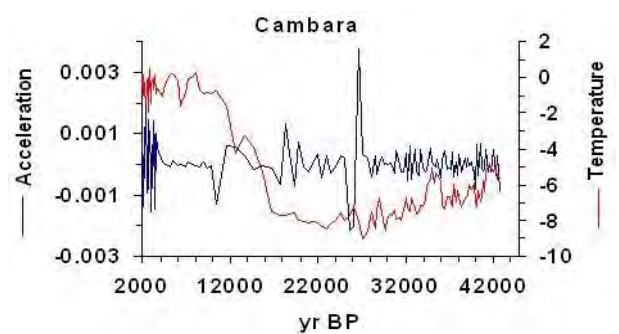
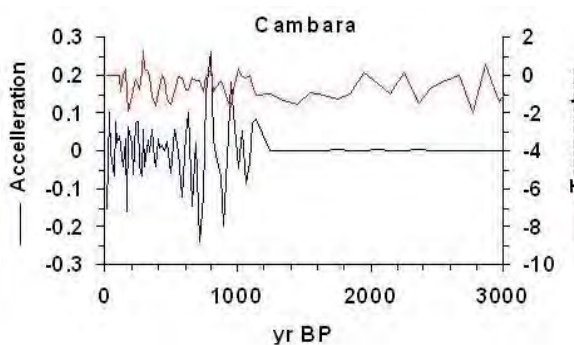
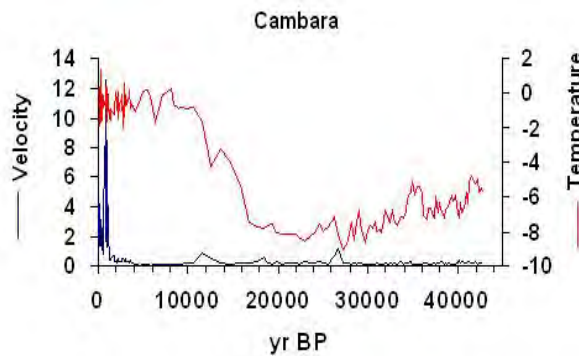
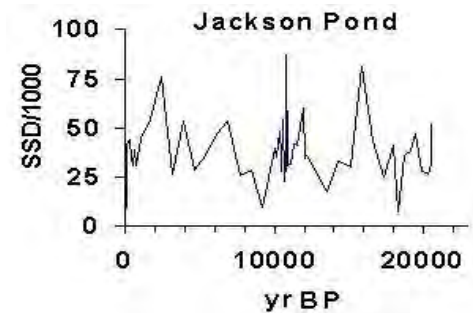
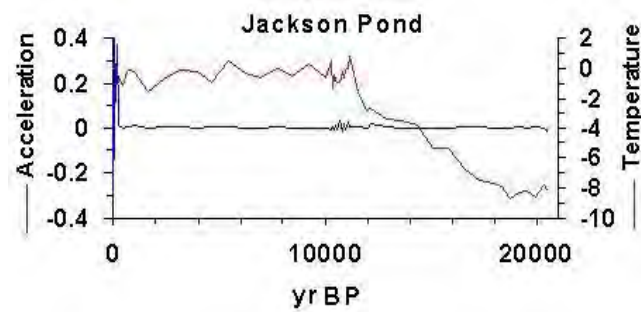
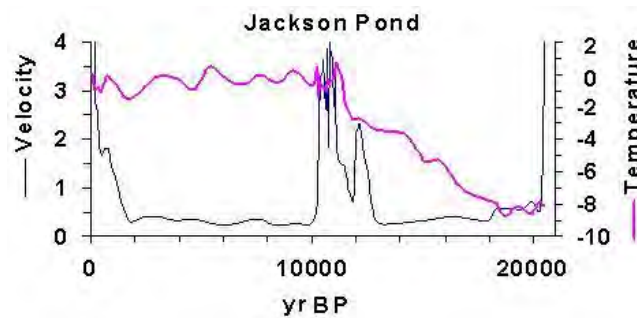
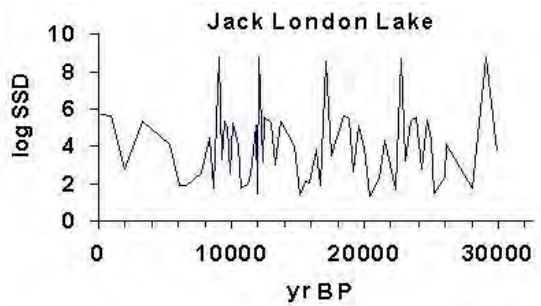
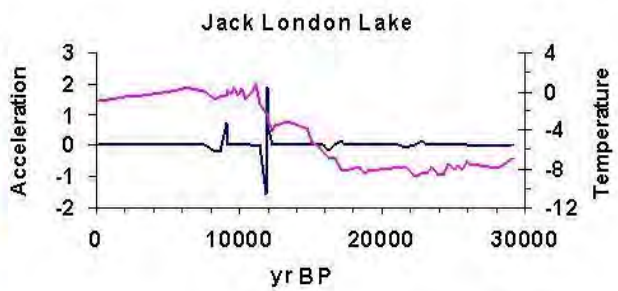
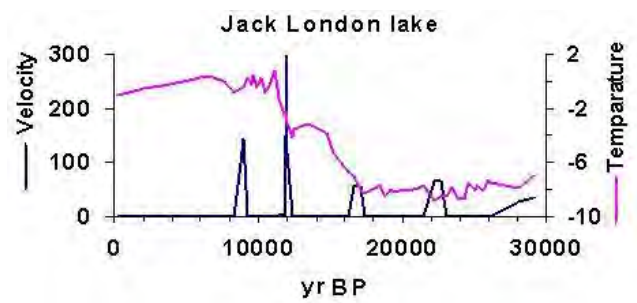
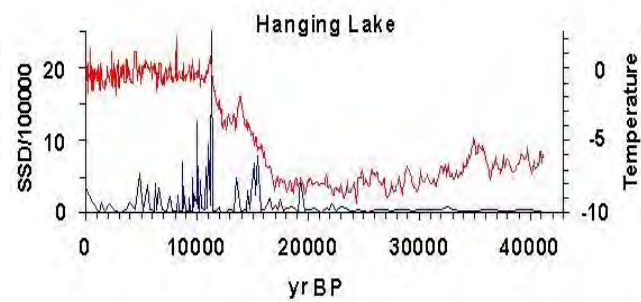
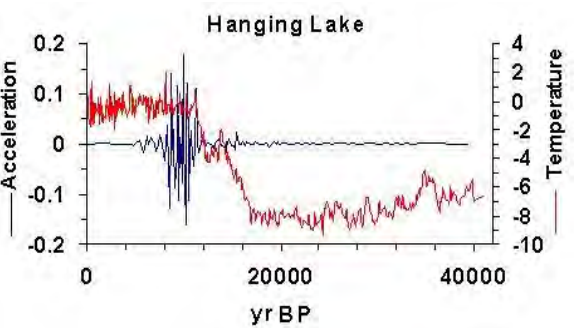
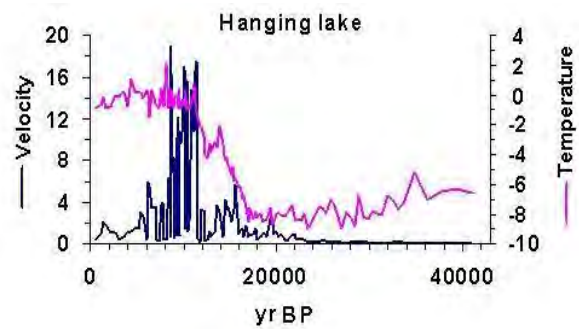
Appendix EA7-4. Vostok temperature and taxon deviation graphs for taxa as identified in Cwynar's Hanging Lake and Behling's Cambará data sets.

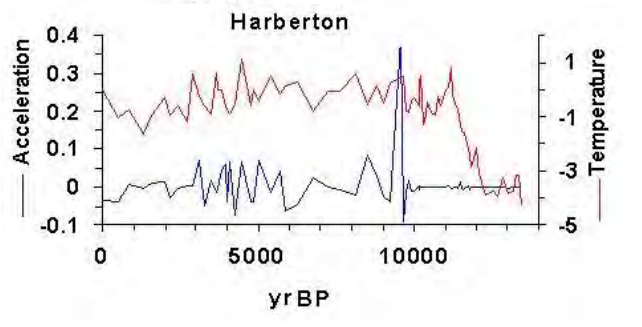
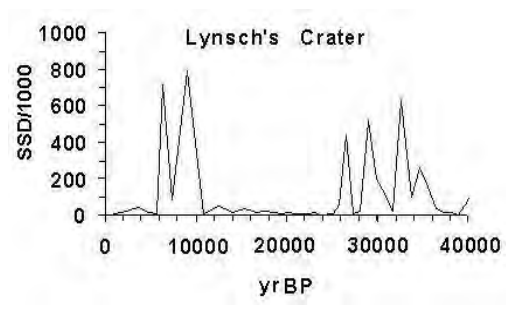
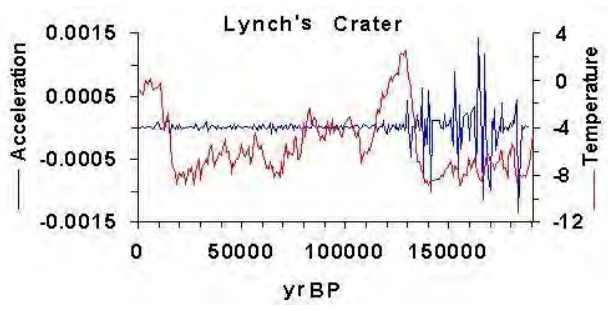
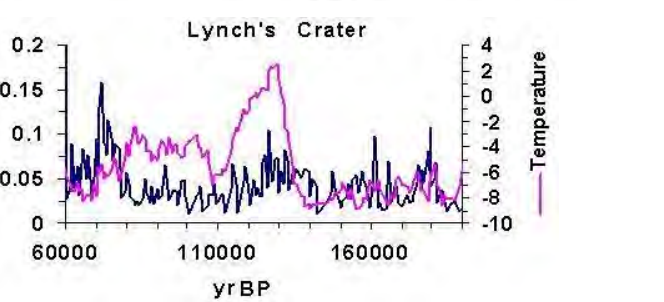
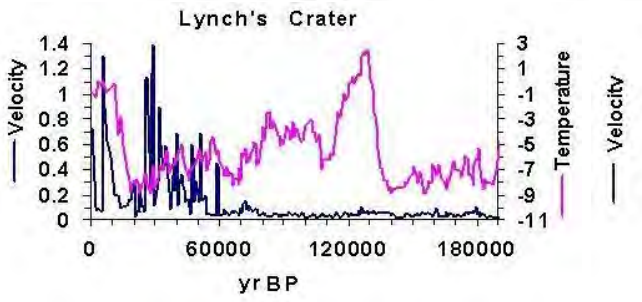
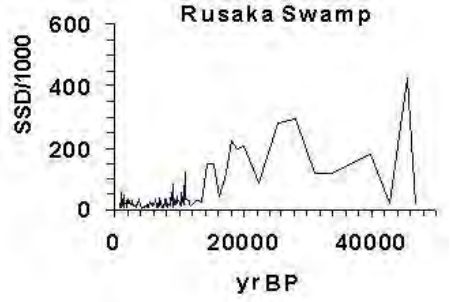
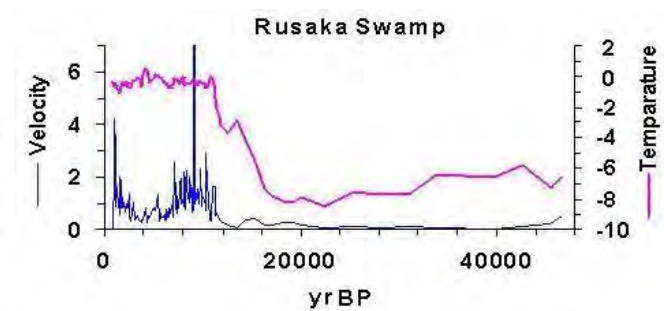
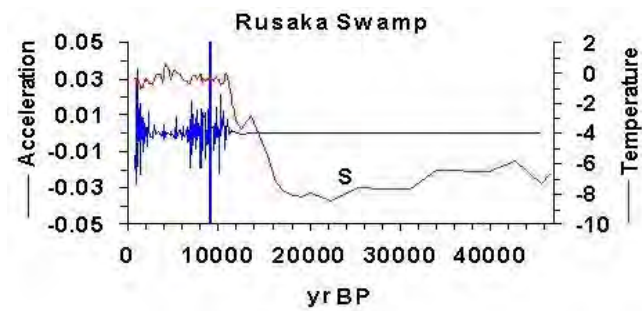
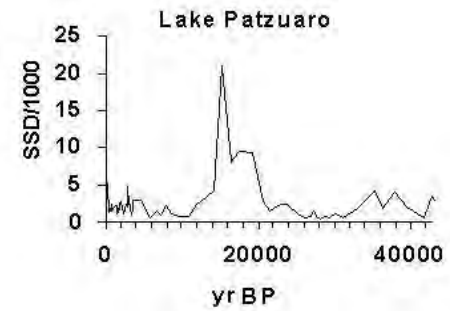
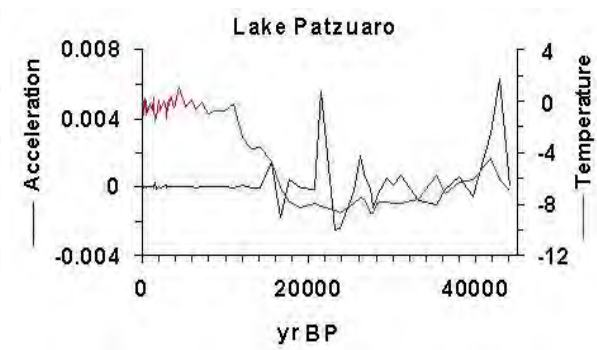
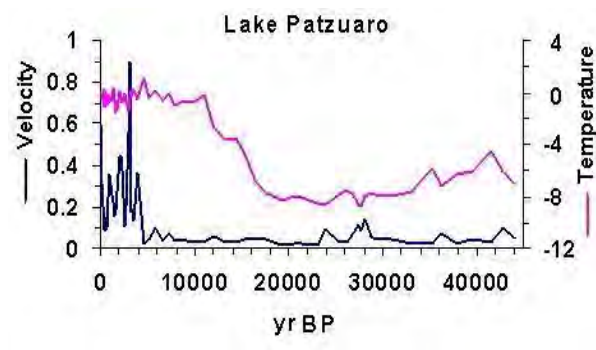
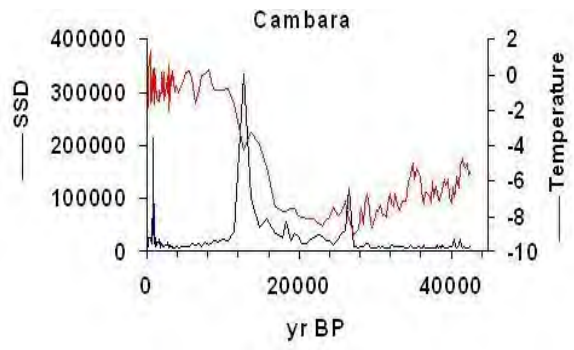
Appendix EA7-5. Comments on results from calibrated and uncalibrated Cambará ages.

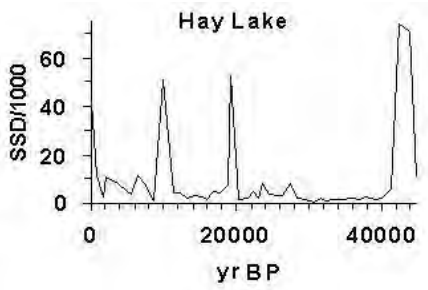
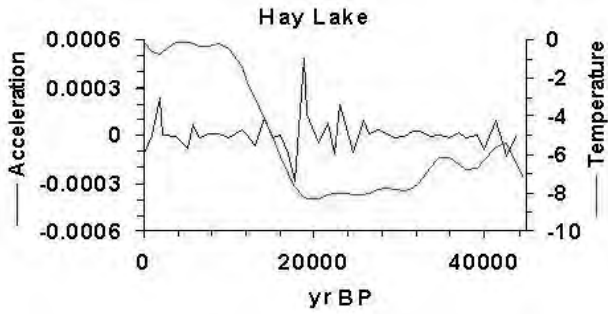
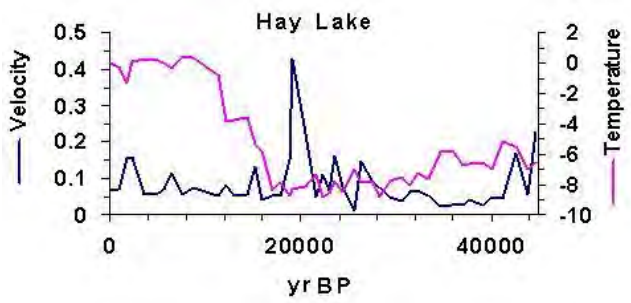
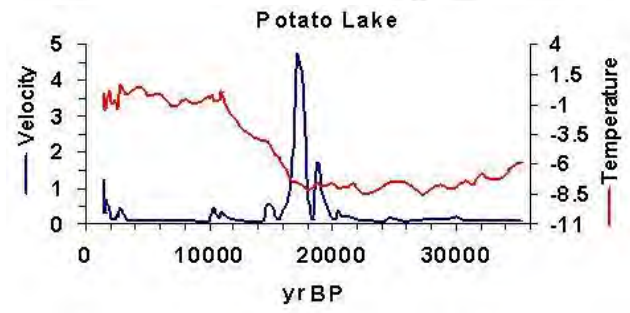
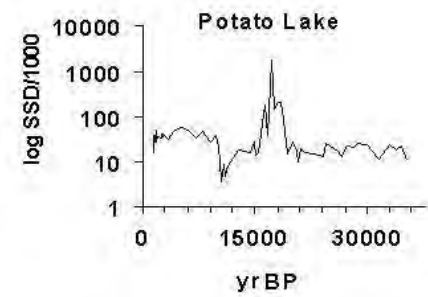
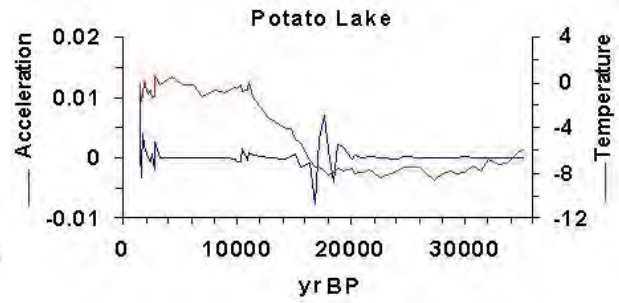
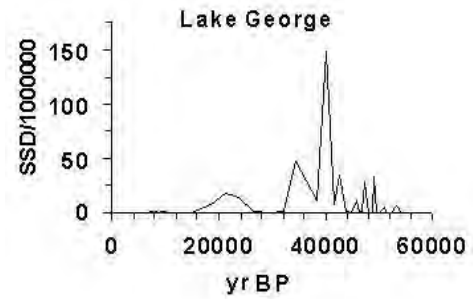
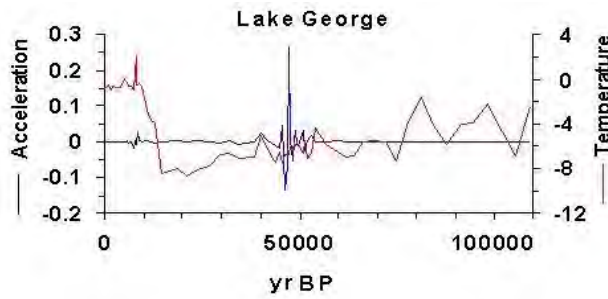
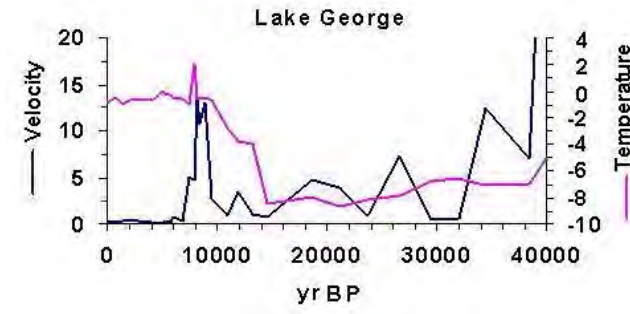
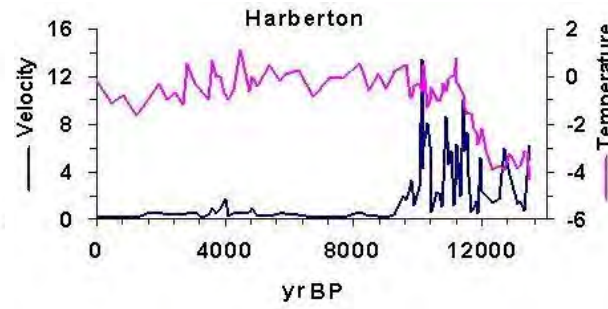
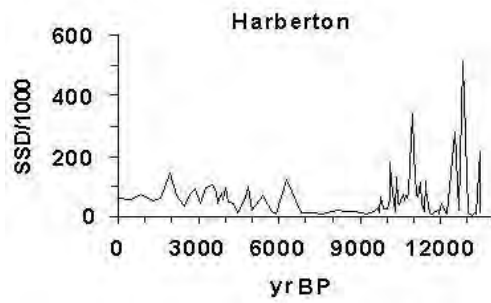
Received March 3, 2006
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Appendix 1. Vostok temperature differences (T), compositional transition velocity (V), acceleration (A), and sums of squared compositional deviation (SSD) from random expectation over time (yr BP). Sites are presented in order as listed in Table 1. See Figure 3 as the model, details and references in the main text. Petit et al. (1999, 2000, 2001) present the temperature records. Time (horizontal axis) begins at the virtual top sediment horizon, missing in some of the records.

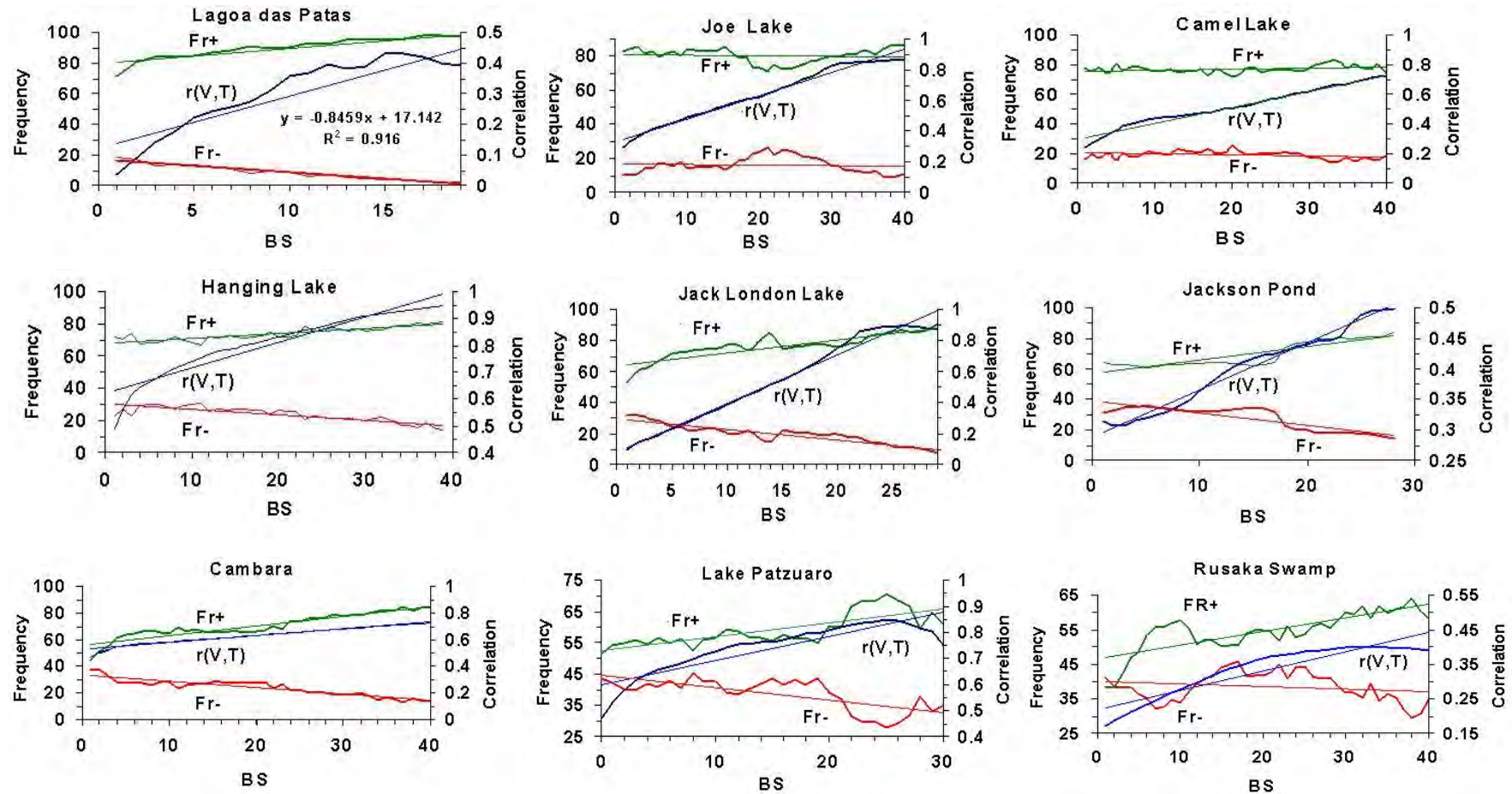


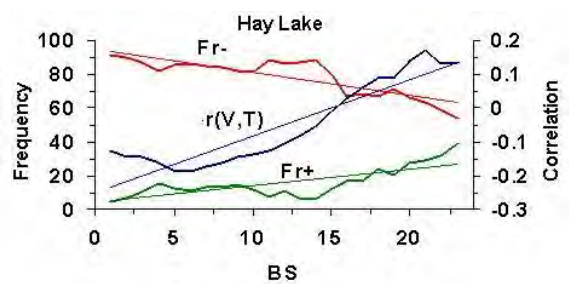
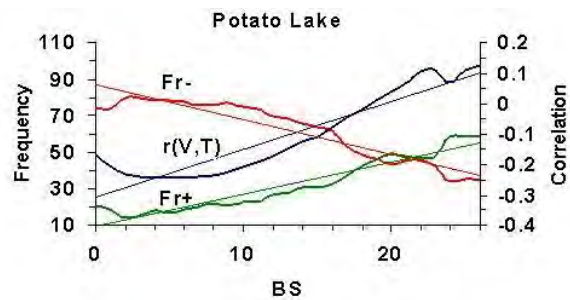
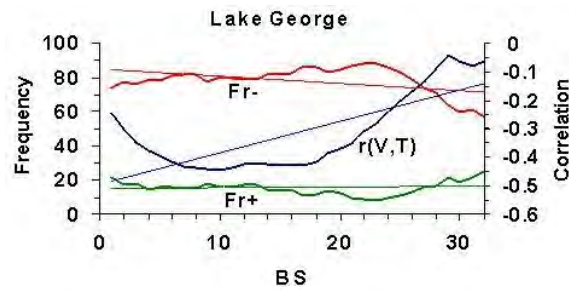
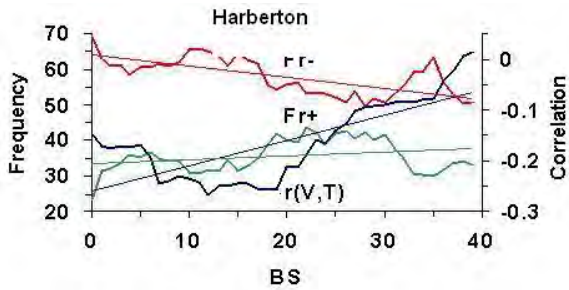
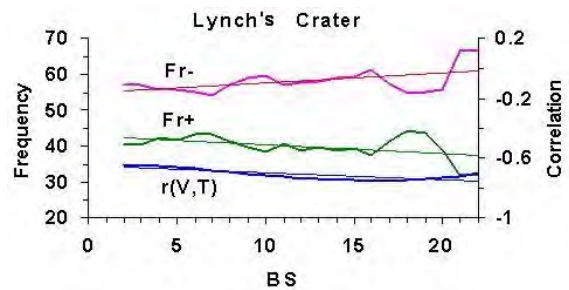




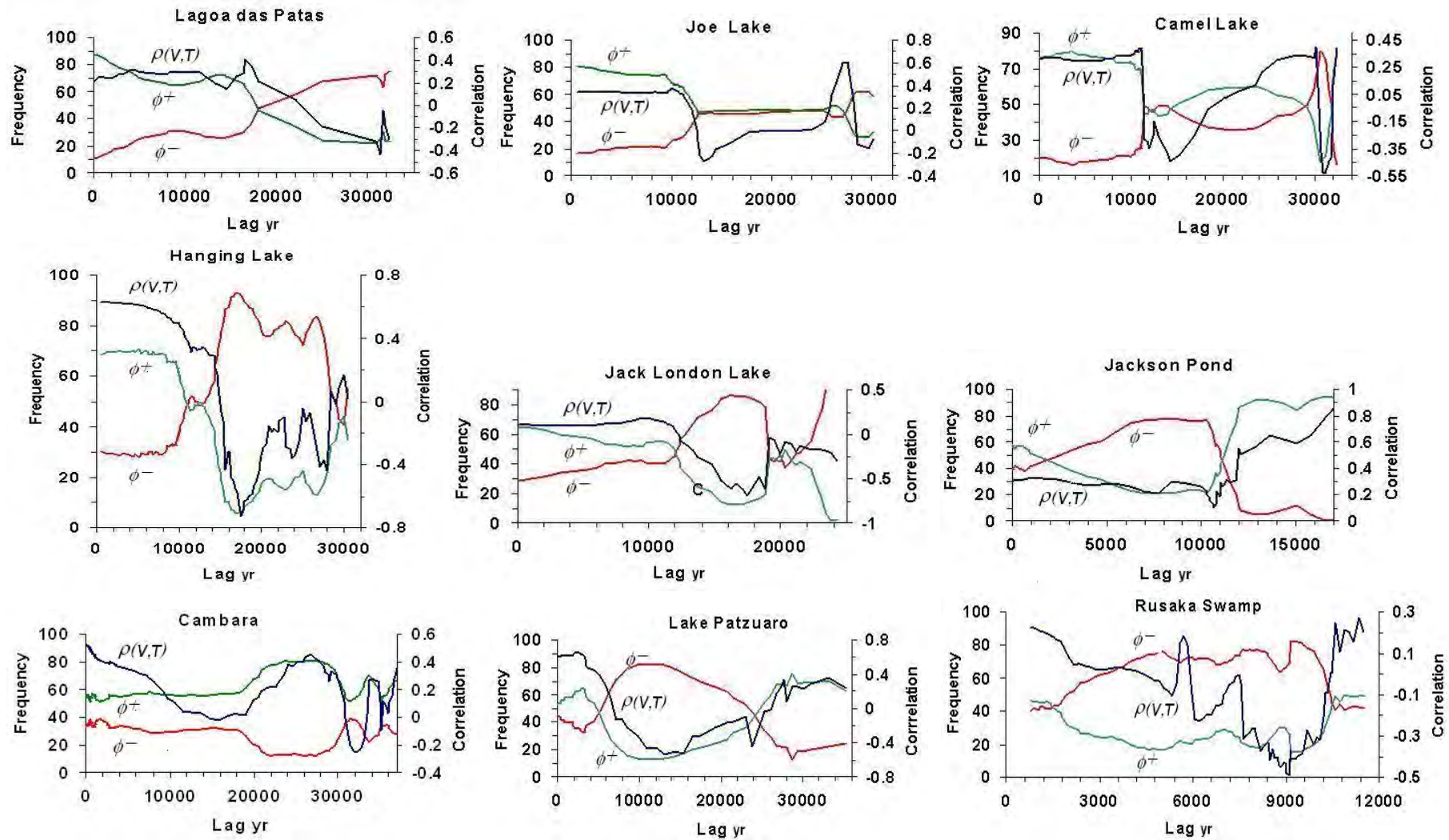


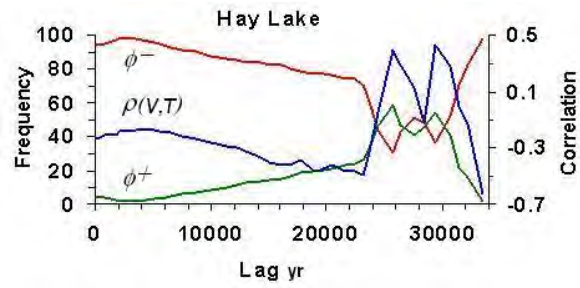
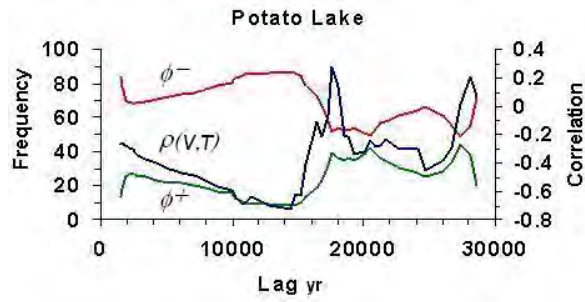
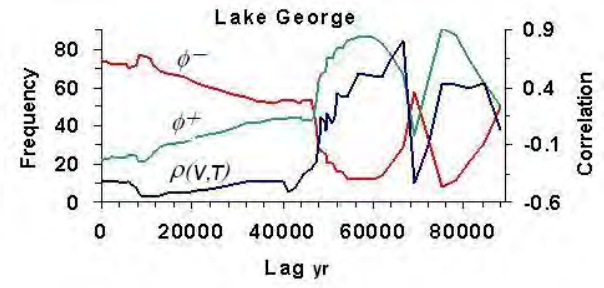
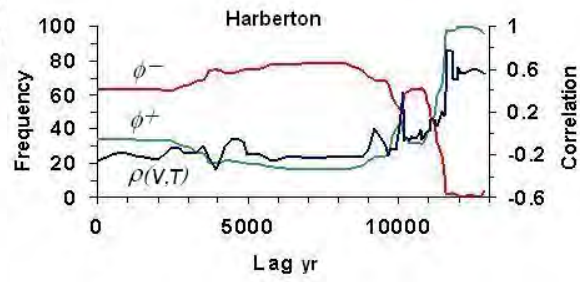
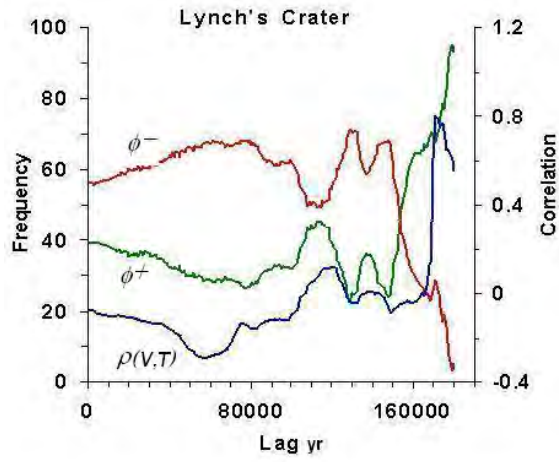
Appendix 2. Graphical outline of the regression method for estimation of stable synchronicity and frequency values. Legend of symbols: V - compositional transition velocity; T - Vostok temperature; BS – block size for averaging; $r(V,T)$ – synchronicity; F^+ and F^- - synchronicity sign frequencies; R^2 - coefficient of determination. See Figure 4 as model and explanations in the main text. Numerical results are summarised in Table 3. The values at $BS=1$ are the stable estimates.



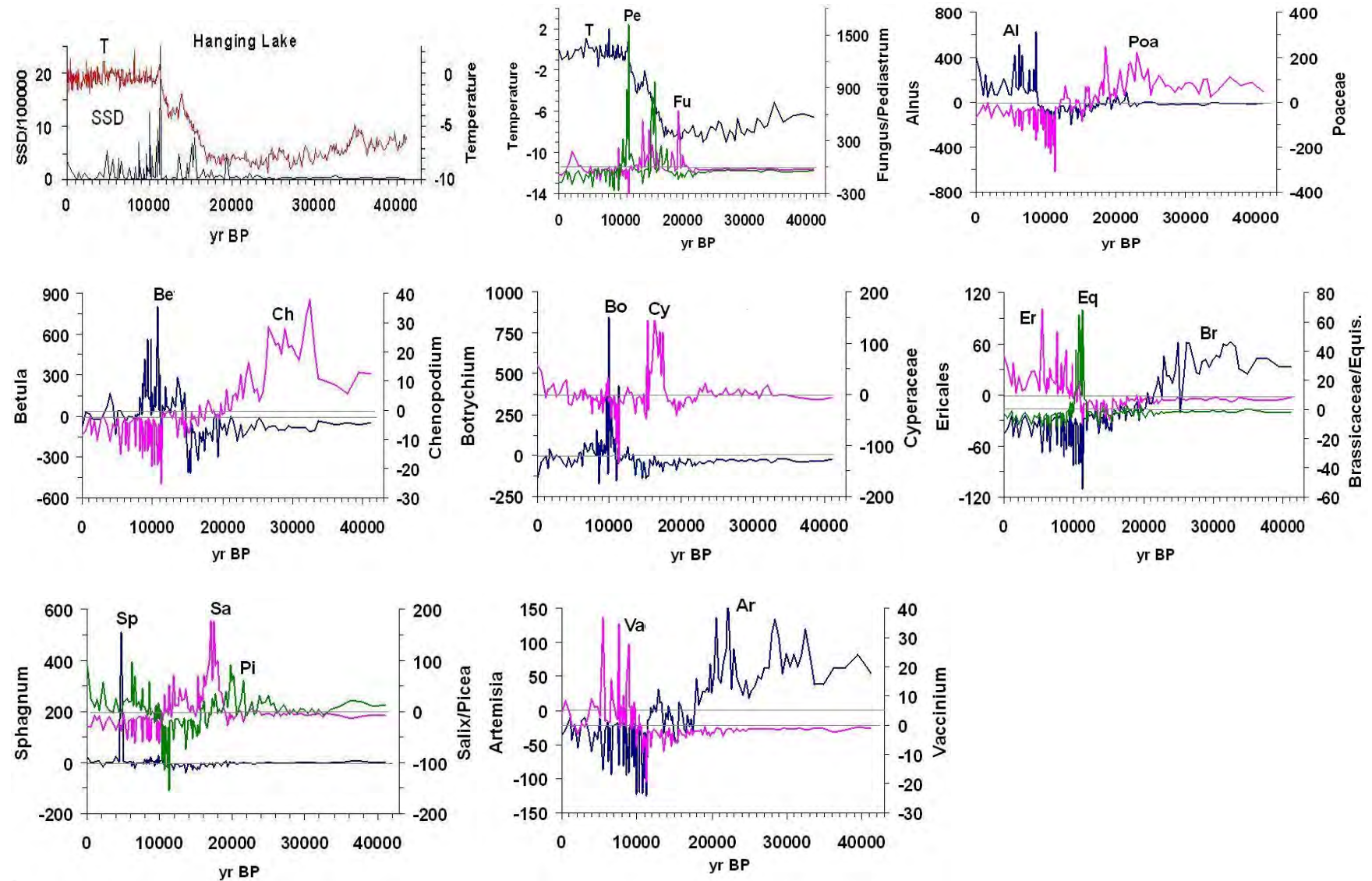


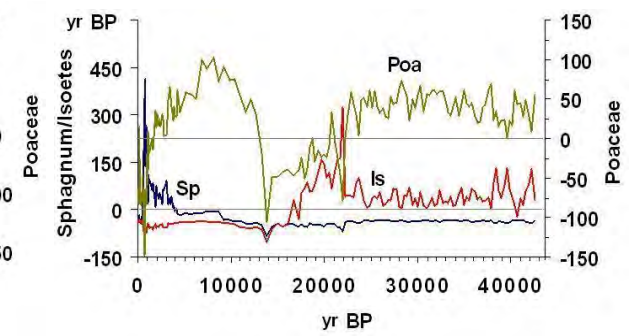
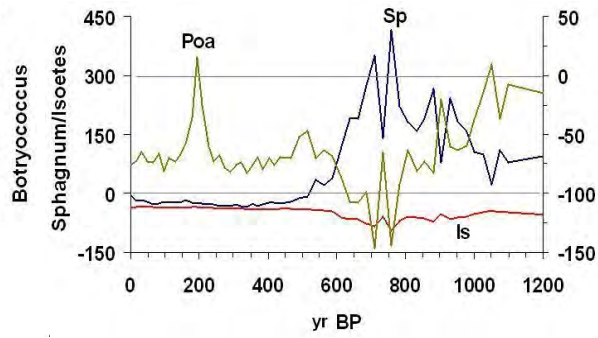
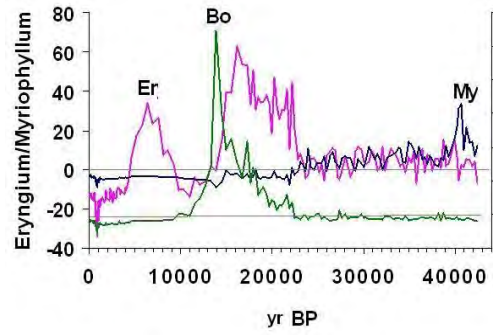
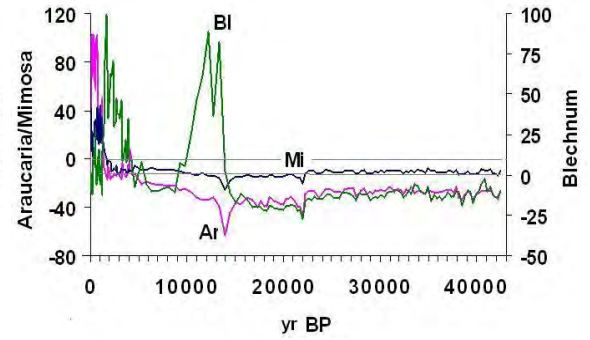
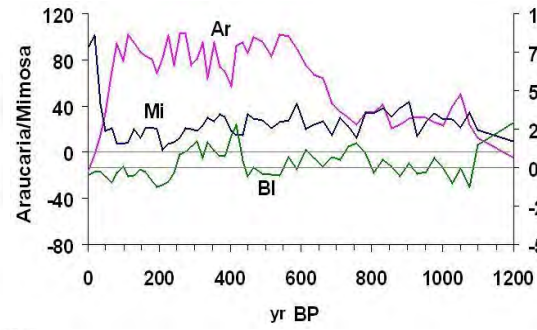
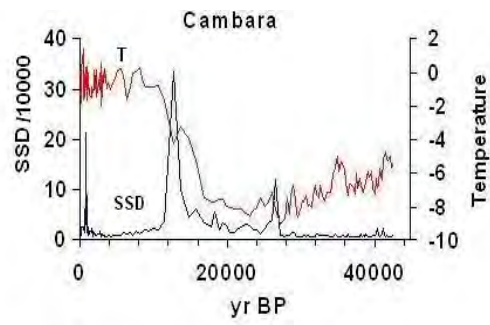
Appendix 3. Lag-dependent synchronicity $\rho(V, T)$ and sign frequency estimates ϕ^+ , ϕ^- . *Lag yr* indicates the number of years the temperature series is shifted to the left before re-pairing the T and V values. See Figure 5 in the main text as model and the explanations therein for interpretation of graphs. The graphs are presented in order of the locations listed in Table 1. All values graphed pertain to $BS=1$.





Appendix 4. Vostok temperature (*T*) and taxon deviation graphs (*D*) for taxa as identified in Cwynar's Hanging Lake (first 8 graphs) and Behling's Cambarà data sets. Horizontal line across the graphs at zero is the base line for random expectation on the taxon scales. Deviations of taxa above or below the zero line indicate over or under-representation in the palynological collection relative to expectation. See method and references in the main text. Locations are identified in Table 1. Use Figure 6 as model for interpretation. See explanation of the time scale (*yr B*) in the caption of Appendix 1.





Appendix 5

Comments on results from calibrated and uncalibrated Cambarà ages

This discussion is based on the text in Wikipedia web-based encyclopedia with our results added. According to the encyclopedia:

"Radiocarbon dating is based on the naturally occurring isotope carbon-14 to determine the age of carbonaceous materials up to ca 60,000 years. Within archaeology it is considered an absolute dating technique. The technique was discovered by Willard Frank Libby and his colleagues in 1949 (Libby, W. F. 1985. *Radiocarbon Dating*, 2nd ed. Univ. of Chicago Press, Chicago)."

"The current maximum radiocarbon age limit lies in the range between 58,000 and 62,000 years. This limit is encountered when the radioactivity of the residual ^{14}C in a sample is too low to be distinguished from the background radiation."

"The raw radiocarbon dates, in BP years, are calibrated to give calendar dates. Standard calibration curves are available, based on comparison of radiocarbon dates of samples that can be independently dated by other methods such as examination of tree growth rings (dendrochronology), ice cores, deep ocean sediment cores, lake sediment varves, coral samples, and speleothems (cave deposits)."

H. Behling's data set (see Table 1 in the main text for details) includes both calibrated and uncalibrated age scales. We examined the scales in his data and found an almost perfect linear relationship between the calibrated and uncalibrated dates (Figure 7), and between the transition scalars V , A in linear correlation terms:

$$r(V_{\text{calibrated}}, V_{\text{uncaibrated}})=0.996; \quad r(A_{\text{calibrated}}, A_{\text{uncaibrated}})=0.991; \quad r(\text{Age}_{\text{calibrated}}, \text{Age}_{\text{uncaibrated}}) \\ =0.995$$

While we are aware ambiguities with the linear correlation, we point out the cross plot of the velocity vales between the two age scales (Figure 8) as clear indication of an almost perfect linear relationship. But where a difference arose between the scales is the dating of hotspots. In all cases we relied on the uncalibrated scales. We mention the same conclusion for the synchronicity scalar $r(T, V)$ as for V . The *SSD values* are time scale independent. See further comments I the main text.

Reference

Stuiver, M., P. J. Reimer and T. F. Braziunas. 1998. High-Precision Radiocarbon Age Calibration for Terrestrial and Marine Samples. *Radiocarbon* 40, 1127-1151.

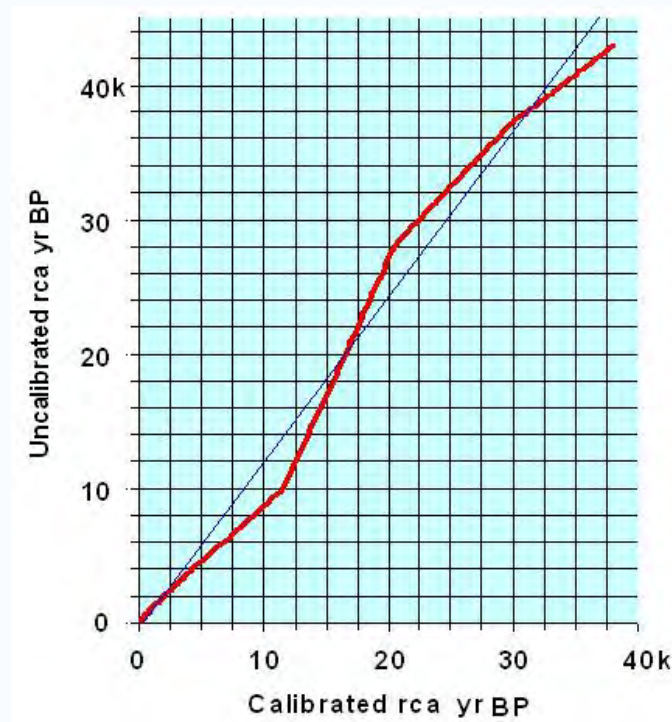


Figure 7. Behling's Cambarà calibrated and uncalibrated radiocarbon ages (rca) are compared. See data and site details Table 1 in the main text. Linear regression line is fitted to the observed line. The R^2 value of regression is 0.990.

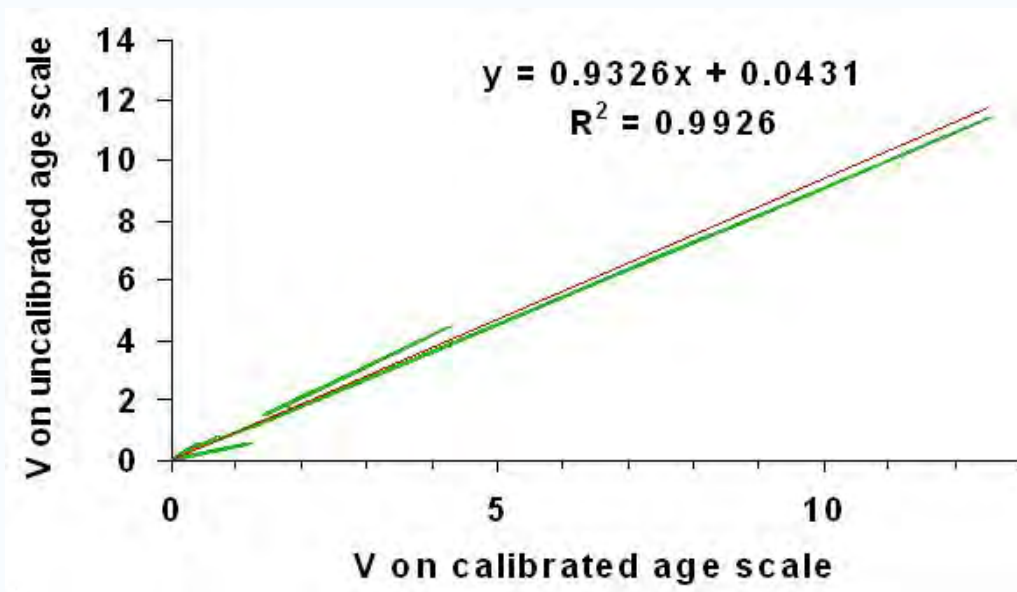


Figure 8. Cross plot of the velocity values between Behling's calibrated and uncalibrated age scales. Regression equation corresponds to fine line in centre. See the text for explanation.

WEB ONLY APPENDICES FOR ...

Trajectory analysis: powerful conceptual tool for understanding change

and

The governance of the long-term vegetation process. How to discover the rules?

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Abstract

The model at the basis of trajectory analysis is conceptually simple. When applied to time series vegetation data, the projectile becomes surrogate for vegetation state, the trajectory for the evolving vegetation process, and the properties of the trajectory for the true process characteristics. Notwithstanding its simplicity, the model is well-defined under natural circumstances and easily adapted to serial vegetation data, irrespective of source. As a major advantage, compared to other models that isolate the elementary processes and probe vegetation dynamics for informative regularities on the elementary levels, the trajectory model allows to probe for regularities on the level of highest process integrity. Theory and a data analytical methodology developed around the trajectory model are outlined, including many numerical examples. A rich list of key references and volumes of supplementary information supplied in the Web Only Appendices, round out the presentation.

Keywords: Attractor migration; Determinism; Fractal dimension; Parallelism; Periodicity; Phase structure.

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Page for downloadable Web Only Appendices: <http://www.vegetationdynamics.com> link *Appendices for Ta*

APPENDIX A. Eigenanalysis

Eigenanalysis is a tool for rigid rotation of the reference axes to positions of mutual linear independence. Eigenanalysis is the mathematical basis of Principal Components Analysis (Hotelling 1933). PCA was introduced to ecologists in 1954 by David W. Goodall. He called the technique 'ordination'. Others followed using the same terminology for this technique and also for all the others that involved the arrangement of objects on axes as points based on their measured resemblances (Greig-Smith 1957).

There are two basic transformations in most ordination techniques: raw data to resemblance values and resemblance values to new co-ordinates. Given p variables and n units, there will be $p(p-1)/2$ or $n(n-1)/2$ pair-wise resemblance values (depending on the mode of analysis). The second transformation takes the resemblance matrix and produces a new description of the sample in terms of t sets of n ordination co-ordinates. Resemblance functions and ordination techniques are described by Orłóci (1978).

Eigenanalysis is a parsimonious linear method of ordination. It is said to be parsimonious because of the independence of the t co-ordinate sets. In a parsimonious ordination t is smaller, usually much smaller, than p .

Eigenanalysis can lead the same t set of n co-ordinates via two alternative pathways (Orłóci 1966, Orłóci 1967) made obvious by the characteristic equations $\mathbf{AA}'\boldsymbol{\alpha}=\boldsymbol{\alpha}\boldsymbol{\lambda}$ (1) and $(\mathbf{A}'\mathbf{A})(\mathbf{A}'\boldsymbol{\alpha})=(\mathbf{A}'\boldsymbol{\alpha})\boldsymbol{\lambda}$ (2). In these, Matrix \mathbf{A} is a row-centred $p \times n$ data matrix and $\boldsymbol{\alpha}$ is a $p \times t$ matrix of component (transformation) coefficients. The t columns of matrix $\boldsymbol{\alpha}$ are the normalised Eigenvectors of \mathbf{AA}' . Vector $\boldsymbol{\lambda}$ is t -valued with Eigenvalues being the elements. Note: \mathbf{A} has the same definition in (1) as it has in (2). Also, \mathbf{AA}' is a $p \times p$ product matrix defined for the p rows in \mathbf{A} . Further, $\mathbf{A}'\mathbf{A}$ is an $n \times n$ product matrix defined for the n columns of \mathbf{A} . Since the component scores of the n column entities of \mathbf{A} are defined by $\mathbf{Y}=\mathbf{A}'\boldsymbol{\alpha}$, the same scores can be obtained directly by way of (2) as elements in the Eigenvectors of $\mathbf{A}'\mathbf{A}$. Adjustment is required such that the sum of squares of elements in any Eigenvector of $\mathbf{A}'\mathbf{A}$ will be equal to the corresponding Eigenvalue. Analysis via solution (2) is practical when p is larger than n . The following definitions should clarify the technical terminology consistent with our examples:

$\boldsymbol{\lambda} = \lambda_1 \lambda_2 \dots \lambda_t$ – vector of t Eigenvalues

Y_{ij} – component score of paleorelevé j on component i

$\lambda_i = \mathbf{Y}_i \mathbf{Y}_i'$ for any i

$A_{hj} = \frac{X_{hj} - \bar{X}_h}{\sqrt{n-1}}$ – centring of taxon (variable) vector b

X_{hj} – value of taxon b in relevé j

\bar{X}_h – sample mean of taxon b

α_{hi} – component coefficient (direction cosine) of taxon b and Eigenvector i

$\alpha'_i \alpha_i = 1$ for any i

$\alpha'_h \alpha_i = 0$ for any i, b ; this does not exclude the possibility of higher order correlation between components i, b .

$L_{\%} = 100 - E_{\%}$ where $E_{\%} = \frac{100 \sum_{i=1}^{t-k} \lambda_i}{\sum_{i=1}^t \lambda_i}$ – information loss by discarding the last k sets of

component scores, sets arrange in order of decreasing Eigenvalues.

$E_{i\%} = \frac{100 \lambda_i}{\sum_{i=1}^t \lambda_i}$ – efficiency of i th Eigenvector in accounting for variation in the sample.

The decision to discard the last k sets of component scores is ideally the outcome of a test of the null hypothesis $H_0: E(\lambda_{\tau, k+1}) = \dots = E(\lambda_{\tau})$. Symbol E signifies 'expectation'. When H_0 is true, that is when the k smallest population variances are equal, the point cluster in the subspace of the k components is hyperspherical. Such a cluster shape indicates random variation. Provided that n is large, H_0 is true, the population distribution is multivariate normal, and the sample is taken at random, the

test criterion given by $\chi^2 = -(n-1) \sum_{i=t-k+1}^t \ln \lambda_i + (n-1)k \ln \frac{\sum_{i=1}^t \lambda_i}{k}$ should have the theoretical Chi-

squared distribution (see Morrison 1976, pp. 296) with degrees of freedom $\nu = \frac{k(k+1)-2}{2}$. The

popularity of this technique in statistical applications justifies reminding users that the regularity conditions as stated may never be fully satisfied in ecological samples, and the test as described may never be fully justified. APPENDICES I and K further clarifies this point.

APPENDIX B. The Markov chain

We mention Feller's (1957) book as the premier reference on Markov chains. We recommend Feller to statistically minded ecologists. The first point to be made to demystify the Markov chain is that any series of numbers (trajectory) generated by the simple recursive law $\mathbf{X}_{t+1} = \mathbf{X}_t \mathbf{P}$ defines a Markov chain. The chain is either "stationary" or "moving". This depends on \mathbf{P} staying constant or changing. No time series will be stationary in Nature for any length of time. The second point is that any square matrix of normalised rows, i.e. the elements add up to 1 in any row, qualifies as \mathbf{P} . Further regarding the symbols, \mathbf{X}_t is an s -valued data vector. We use it to describe the composition of the paleocommunity at time t . We call such a vector a paleorelevé. We use symbol s to designate the number of taxa, \mathbf{P} is an $s \times s$ transition probability matrix such that an entry in the intersection of row b and column i is the probability of taxon b being replaced by itself ($b=i$) or by another taxon ($b \neq i$) in the next time step. Accordingly, the sum of the elements within any row of \mathbf{P} is equal exactly one. The sum of the elements within the columns may be different.

For purposes of illustration we should consider a simple case where a single taxon is involved: $\mathbf{X}_0 = [10]$ and $\mathbf{P} = [0.5]$. With these given, the stationary Markov chain unfolds like this: 10, 5, 2.5, ... Carrying on in the same manner, we have $\mathbf{X}_{t_0} = 0.01953125$. The series converges to a value that will not change significantly, no matter how many new steps are calculated. In practice using calculations, the number of steps after which the stable value occurs will depend on the precision of the computer.

The basic problem in Markov chain applications is the determination of the transition probabilities. These cannot be foretold from first principles with any accuracy in natural communities. Therefore they have to be estimated from observations as postdictions. Orlóci et al. (1993) offered a practical solution to the problem of estimation (the first as far as we know) in the context of survey-type, time series vegetation data.

It should be remembered that the Markov chain requires two things to be completely defined: \mathbf{X}_0 and \mathbf{P} . Regarding the frequently asked question whether or not the stationary Markov chain has memory, the answer is definitely yes for path. This is easily seen from the possibility of backtracking, namely $\mathbf{X}_{t-1} = \mathbf{X}_t \mathbf{P}^t$. A word of warning: this will only work if \mathbf{X} has not yet reached stability and definitely not a likely possibility when the natural process is considered.

In practice, the Markov chain is best regarded as a 'moving' chain, i.e. a chain with \mathbf{P} not being constant. We should direct attention Orlóci et al. (2002a), from which this short section is adopted.

APPENDIX C. Important data properties

Trajectory analysis takes time series data as input. The main data sources include palynological spectra and permanent plot records like in examples of the main text, and time static surrogates involving space for time substitutions (Kerner 1863, Wildi and Schütz 2000). The specifics of time series actually used in this essay are listed in Table 2 of the main text or mentioned at points of first use in the paper.

The objective being estimation of reality, the outcome will be affected by the way the data are obtained and by the type of the objects actually measured. Errors should be expected. Errors that have to do with measurements and sampling, excluding the barefaced mistakes scientists may commit but cannot explain, are considered further:

1. Measurement errors. These depend on the calibration of the measuring scale. The calibration of a diameter tape, for example, will define the limiting error properties in diameter measurements. Measurement errors have a life history of their own in data analysis. The worst case scenario expects complete error accumulation. Orlóci and Orlóci (1995) discuss error handling in connection with ecological examples and Shchigolev (1960) presents the mathematical theory. A special case of great importance in palynological studies is the accuracy of time measurements. The time scale in all cases except direct observations is the product of some dating technique. Considering the dating problem, the earliest attempt for solution is the space for time substitution technique that Kerner (1863) used. It is still applied in community ecology (Wildi and Schütz 2000, Kovács-Láng et al. 1998). With this the chances for inaccuracy are considerable. Two of its reasons are readily seen: (1) the temporal order established for plant communities on the ground need not be the same as their arrangement in time; (2) the set of community types currently existing in the site need not have all existed in historic times. Dating in palynology has an equivalent to the Kerner method in the disguise of depth for time substitution (Anderson 1896, Lagerheim 1902, von Post 1916, 1946). The invention of the isotope dating techniques (Libby 1955) helped to put dating on firmer ground. But isotope dating is very expensive and has a considerable error margin.

2. Sampling error. This is a direct consequence of unit selection. A typical case is the selection of the site for a sediment core, selection of a horizon in a sediment core, and then selection of the sediment sample within the horizons. The type of choice, random or preferential (see Orlóci and

Orlóci 1995, Web Based Appendix J), will determine the properties of the sampling error. When the choice is random, error limits can be set onto the estimates by the usual statistical tools. Error handling becomes a much more difficult problem when the choice is preferential.

3. Taxon identification. There are error sources without direct connection to unit selection or measurement. Taxon identification is an example. Taxonomic expertise is assumed, so the sole remaining source for error is the incompleteness of the specimens available for identification. This problem is epidemic in palynology. The incompleteness of the materials tends to push the systematic level of identification up. The result is heterogeneity in the definition of taxa, clearly seen in Fig. 2 of the main text. The consequences of the taxonomic error are rather serious in the precision of vegetation description. Clearly, taxon identification is scaling, but in this case the meter stick is the taxonomic system defined along phylogenetic, morphological, or functional lines. To enhance the automation in identification, it is practical to think of a taxonomic system as a character hierarchy in which the character states are arranged in a nested scheme (Orlóci 1991a and Pillar and Orlóci 1993a,b). In this scheme, plant identification reduces to a mapping problem in which the taxa represent distinct runs through the nodes vertically in the hierarchical character scheme. When the number of characters is s and character i has n_i states, the number of distinct runs (the taxa) is $n_1 n_2 \dots n_s$. In this context taxa are character set types (CSTs). When the characters are describing plant functions the taxa represent plant functional types (PFTs, Pillar 1999, Pillar and Sosinski 2003). When the characters emphasise common inheritance, the resulting plant taxa will in essence will qualify as species. The CSTs or PFTs will lump or fragment species, but will not qualify as species. An example for lumping species on a plant functional basis has typical example in the functional type that includes *Cercidium microphyllum* (Leguminosae, Sonoran Desert, North America) and *Bulnesia retama* (Zygophyllaceae, the Monte, Argentina). These species converged into identical functional types through evolution independently in distant geographic sites.

4. Incompleteness of the taxon list. This can be problematic, since the list is the taxonomic basis of trajectory mapping. Topics relevant to sampling and to testing the sufficiency of the taxon list are discussed elsewhere (Orlóci 1978, Orlóci and Pillar 1989, Pillar and Orlóci 1993a,b).

Whatever the error sources, the data is the sole basis to lay open the vegetation process for interpretations in a thoroughly scale-dependent manner. The process properties involved include type and intensity of process determinism; level of random oscillations; phase types and sharpness; complexity level; type and intensity of periodicity; level of parallelism; and attractor migration

pattern in time space; identity of forcing factors; hot spots of change in time and space; vegetation indicators of change; mechanisms of governance; and implications in the broader economic and political context.

APPENDIX D. Scale effect on perception

Trajectory analysis leads to inferences about patterns and structures that are not obvious on simple inspection of the data set. But what is also important, the inferences are optimised with respect to the scale effect. To illustrate how the scale effect can manifest itself, it is sufficient just to think of what happens when time step width and period length are changed. The effect is far reaching on the conceptualisation of the vegetation process with it on the spanning of contradictory theories, while the object medium remains the same:

1. Spatial scale at the site or stand level (forest gap, experimental plot, community patch), time steps in years, period length in decades. This is the time scale used in Table 1 of the main text. What makes the narrow time step so interesting is the increased power of resolution for seeing details. Taking time steps at the year or decade level, the observations will bring aspects of the vegetation process into view whose leading characteristic is dominance sorting. This is also the scale used in early investigations of gap dynamics (Morozov 1912) and more recent forest growth models (Shugart 1984). At this scale vegetation dynamics is readily linked to population processes. The later is highlighted in works with tolerance and inhibition (Connell and Slatyer 1977), life history types (Grime 1977), cohort senescence (Mueller-Dombois 1992), reproductive strategies (Harper 1977), propagule bank composition (Egler 1954). At this scale, the immensity of chance effects cannot be missed.

2. Spatial scales at the landscape or life zone level, period length at the longevity of the same type of climate, time step in decades or centuries. This is the Kernerian facilitation time scale. The period length is already too long for direct observation of the process, and any inference has to rely on palynological fixing or other long-term time series data. Feedback is functioning process, known well to foresters having had to deal with secondary pedogenesis in the form of ortstein development. Typically in this, raw humus accumulates under Pine monocultures planted on sand, the percolating rain water becomes acidic and the leaching of soluble soil components (much clay minerals and sesquioxides) from the upper soil horizon intensifies. The leachates accumulate in a lower horizon and eventually an impervious hard pan, the ortstein layer develops. Soil depth reduced and moisture

drainage obstructed, the altered conditions facilitate invasion of species from heath-land communities.

3. Spatial scale global, period length spanning entire cooling and warming cycles, time step in centuries of millennia. This is the level the palynological spectrum captures the vegetation process. For the vegetation process at this level in dynamics the technical literature has two terms: secular succession and precession dynamics. The term 'secular' emphasizes the broadness of the scale while the term 'precession' stresses the scale's coincidence with the climate-defining Milankovitch (1941) cycle in the Earth's motions, *i.e.* the precession of the equinoxes. Delcourt and Delcourt (1987) study of the Late Quaternary vegetation history of Eastern North America is on this level. On this scale, the determinism appears dominant compared to much weaker random oscillations.

The appearance of process properties being unique to the observer's scale(s) do not change the basic fact that the vegetation process viewed is the same unified process on any scale. Only what is being perceived differs. Therefore, an accurate picture of the integral process can emerge only when data and data analysis span the scales at breadth.

APPENDIX E. Shape complexity: the Hausdorff (fractal) dimension

We can characterise a graph by its shape complexity. The question is how to measure shape? Mandelbrot's (1967, 1977) fractal geometry supplies one of the tools. The reader is referred to Schroeder (1991) for a broad perspective on fractals, and to Palmer (1988, 1992), Kenkel and Walker (1993), Scheuring (1993), and Walker and Kenkel (1998) for ecological applications. The following method description is based on an application by Orlóci et al. (2002a). Specifically, we measure complexity as a length related fractal dimension D . We use the power law to link graph length $L(r)$ to scale unit r , and to D in the manner of $L(r) \sim r^{1-D}$ or $\log L(r) \sim (1-D) \log r$ which we may re-write in the form of the regression equation $y = a + b \log r$. Note that $b = 1-D$, the regression coefficient, and $D = 1 - b$. Therefore to find the value of D , we have to find the value of regression coefficient b . To this end, we do many length measurements $L(r)$ using different calliper widths r , then regress $L(r)$ on r to find an estimate for $D = 1 - b$. The signs of b have to be carefully observed. It will be negative when $L(r)$ increases with r decreasing. This is the case if graph shape is not smooth. D has theoretical values ranging from 1 to 2 depending on the level of complexity. When the graph is the map of a completely random process, the theoretical fractal dimension comes to its maximum 2. The following example illustrates method:

1) Step through the whole length of a graph with different calliper settings to obtain length records.

When implementation is analytically based on co-ordinate data (algorithm available from us), the physical dimension of the graph may take any value. Physical implementation can handle graphs only in two dimensional projections. The data set generated in one case is as follows:

Calliper setting (r) mm	2	6	10	16	24	32	40	48
Graph length in number of calliper steps	163	47	24	13	5	3	3	2
Approximate length $L(r)$ mm*	326	282	240	208	120	96	120	96
$\log r$ bits	1	2.6	3.3	4	4.6	5	5.3	5.6
$\log L(r)$ bits	8.4	8.1	7.9	7.7	6.9	6.6	6.9	6.6

2) Perform linear regression analysis of $\log L(r)$ on $\log r$ to obtain equation $y=9.087-0.433r$ (see Fig. E1).

3) Calculate fractal dimension in the manner of $D=1-(-0.433) = 1.433$

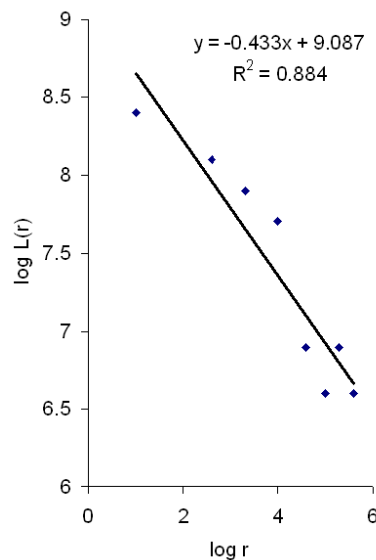


Fig. E1. Regression line fitted to $\log L(r)$ as function of $\log r$ in the data set above. The regression coefficient b (slope of line) is -0.433 , therefore $D=1.433$.

APPENDIX F. Trajectory parallelism

The data set to be used in the numerical example is taken from Fig. F1. The trajectories include clear cases of time-forward progression (*A* and *B*), a case in reverse (*C*), a set of random numbers (*D*), and two observed cases (*E* and *F*). The comparison scalar for any trajectory pair is the topological similarity coefficient, $TC = \frac{M}{p(s-1)}$. The term 'topological' is used with the explicit purpose to link the notion of similarity with the general idea of topography. 'Topology' is then the study of the topography of objects not unlike in land surveys, landscape ecology, morphometrics, etc. 'Topology' is definitely not intended here to imply the mathematician's geometry on a 'rubber sheet' as S. Smale has used the term to make vivid the nature of the mathematical concept. The values of TC range from 0 to 1. Values indicate concordance above 0.5 and discordance below 0.5. The symbols: M - number of matching directional scores on the phase space axes (+, -, 0); p - number of axes (taxa) of the reference space for the trajectory with the lesser number; s - elapsed period in equal time steps for the trajectory with the lesser period length. The theoretical expectation of TC is taken to be 0.5 under an equal probability law.

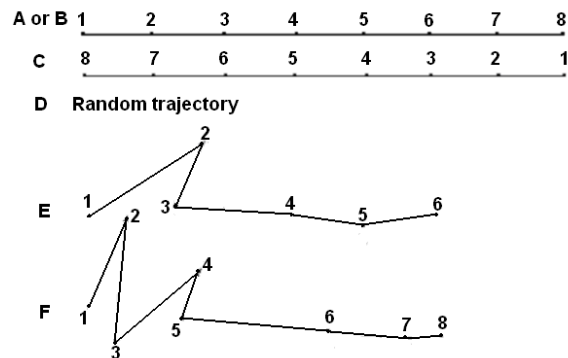


Fig. F1. Sample trajectory mappings (*A,B,C,D,E,F*) based on the data in Table E1. Each trajectory is described by two co-ordinate sets (a, a). *A* and *B* are identical trajectories, *C* is ordered in the reverse, and *D* simulates chance transitions. *E* and *F* represent two observed cases. The example is adopted from L. Orlóci in Fekete (1998, He and Orlóci 1998) with revisions.

APPENDIX G. Logarithmic measures of diversity and divergence

Rényi's logarithmic expressions

Rényi's (1961) expressions generalize the entropy (H_α) and information (I_α) of distributions in order

terms. The basic definitions are $H_\alpha = \frac{1}{1-\alpha} \ln \sum_{i=1}^s p_i^\alpha$ for entropy and $I_\alpha = \frac{1}{\alpha-1} \sum_{i=1}^s \frac{p_i^\alpha}{\alpha-1}$ for information. Symbols p_j and q_j are elements in two s -valued distributions, \mathbf{P} and \mathbf{Q} . These are identically ordered and have identical totals, $\sum_{i=1}^s p_i = \sum_{i=1}^s q_i$. The p and q terms are defined as:

$$p_i = \frac{f_i}{T}, T = \sum_{i=1}^s f_i \text{ and } q \text{ an expectation of } p. H_\alpha \text{ and } I_\alpha \text{ describe curves as a function of } \alpha \text{ (Orl\u00f3ci}$$

1991b). The curves are descending (if not a straight line) for H_α and ascending for I_α . Both are discontinuous at $\alpha=1$, but otherwise continuous over the range from $\alpha=0$ and up. To determine the value of entropy or information of order one, α may be set to a value close to one, say 0.9999 ... or

the alternative expressions would have to be used, $H = \sum_{i=1}^s p_i \log p_i$ and $I = \sum_{i=1}^s \frac{p_i}{q_i}$. What is the

significance of α in these expressions? Alpha is the scale variable and as such it defines an infinite number of possible entropy and information measures. Three of these had special significance for ecologists. Entropy of order zero is the upper limit. Entropy of order one is the Shannon entropy, and information of order one is one half of Kulback's (1959) minimum discrimination information statistic (Kullback et al. 1962). Entropy of order two is a log Simpson index (Simpson 1949). Alpha is useful also in other respects, such as in the detection of the region on the curve at which the diversity or information value becomes stable. This is an advantage when comparisons are made between cases.

H_α has some interesting properties. It has maximum value equal to $\ln s$, corresponding to maximum disorder in the distribution, *i.e.* where $p_1 = p_2 = \dots = \frac{1}{s}$. The degree to which an equidistribution is approached in \mathbf{P} is measured by $E = \frac{H}{\ln s}$ called the evenness or flatness of \mathbf{P} . H_α has minimum value when \mathbf{P} is most contagious, *i.e.* when $s-1$ of the elements are equal to $\frac{1}{T}$ and the remaining single element is equal to $\frac{T-s+1}{T}$.

I_α is a measure of the information divergence of distribution \mathbf{P} relative to \mathbf{Q} . I_α has minimum value at zero when \mathbf{P} and \mathbf{Q} have element-by-element identity, and maximum value when both \mathbf{P}

and \mathbf{Q} are most contagious with the $\frac{T-s+1}{T}$ quantity placed in offset positions. Kullback (1959) discusses regularity conditions under which $2I$ (of order one) is distributed as a Chi-squared variate with $s-1$ degrees of freedom. This property has been used to facilitate statistical tests of hypotheses about the relationship of \mathbf{P} and \mathbf{Q} . As ecological practice has it now, Monte Carlo experiments provide a flexible alternative to finding probabilities for the test. We make reference in this regard to Edgington (1987) for the underlying theory randomization testing in general, to Pillar and Orłóci (1996) and McArdle and Anderson (2001) for contrasting ecological applications, Orłóci (2001a) for consideration of an important dichotomy in applications of Monte Carlo testing with theoretical consequences, and to Orłóci (2006) for useful partitions and examples.

Anand's structural complexity

The complexity measure Δ in $L=\Delta+H$, is of particular interest, since Δ is a complement of disorder based entropy H . As such it has to do with order, which is structure. The Anand and Orłóci (1996, their Fig. 1) should be consulted on specific details regarding Δ and Anand and Orłóci (2000) on its additive partitioning.

Simpson's index (Simpson 1949)

This is one of the probability-based indices in the manner of $SI = \sum_{i=1}^s p_i^2$, such that $\sum_{i=1}^s p_i = 1$. As given, the index SI expresses the probability of finding a compositional duplicate of the community under the assumption that chance rules composition. When Simpson's function expressed in the manner of $H = -\ln SI$ is equivalent to Rényi's entropy of order 2. Considering that SI at given s has minimum value when $p_1 = p_2 = \dots = \frac{1}{s}$ where H reaches its maximum, SI is a measure of order in the distribution. Energy-focussed ecologists, like Fosberg (1965), have used negentropy in characterisations of SI . 'Negentropy' is a term borrowed from thermodynamics (see Prigogine 1968) where it refers to the available energy in a system. 'Negentropy' is mirrored by 'entropy', the energy that has been spent. In these terms, SI has maximum value when 'negentropy' is maximal, *i.e.*, when the distribution \mathbf{P} is most contagious. The limits are reversed when the Simpson index is inverted in the manner of $SD = \frac{1}{SI}$, which is some measure of 'entropy'. The maximum value of SD is s . As a possible point of interest to some ecologists, we computed values for Simpson's index for the following distributions:

Observed	$\mathbf{P} = [13/16 \ 1/16 \ 2/16]$
Most dispersed	$\mathbf{P}_U = [1/3 \ 1/3 \ 1/3]$
Least dispersed	$\mathbf{P}_L = [14/16 \ 1/16 \ 1/16]$

\mathbf{P}_U and \mathbf{P}_L define \mathbf{P} 's hypothetical upper and lower bounds. The numerical results are presented in Table A8. I leave the interpretation to the interested reader.

Table A8. Values of the Simpson index computed for distribution \mathbf{P} , \mathbf{P}_U , \mathbf{P}_L from above. See earlier sections for the explanation of symbols.

	\mathbf{P}	\mathbf{P}_U	\mathbf{P}_L
$SI = \sum_{i=1}^s p_i^2$	0.50617284	0.33333333	0.62962963
$SD = \frac{1}{SI}$	1.9756098	3.0000000	1.5882353
$SDE = \frac{SD}{s}$	0.65853659	1.0000000	0.52941177
$H_2 = -\ln SI$	0.68087709	1.0986123	0.46262352
$E = \frac{H_2}{\ln s}$	0.61976103	1.0000000	0.42109808

The metric connection

A typical example in the use of the Euclidean metric for diversity measurement is the McIntosh diversity index (McIntosh 1967). The Simpson index is also this kind when given in the form of \sqrt{SI} . Another information theoretical measure, Rajski's (1961) metric is not Euclidean (Orlóci 1978). Additive partitioning can be performed directly on Euclidean metrics in the manner of an analysis of variance, or such as in the method of sums of squares partitioning used in Edwards and Cavalli-Sforza (1965, Pillar and Orlóci 1996, Legendre and Anderson 1999, and McArdle and Anderson 2001). The numbers may not add up in the case of non-Euclidean metrics. To broaden the field covered in this appendix we refer for additional materials in Peet (1974), Pielou (1975), Patil and Taillie (1979), Rao (1982), Juhász-Nagy and Podani (1983), Magurran (1988), Orlóci (1978,1991a), Tóth-Mérész (1997,1998a,b) and Levin (2001).

Table G1. Co-ordinate pairs (a_1, a_2) and directional scores (b_1, b_2) corresponding to the trajectories drawn in Fig. F1. Legend: pa – past; pr – present.

A or B				C				D				E				F			
a_1	b_1	a_2	b_2	a_1	b_1	a_2	b_2	a_1	b_1	a_2	b_2	a_1	b_1	a_2	b_2	a_1	b_1	a_2	b_2
1		1		8		8		4		3						13		14	
<i>pa</i>																			
2	+	2	+	7	-	7	-	8	+	5	+					25	+	21	+
3	+	3	+	6	-	6	-	2	-	4	-	12		26		21	-	07	-
4	+	4	+	5	-	5	-	6	+	2	-	38	+	45	+	48	+	20	+
5	+	5	+	4	-	4	-	3	-	7	+	31	-	28	-	42	-	11	-
6	+	6	+	3	-	3	-	1	-	1	-	59	+	27	-	68	+	10	-
7	+	7	+	2	-	2	-	5	+	8	+	74	+	23	-	90	+	09	-
8	+	8	+	1	-	1	-	7	+	6	-	91	+	26	+	120	+	10	+
<i>pr</i>																			

As the computations progress, trajectory co-ordinates are transformed into forward (+) or backward (-) directional scores, or left 0 if no change occurred. Following this, matches are counted. The scoring follows specific rules:

- 'Present' is the same time point or the same narrow time interval in all trajectories. When working with paleopollen samples, the top sediment horizon may miss being from the 'present', owing to possible erosion, decomposition, or other processes active in the sediment profile. Because of this, it makes sense to repeat the comparison of the trajectories at varying lag forward or backward. The aim is to maximise TC .
- In the interest of finding comparable points on different trajectory lines, we should assume uniform time step widths. See Appendix H for method.
- Noting the above, any given state of the process, symbolically X , is endowed with the potent property of being at least to some extent the outcome of random effects, and as such, of being at a locus in phase space unpredictable before the fact. It is justified, therefore, to regard any X as one point in a swarm, any member of which could materialise as an observation, should chance dictated it to be that way. One cannot know exactly the radius of the swarm, but one can make provision for it by expanding the limits of a tolerance sphere around X in a stepwise manner. 'Tolerance sphere' should not be confused with the probabilistic confidence sphere, belt or interval of statistical estimation. While confidence spheres, belts or intervals help to control the effect of the sampling error, tolerance spheres, belts or intervals help to reduce the effects of small-scale stochasticity in the

analysis when making comparisons between the trajectory points. The tolerance sphere is enlarged, starting with radius 0, in small steps up to some arbitrary upper percentage limit defined for the co-ordinate values. All co-ordinates on all axes undergo tolerance transformations with the following possible results for two co-ordinates of the same trajectory on one axis:

0 assigned when the tolerance belt around X includes the chronologically next point on the same axis. If it does not, then:

+ assigned when the co-ordinate value of the first point given is greater than the co-ordinate value of the chronologically next point (forward).

– assigned when the above relation is reversed.

d. When matches are counted, reference axes have to be paired between the trajectories. We refer to the members of a selected pair of axes as dual axes. There is no natural way for pairing the axes of different reference spaces. To overcome this problem, finding dual pairs may be in a manner that will maximise the value of TC . A method is described in the example below, which pre-empts the so-called Procrustes manipulations of Shönemann and Carrol (1970). In the present example, the choices are based on local maxima within the 2×2 sub-matrices of between-axes correlations as in the following --

<i>Axis</i>	<i>B1</i>	<i>B2</i>	<i>C1</i>	<i>C2</i>	<i>D1</i>	<i>D2</i>	<i>E1</i>	<i>E2</i>	<i>F1</i>	<i>F2</i>
<i>A1</i>	1.00	1.00	-1.00	-1.00	0.00	0.38	0.94	-0.43	0.95	-0.55
<i>A2</i>	1.00	1.00	-1.00	-1.00	0.00	0.38	0.94	-0.43	0.95	-0.55
<i>B1</i>			-1.00	-1.00	0.00	0.38	0.94	-0.43	0.95	-0.55
<i>B2</i>			-1.00	-1.00	0.00	0.38	0.94	-0.43	0.95	-0.55
<i>C1</i>					0.00	-0.38	-0.94	0.43	-0.95	0.55
<i>C2</i>					0.00	-0.38	-0.94	0.43	-0.95	0.55
<i>D1</i>							0.59	-0.09	0.21	0.55
<i>D2</i>							0.23	-0.52	0.29	-0.22
<i>E1</i>									0.99	-0.07
<i>E2</i>									-0.27	0.89

A quick example will clarify the arithmetic in the calculation of TC . Consider trajectories E and F . Quantity M of the shared directional scores is equal to 10. Since $p=2$ and $s=6$, $TC=1.0$ or 100%. This implies that the two trajectories are indistinguishable in terms of their topologies. The entire set of similarity values and probabilities (α) for the trajectories portrayed above are as follows:

Trajectory pair	<i>AB</i>	<i>AC</i>	<i>AD</i>	<i>AE</i>	<i>AF</i>	<i>Expectation</i>		<i>Bias in iteration</i>
						<i>Theoretical</i>	<i>Iterated</i>	
<i>TC</i>	<i>1.00</i>	<i>0.00</i>	<i>0.50</i>	<i>0.60</i>	<i>0.57</i>			
α	<i>0.003</i>	<i>1.00</i>	<i>0.63</i>	<i>0.33</i>	<i>0.44</i>			
	<i>BC</i>	<i>BD</i>	<i>BE</i>	<i>BF</i>	<i>CD</i>			
<i>TC</i>	<i>0.00</i>	<i>0.50</i>	<i>0.60</i>	<i>0.57</i>	<i>0.50</i>			
α	<i>1.00</i>	<i>0.63</i>	<i>0.33</i>	<i>0.45</i>	<i>0.63</i>			
	<i>CE</i>	<i>CF</i>	<i>DE</i>	<i>DF</i>	<i>EF</i>			
<i>TC</i>	<i>0.4</i>	<i>0.43</i>	<i>0.60</i>	<i>0.64</i>	<i>0.70</i>	<i>0.500</i>	<i>0.516</i>	<i>+0.016</i>
α	<i>0.81</i>	<i>0.74</i>	<i>0.33</i>	<i>0.27</i>	<i>0.176</i>			

The *TC* values are measures of the strength of topological similarity. The corresponding probability values are generated under the assumption of chance compositional transitions. A *TC* value is considered significant if the probability associated with it is small. One more thing is mentioned. The number of reference axes may be unequal in the two trajectories. To resolve the comparison problem, the comparison is limited to axes up to the common number.

e. Order transformation of co-ordinates is implicit when we use +, -, 0 scores. Speaking about process trajectories in real time, trajectory **A** above has a perfect relationship of process time and compositional change in trajectory **B**. Nothing of the sort exists in the case of the trajectory pair **A** and **C**. The value 0.5 is random expectation from first principles. The expectation generated in Monte Carlo experiments may differ. The difference of the theoretical expectation and the experimental expectation is a measure of bias (see table above).

f. Up until this point, the tolerance radius was set to 0%. When it is raised to 100% in 1% increments graphs are generated for *TC* and for related statistics. Fig. G1 displays the resulting graphs for the trajectories of in Fig. F1.

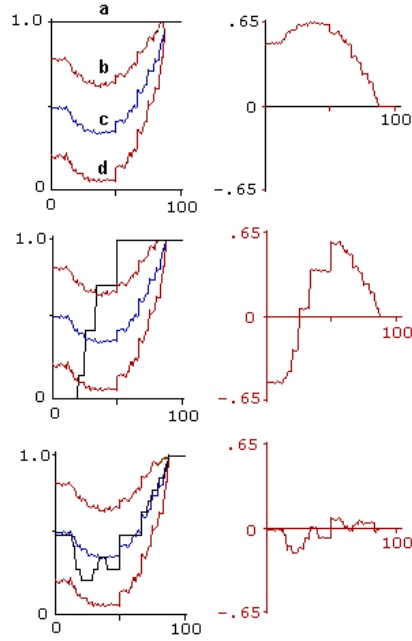


Fig. G1. Graphs of the topological similarity coefficient (TC) in left column: a -observed value; c - random expectation (iterated), b,d - limits of the 0.95 confidence belt. Graphs of deviations ($a-c$) are in the right column. On all graphs, the vertical scale is TC . The horizontal scale is the tolerance radius from 0% to 100%. Three cases of parallelism are portrayed: (1) Perfect (top graph, trajectories **A** and **B**) indicated by the horizontal TC line across the top at 1.0 outside the tolerance radius b,d . (2) Complete directional reversion (middle graph, trajectories **A** and **C**); much negative deviation from expectation. (3) No relationship (bottom graph, trajectories **A** and **D**). The TC graph is hugging expectation.

The more adventurous may try an alternative method. In this, after equal time step transformation of the trajectories inner angles are computed in the manner of the angle scalar in the main text. For angles less than 90 degrees minus sign is assigned to points B. Otherwise plus sign is allotted. In other respect the comparison is following the original method.

APPENDIX H. Equal time step transformation

Equal time steps are established by interpolation techniques. The method used here is simplest to explain by example:

- (i) Take a set of observations like these:

Depth interval cm	0-10	10-20	20-30	Total
Time interval	5	3	7	15
Pollen count of taxon A	15	6	42	63
Average count per unit time	3	2	6	--

(ii) Arrange the averages into a 15-valued string in the manner of

3 3 3 3 3 2 2 2 6 6 6 6 6 6 6

(iii) Selecting 3 basic steps as the common step width, we obtain the interpolated pollen counts

Time step width	3	3	3	3	3	15
Pollen count for taxon A	9	8	10	18	18	63

Clearly, interpolation is smoothing the series and as a possible payoff it clarifies the trend.

APPENDIX I. Non-linearity, prediction, testing

We included materials in this section on non-linearity, on prediction by analogues, and on tests of generality after Orlóci (1993). The discussion of these is not an organic part of the note's main text, but they are target of frequently asked questions.

11. Non-linearity

The point should not be missed that in performance terms the expected type of response individually or jointly is as a rule non-linear under natural conditions. This has consequences as a revelation about the system and about the choice of methods to analyse the system. An idealised two-species case is shown in Fig. I1.

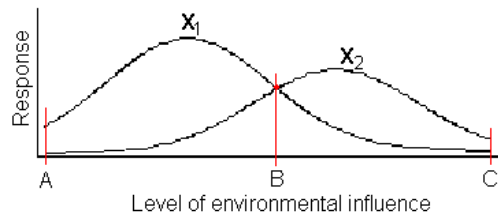


Fig. I1. Idealised species response graphs of the Groenewoud-Whittaker type shown as trend lines without showing stochastic oscillations.

Observing Fig. I1 it should not be missed that under communal existence and natural conditions responses are stochastic, implying that an amount of chance variation is superimposed on the main trend line of the response. It may clarify the point further if we contrast stochastics with the case of the fractal in which regular patterns arise from pure chaos. They may have seen response curves like the one in I1, but readers may not remember that these graphs show response shape and not a frequency distribution.

The consequence of the responses not being linear is a non-linear joint scatter as seen in Fig. H2

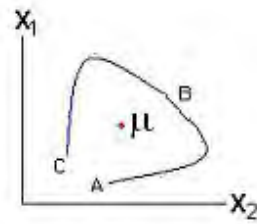


Fig. I2. Trend line in the presence of joint response of two species without stochastic oscillations for which the response graphs are shown in Fig. I1. Symbols X_1 , X_2 , A, B, C have identical meaning as in Fig. I1. Symbol μ denotes the centroid.

Figs. I1, I2 picture the case of only two populations (X_1 , X_2) exhibiting pure Groenewoud-Whittaker type response along a dominant environmental gradient. The gradient is long, and competition is absent. The populations' joint response depicted in Fig. I2 has a horseshoe shape. Multi-modal responses are not uncommon in the presence of competition, in which case the joint scatter could be quite different from case to case under natural conditions.

The consequences of having a horseshoe-like joint scatter, and possibly even more complex non-linearity in the presence of many species for which the joint scatter would have to be drawn as some spiralling manifold in higher dimensions, can be devastating on the reliability of traditional statistical techniques of inference. The reason is, in part, their reliance on the moments-product moment and the p -variate Normal distribution with density function

$f(X_1, X_2, \dots, X_p) = Be^{0.5(\mathbf{X}-\boldsymbol{\mu})'\boldsymbol{\Sigma}^{-1}(\mathbf{X}-\boldsymbol{\mu})}$. Since the product moment is useless to describe the non-linear relationship of the variables, the normal density function itself is rendered meaningless (see Orłóci 1993).

Choices have to be made and the question is whether to choose the centroid (centre of gravity, arithmetic mean vector as in Fig. I1) or the type (such as in preferential sampling) as the basis of prediction. Traditional statistics is interested in the centroid and it bases all inferences about

populations on the 'centroid' in the sense of $E(\bar{X}) = \mu$ with sample value on the left and its expectation on the right. When the sample consists of typical units, the behaviour of the 'type' is of interest. Will the behaviour of the centroid still have utility? The centroid could replace the 'type' if the responses were tested and found to be linear (Orlóci 1993). Should an actual case fall outside this specific type of response, such as in the aforementioned horseshoe configuration, the centroid will likely reside within a void where no natural state may ever materialise. In such a case, the centroid is the least likely state and it cannot be used to represent the 'type'.

It may be useful, with intentions to further clarify the notion of non-linearity and the problems with it, if we cast non-linearity in a broader context. Nayhef (2000) makes his point regarding non-linear systems an interesting way: the (geometric) principle of superposition does not hold and the source of non-linearity is the governing equation. To us engineers, it is quite natural to put the definition of non-linearity in these terms for reasons related to the non-linear relationship of stress to strain upon which the stability of a structural element, like a concrete beam, will depend. Such a beam normally contains steel, gravel, and cement in just the right proportions with a specific shape that experiments suggested. One of the peculiarities in the engineer's scenario is that the system is designed and the design does not violate the criterion equation(s) that are *a priori* chosen. Although stress and strain involves all the constituent materials of the beam, the total stress is not reproducible by superposing the individual stress and strain relations individually in the component parts: steel, gravel and cement. In other words, the non-linear system cannot be reproduced like a montage of its constituent parts. Dawkins' (1986) makes this idea vivid when he makes a distinction between a heap of aeroplane parts and the aeroplane that flies.

In the ecologist's study scenario, the nonlinear system is a given, designed by nature. The governing equation is unknown and finding it, or using a less mathematical term, discovering the governing principles of the system, is the ultimate objective. It is exactly for the untenable principle of superposition that reductionism has utterly failed in ecology in its attempts to reveal governing principles of community dynamics. This is of course not to imply that the effort was wasted in other respects, such as the discovery of new population and individual behaviour patterns when populations are under stress.

Nash and Walker-Smith (1987) give simple examples, which reflect their view of non-linearity and its statistical analysis, non-linear parameter estimation:

-- relationship of plant yield and the density of planting;

-- change over time of the size of plants, animals or economic activities, *i.e.*, growth curves;
-- rate of production or disappearance of a chemical or radioisotope in a chemical or nuclear reaction. These are examples of non-linear responses (effects, stresses) to factor influences (causes, strains), be it the planting density or something analogous in manner, but not necessarily in functional form, to the case pictured in Figs. I1, I2 in the present essay. Nash and Walker-Smith (1987) see the statistical problem amounting to parameter estimation, but the scenario they outline is based on the assumption of the functional form of response(s) and the form of distribution of the error (noise, random oscillations) component about the response function. Their model is in fact regression analysis, the most used and abused statistical technique ever devised, for which the basic mathematical tools include Newtonian minimisation and Gaussian least squares.

It is relevant that regression tools have been used successfully in the modelling of complex ecological problems, such as the modelling of dynamic systems (Goodall 1967 and Wildi 1978, 1998, 2000). It is also true, of course, that in some ways successful models incorporate governing or state equations that the modellers construct to conform to educated guesses of the non-linear process, which they then improve in the course of successive approximation. So important and revealing is the fact that these equations are not the shorthand expressions of all encompassing truths, like Newton's or Einstein's, which as Mees (2001) points out are an impossibility to achieve in the circumstances of a 'real systems' on this planet that are noisy, non-stationery and having high-dimensional dynamics, such as in Goodall's paddock, Wildi's (1978) peat bog, our heathland and rain-forest examples. In characterising this kind of modelling, Mees is adamant that Kepler's approach is the more relevant model, because it works from masses of data and thus in that manner reconstructs the governing equation. The ecologist approach, clearly, must avoid the mistake of committing itself to and staying with a preconceived idea about dynamics, such as for example the assumption that basic behaviour of change is a derivative of the exponential function, which was proven not to be the case in all but the most trivial type of communal existence.

Prediction: the method of analogues

The reader is referred to examples for the use of 'analogues' by Box (1981), K uchler (1974) and Aszal os and Horv ath (1998).¹ The method assumes that survival of specific plant forms in a site is not a straight chance event, and prediction is inherently an exercise in making choices among probable outcomes. But the outcome chosen for being most probable also has a certain probability

¹ Other predictive models are used as well in ecology. Particularly good example is the Markov chain for which the reader finds examples and sources listed in Appendix B..

of not being the one that actually materialises.² The *modus operandi* of predicting, say, community diversity as an outcome may go like this:

- a. Determine probabilistic linkage $p_{t|e}$ of each community type t to a specified type of the environment e .
- b. Community type t that has highest probability $p_{t|e}$ with regard to environmental type e , that has the highest probability p_e of occurring at a future point of time on a specific site, or at a different site in the same time, is the predictor community. The 'diversity' in the predictor community is the prediction. The probability of the prediction being right is $p_{t|e}p_e$.

Testing generality

Conclusions that have high value to science at large have validity broader than the data set itself. Such a conclusion of course has generality. How to test for generality? Two methods:

- a. Statistical testing. We have to emphasise the importance of the sampling design by the use of which data are collected, and the analytical methods by which the conclusions are drawn from the data. We discuss aspects of sampling in APPENDIX J. As far as statistical testing is concerned, basic conjectures called 'hypotheses' are formulated and then the question asked: what is the probability that a case specified by the hypothesis can come about by chance alone. If the probability is large, the hypothesis is validated, otherwise it is falsified. The technique requires a test criterion by which we can measure how far an observation has fallen from the hypothesised state, a probability distributions that describe the behaviour of the test criterion under the assumption that the hypothesis tested is true, and a decision rule to be invoked when rejecting (or accepting) a hypothesis. Given $\hat{\theta}$, an observed state, and θ_o , a state we would expect under a hypothesis H_o whose validity we wish to test, the test criterion may take the form of $\Delta = \hat{\theta} - \theta_o$. If we find that Δ is unusually large, so much so that it could not be expected to occur as a low probability event under the null hypothesis, then we would consider Δ significant and the H_o rejected. We would consider Δ having reached rejection limit when the probability of a difference at least as large as the observed Δ occurring by chance and chance alone when the null hypothesis is true is smaller than a set value.

² Chance interplaying with the deterministic laws of adaptation and ecological plasticity may be in the manner of randomness infesting determinism. This is a case of stochastics and it have to be treated as such (Orlóci 2001a). It is not inconceivable that determinism could arise from complete randomness, the case of the fractal (Mandelbrot 1977), albeit not a likely mechanism on which to base the practice of prediction.

This probability has to be found. It may come from considerations of basic principles, a method standard in statistics of the classical type, or more likely, it may come from Monte Carlo experiments on which we have commented earlier in the text.

2. Testing by analogues. What we just described is a rather formal way of approaching the validation of a conjecture. More likely, one will follow a less formal approach where significance is linked to the consistency of similar results reoccurring in repeated surveys or experiments. In this, the idea of recursive sampling and analysis are key ideas (APPENDIX J). Significance is declared if a stable $\Delta = \hat{\theta} - \theta_0$ is found to be unusually large, consistent with expert experience.

APPENDIX J. Sampling

J1. Contrasting views of the sampling environment

Science is done by way of surveys and experiments, contemplative or applied. Applications tend to rely on samples, rarely on complete enumeration. The conceptualisation of the sampling environment is far from being uniform (Orlóci 1993). In fact, conceptualisations divide along a sharp dichotomy with traditional statistics on one side and ecological statistics on the other:

a. The traditional statistics assumes that the sampling environment is homogeneous or can be made that way. It also holds that the sampling units are crisply defined and have unhindered access when chosen, the linear form of joint response is universal. Inference can become a matter of tracing the behaviour of moments and product moments, and probability scaling is possible based on theoretical sampling distributions derivable (axiomatically) from first principles.

b. From an ecologist's point of view these assumptions should be tantamount to self-deception. It is a fact of the ecological environment that heterogeneity is the norm and not the exception; the population units are fuzzy, access to sampling units is far from being unhindered, joint responses are never linear, and probability distributions cannot be derived from first principles.

J2. Unit selection: random or preferential?

We take samples since we cannot enumerate all population units. Which method of sampling should we choose? Unfortunately what could be an easy way out, namely random sampling, is not a viable option (Pielou 1977, Edgington 1987), except in the most trivial cases. This leaves us with the only practical method left: preferential sampling (Orlóci 1993). We replace letting chance govern the choice with selecting the type. The result is a sample in which the units are typical specimens, typical sola, typical community stands, or typical things of some other kind. After having said these,

let the statistician in us be comforted by further suggesting that much of what is known about the biota on all scales from life zone to molecule, and about the environment on all scales from Ice Age climates to pedogenic processes, is the consequence of smart people looking closely at materials that they considered suitable for analysis, rather than having bothered working with materials that blind chance hands to them.

J3. Stopping rule in sampling: variance based or structural stability based?

Two criteria are particularly relevant when we formulate the stopping rule in sampling (Orlóci and Pillar 1989). The sampling variance written in the least cumbersome manner as in Sampford (1962), $SV = \frac{V}{n} \left(1 - \frac{n}{N}\right)$ incorporates all the essentials we need, to see what is happening when the stopping rule is SV based. In this n is sample size, N the population size, V the population variance. Clearly, the larger is n , the smaller will be SV . The SV graph is a rapidly descending curve which levels off early if N is reasonably large (Fig. J1). The sampling process stops when an *a priori* chosen sampling intensity is reached.

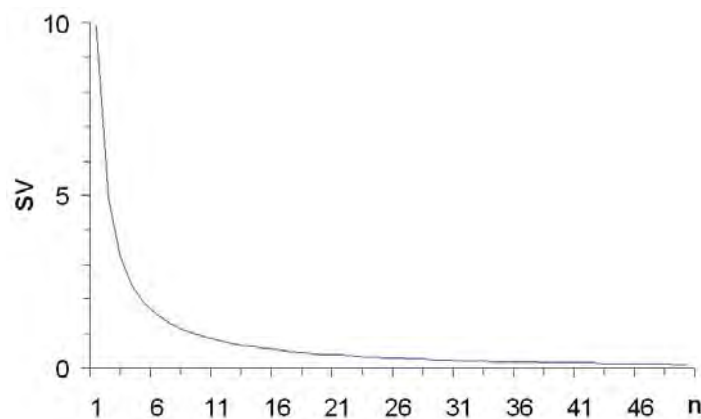


Fig. J1. The graph SV as a function of sample size n .

The fatal problem with the use of SV is that there is nothing inherently ecological about SV and even if there were its use would be hindered by V or N not being known in all but the most trivial cases in ecology. Beyond these, ecological studies are interested in structures and structural connections for which reason they will do better when the stopping rule is formulated about the stability of structures and structural connections in the sample (Orlóci and Pillar 1989). What is involved? Examination of Fig. J2 should help clarify this point. Suppose that two structural descriptions of the same n sampling units are given in the manner of two distance configurations.

The first is $\mathbf{D}_{n \times n}$ based on vegetation data and the second $\mathbf{\Delta}_{n \times n}$ based on environmental data.

The signal for optimal sample size n having been reached is the levelling off of the stress function $\sigma(\mathbf{D}; \mathbf{\Delta})$. It is noted that even though $\sigma(\mathbf{D}; \mathbf{\Delta})$ is a measure of stress, its actual magnitude will reflect on the strength of linkage between \mathbf{D} and $\mathbf{\Delta}$ and will not affect the determination of the optimal sample size.

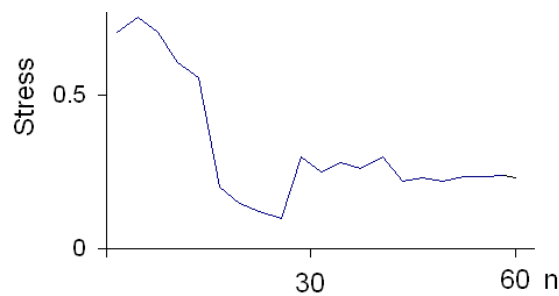
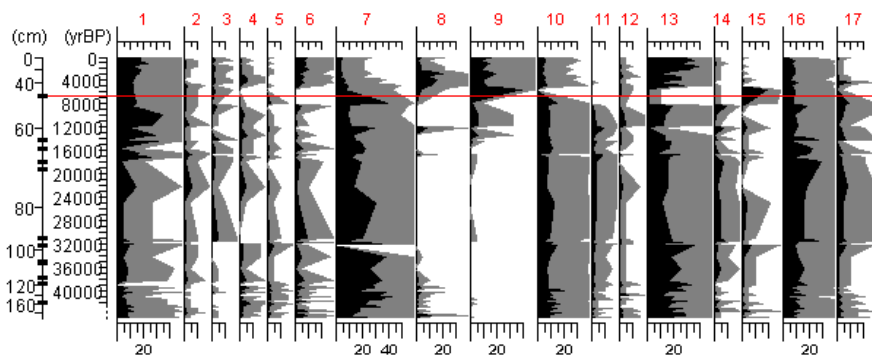


Fig. J2. Stress graph for distance configurations \mathbf{D} and $\mathbf{\Delta}$, corresponding to vegetation structure and environmental structure in the sample according to Orłóci and Pillar (1989). \mathbf{D} and $\mathbf{\Delta}$ change in the sample by addition of new units. They attained reasonably high stability in the example by the time the sample size reached 30. Note, low stress in terms of $\sigma(\mathbf{D}; \mathbf{\Delta})$ implies high concordance of \mathbf{D} and $\mathbf{\Delta}$.

APPENDIX K. The Hanging lake pollen spectrum



Spectral representation the Lagoa das Patas pollen spectrum (URL www.ncdc.noaa.gov/paleo/ftp-pollen.html). Only the 15 leading palynomorphs are shown as distinct entities. The remaining palynomorphs are lumped into two groups (16,17). Primary and 5x exaggerated scales are shown for better viewing. Horizontal line at about 7 kyr BP identifies a paleorelevés. Black markings on cm scale identify isotope dating. The particulars of the site and the palynomorphs are given below:

```

# GPD ASCII Format
# 11 Apr 00
# Percentages for the top 15 pollen types
#
# *****
# ** Please acknowledge the contributors and the Latin American **
# ** Pollen Database when using these data. **
# *****
#
# Site name:          Lagoa das Patas
# Place:             BRA:Amazonas
# Latitude:          0.16.00N      ( .266667)
# Longitude:         66.41.00W     ( -66.683333)
# Elevation(m):     300
# Sigle:            DASPATAS
# Entity name:
# Contact person:   De Oliveira, P.E.
# Chron name:       LAPD 1
# Reliable age bounds: 0 - 42210
17 49
 1 Alc/Apm  A Alchornea/Aparisthmium
 2 Aquae    A Aquifoliaceae
 3 Are.x.Ma A Arecaceae (excluding Mauritia)
 4 Caeae.ud A Caesalpiniaceae undiff.
 5 Css      A Cassia
 6 Cec      A Cecropia
 7 Co/Me.ud A Combretaceae/Melastomataceae undiff.
 8 Cpf      A Copaifera
 9 Mau      A Mauritia
10 Mytae    A Myrtaceae
11 Pod      A Podocarpus
12 Tap      A Tapirira
13 Ur/Mo    A Urticaceae/Moraceae
14 Fabae    B Fabaceae
15 Poaae    B Poaceae
16 ot.tr&sh A Other trees and shrubs
17 ot.herbs B Other herbs
0, , 0
17.90      0.00      1.54      1.23      .93      8.33      4.94      3.70      16.05      5.25
 0.00      1.23      31.17      .31      .31      4.94      2.16
5, , 552
18.15      1.54      2.46      1.85      0.00      7.08      3.38      2.15      10.15      5.54
 0.00      1.23      35.38      .92      0.00      9.85      .31
...
190, , 44569
 9.06      .36      1.09      .36      2.17      3.99      27.54      0.00      .36      9.42
 3.26      2.90      15.94      .36      4.35      12.68      6.16

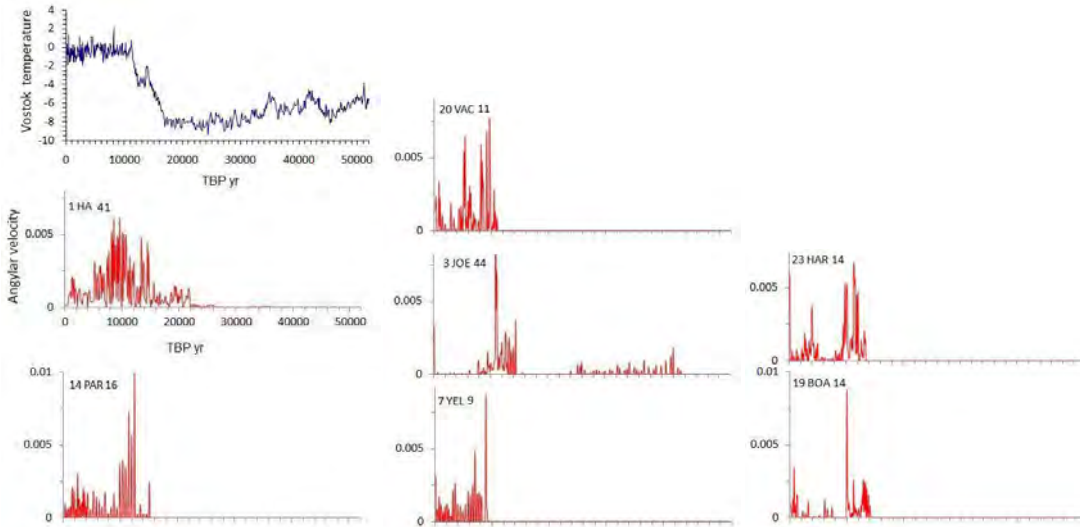
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The original Global Pollen Database format is followed. For further clarification the reader is referred to the URL address above and the publications identified in Table 1. List contains the 15 leading palynomorphs and two groups of the remaining 34.

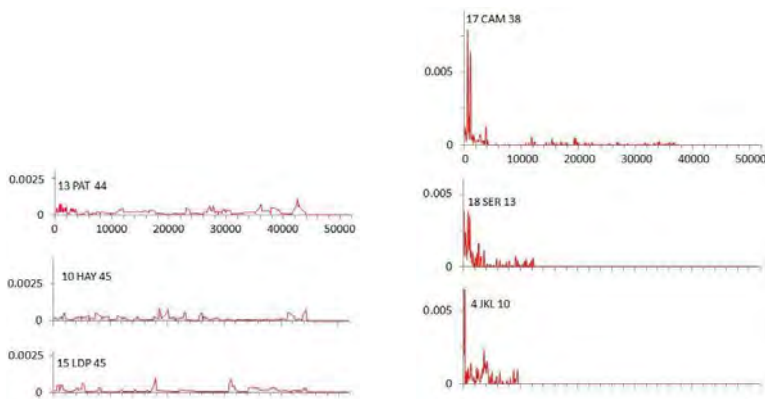
APPENDIX L. Complete set of 23 compositional transition velocity graphs and site descriptions

Angular velocity is graphed. V is measured in radians/100 yr. The grouping is arbitrary. All graphs in this set are based on series with time steps adjusted to 100 yr. Considering the Vostok temperature graph, it shows deviations from the temperature equivalent of present deuterium content in the ocean (Petit et al. 1999). Each graph has a three part code, e.g. 16ITA30. The number first references the entries in Table 1, the second is the spectrum name, and the third the period length in k yr units. The V graphs are directly comparable for shape and amplitudes. Legend: JKL – John Klondike Bog (Boreal); KAI – Kaiyak Lake (Tundra); JOE – Joe Lake (Tundra); HA – Haging Lake (Tundra); FF – Beaver House (Flin Flon, Boreal); HAY – Hay Lake (Semi desert); RIS – Rise Lake (Grassland); CHE – Cheyenne Bottoms (Grassland); YEL – Lac Yelle (Boreal); EL – E Lake (Boreal); PAT – Lake Patzcuaro (Semi Desert); LDP – Lagoa das Patas (Tropical

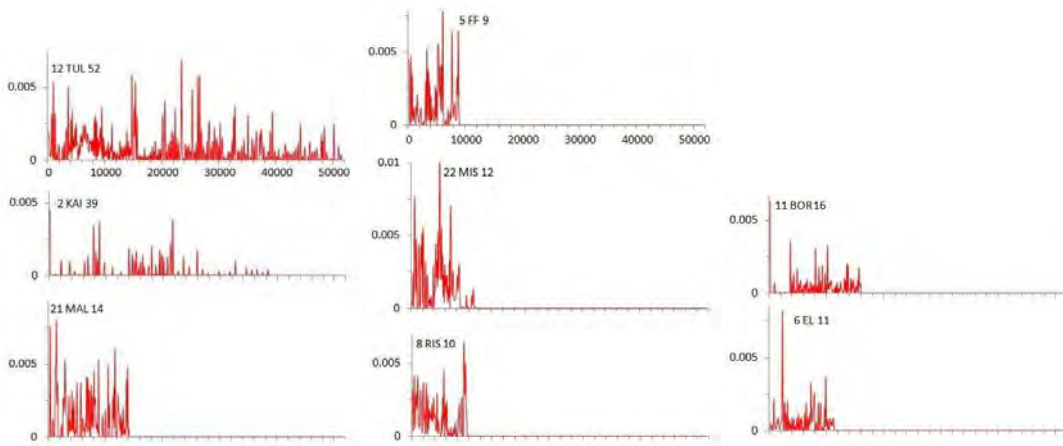
Evergreen); BOR – Boriack Bog (Semi Desert); PAR – Paramo de Miranda (Shrub); TUL – Lake Tulsan (Tropical Seasonal); CAM – Cambará (Tropical Seasonal); GER – Serra Campos Gerais (Tropical Seasonal); BOA – Serra de Boa Vista (Tropical Seasonal); ITA – Morro de Itapeva (Tropical Seasonal); VAC – Vaca Lauquen (Temperate Seasonal); MIS – La Misio (Semi Desert); HAR – Harberton (Semi Desert); MAL – Mallin Book (Semi Desert). See the Process Governance paper for details.



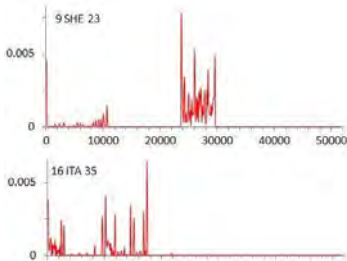
Appendix L1



Appendix L2



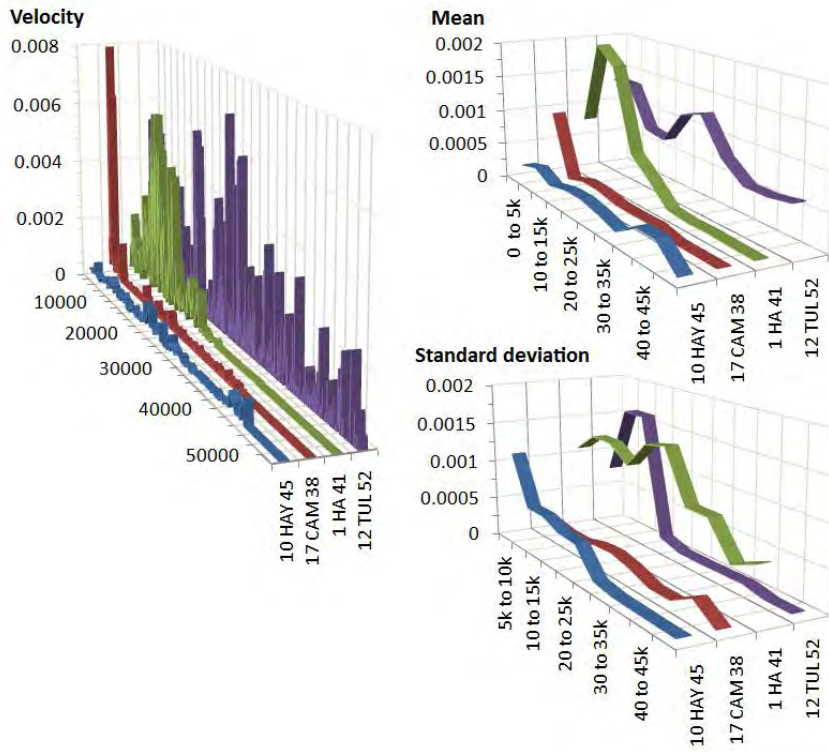
Appendix L3



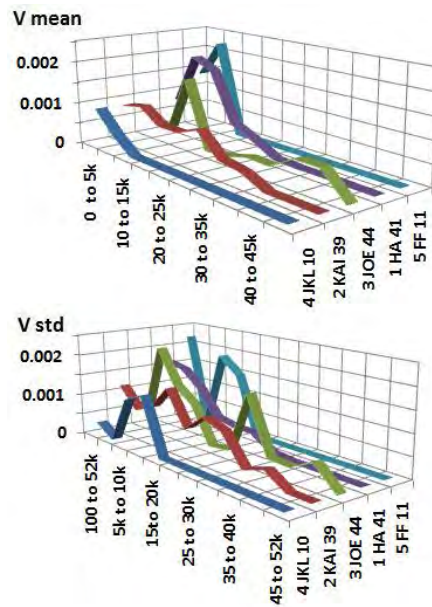
Appendix L4

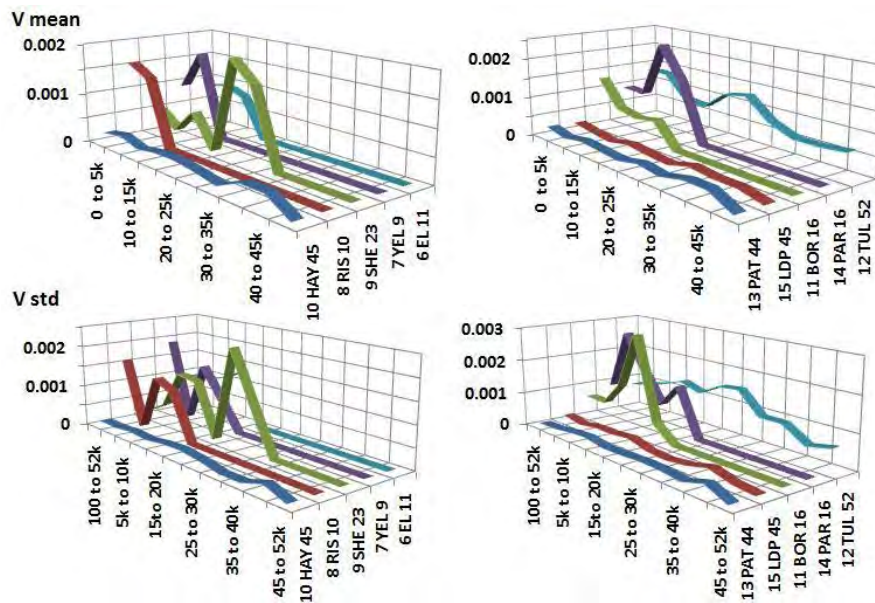
APPENDIX M. Banner graphs

Mean (M) angular velocity (V) and standard deviation of the mean (S) within the time periods shown (Appendix M1) and standard deviation graphs (Appendix M2). The number of observations contributing to the mean is uniformly 50 within the time intervals. Time step width transformation to 100 yr is applied. For abbreviations refer to Table 1 in the Process Governance paper.



Appendix C1. Banner graphs for the typical cases as indicated. For abbreviations refer to Table 1.





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