SpaceMaker2 – User's guide

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Introduction

Program *SpaceMaker2* constructs a matrix of spatial variables obtained by computing either principal coordinate analysis of a truncated matrix of Euclidean distances among sites (PCNM variables), or a polynomial function of the geographic coordinates. The resulting variables can be used as explanatory variables in multiple regression, in canonical analysis, or in the framework of variation partitioning.

Borcard et al. (1992) and Borcard & Legendre (1994) developed a canonical (regression-type) modelling method which allows the decomposition of the variation (sum of squares) of a multivariate (e.g., species abundances) data table into four components: (a) a non-spatially-structured component explained by the environmental variables in the model, (b) a spatially-structured component of environmental variation, (c) a fraction of spatially-structured variation which is not explained by the environmental variables and possibly results from community dynamics, and (d) a residual fraction. The first three components can be mapped separately, providing new insights into community organization and dynamics.

In the 1992 and 1994 papers, we used a polynomial function of the geographic coordinates of the sampling sites to represent broad-scale spatial variation. The use of polynomials for analysing the spatial structure of ecological communities had first been proposed by Legendre (1990). Variation partitioning is also described in Legendre & Legendre (1998).

We have now found a way of representing spatial structures at multiple scales in these analyses. This method is called PCNM analysis, for *Principal Coordinates of Neighbour Matrices* (Borcard & Legendre 2002). PCNM variables are obtained by eigenvalue decomposition (principal coordinate analysis, or PCoA) of a truncated matrix of distances among sites. The behaviour of this method has been investigated using numerical simulations (Borcard & Legendre 2002) and real data sets (Legendre & Borcard 2003, Borcard et al. 2004). When sampling is carried out along a transect or a regular grid, this modelling method allows the estimation of the variance associated with each spatial scale detectable by the sampling design (observation window).

Algorithm

The geographic coordinates of the sampling sites are subjected to the following computation steps in *SpaceMaker2*:

1. The site coordinates, read from an input file or generated by the program, are ranged between the values 0 and 10. Ranging is done in order to prevent the generation of very large monomials, or the overflow of the PCoA algorithm, if very large numbers are entered as site coordinates. Example 1 (below) presents such a case. The coordinates in each geographic dimension are first translated to have a minimum value of zero. The largest value of the translated coordinates (over the geographic dimensions) is calculated and used to divide all coordinates, which are then multiplied by 10. This last, arbitrary multiplication was included to produce monomials as well as principal coordinates that had easy-to-print

values: not too large nor too small. Ranging is a linear transformation. It does not change the explanatory power of the monomials nor that of the PCNM variables in regression or canonical analysis.

2. Obtaining PCNM variables — The ranged coordinates are used to compute a matrix of geographic (i.e., Euclidean) distances among the sites. The distances are truncated using a threshold provided by the user. Any distance larger than the threshold is changed to a value equal to 4 times the threshold; see Borcard & Legendre (2002) for justification. Principal coordinate analysis is conducted on the modified distance matrix. The eigenvalues of the PCoA are printed to the first output file. The principal coordinates corresponding to positive eigenvalues are written to the second output file; they form the set of PCNM variables, ready to be used for statistical modelling.

3. Obtaining a polynomial function — The coordinates are centred on their respective means before computing the monomials. This increases the linear independence of the higher powers with respect to the values representing power 1 of each geographic coordinate (Legendre & Legendre 1998, p. 527). The order of the polynomial, between 2 and 5, is chosen by the user. The orders most often used in ecological analysis are 2 and 3.

Truncation distance in PCNM analysis

The truncation distance should be equal to or larger than the largest distance between first neighbours. The truncation distance should leave all geographic points connected. If this condition is not met and the sites form two or more distinct, connected graphs, a separate set of PCNM variables will be produced for each group of sites. The notion of "first neighbour" is unambiguous along a transect. In Fig. 1, the site coordinates were created by placing U[0,10] random numbers along a line segment; the largest distance between neighbours is between sites 6 and 7. The distance between these two points is 1.44428. Any value as large as or slightly larger than that distance, such as 1.45 or 1.5, could be used as the truncation distance.

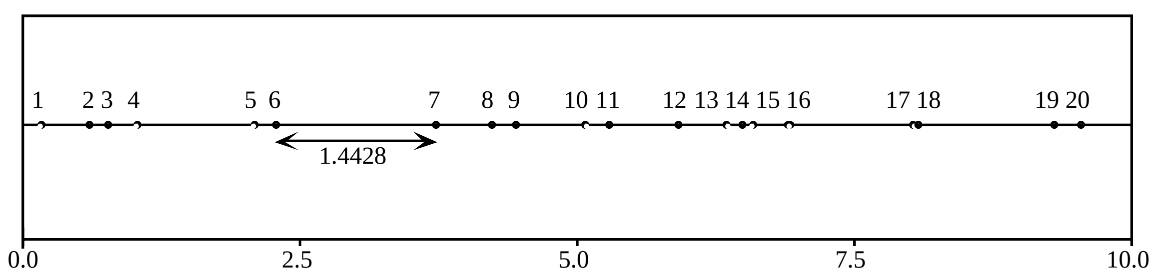

Fig. 1. 20 sites located at random along a transect. The largest distance between first neighbours is shown (double-headed arrow).

For surfaces, the choice of the truncation distance depends on the neighbourhood model. In the following example (Fig. 2), 10 randomly-positioned points are connected by three types of connection networks. These graphs are standard in geographical analysis; they are described in Legendre & Legendre (1998, Section 13.3), among other texts. Connection networks among sites can be computed by *The R Package* (Casgrain & Legendre 2001), among other programs.

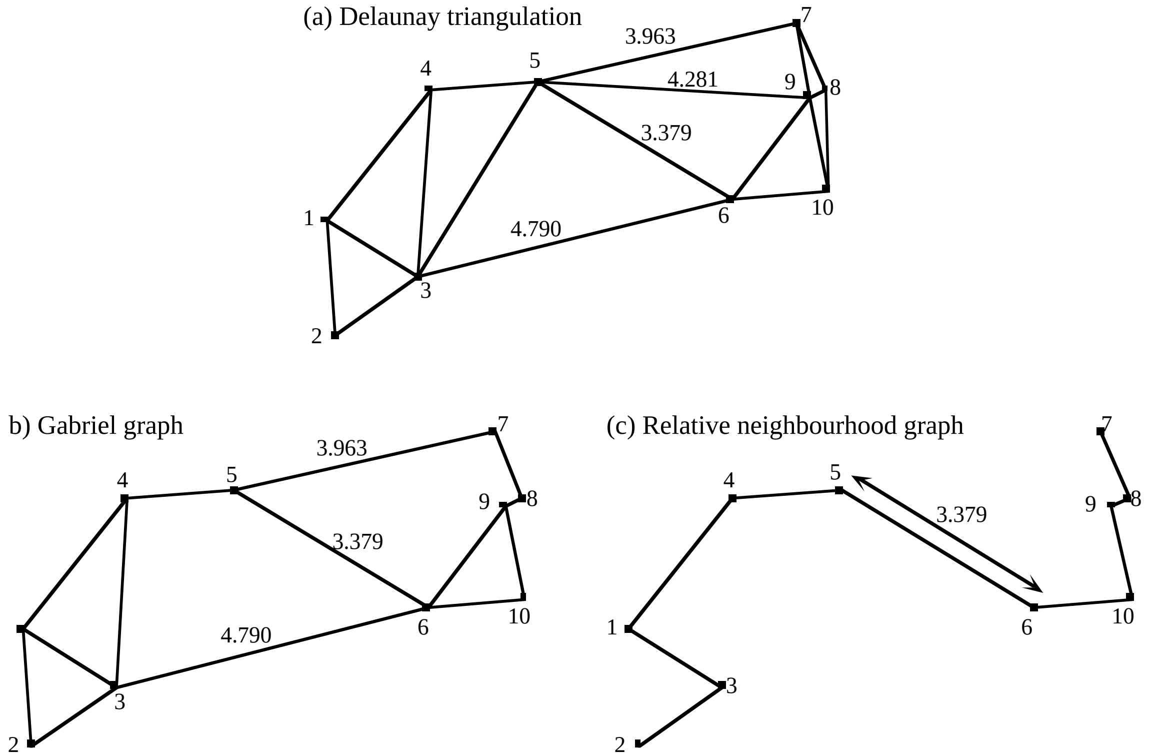

Fig. 2. Ten randomly-located sites connected by three different networks. The edges of the relative neighbourhood graph are a subset of the Gabriel graph. The edges of the Gabriel graph are a subset of the Delaunay triangulation (Toussaint 1980).

The smallest truncation distance that leaves all points connected is 3.379; this is the largest distance between first neighbours in the relative neighbourhood graph. One may, however, prefer to use the largest distance in the Gabriel graph (4.790) or that in the Delaunay triangulation (also 4.790 in this example) in order to facilitate the flow of the PCNM spectral components throughout the graph of sites. The broad-scale PCNM variables so produced will be easier to sort into scales and will have a smoother appearance, but this will be at the expense of resolution at the fine end of the spatial scale.

We don't have, at this point, a theory allowing us to decide among these suggested values of truncation distance. We suggest users to try these various distances in different runs of the *SpaceMaker2* program, obtain the corresponding files of PCNM variables, and use them to analyse the response variables in regression or canonical analysis; obtain a parsimonious model by selecting the significant PCNM variables in each case; compare the models in terms of the total amount of explained variation and the spatial patterns they successfully model.

Supplementary objects in PCNM analysis

The scale of phenomena that can be modelled during PCNM analysis is bounded by the wave lengths of the first and last PCNM variables. The wave length of the first (broadest-scaled) PCNM variable depends on the extent of the study area whereas that of the last (finest-scaled) PCNM variable depends on the truncation distance. So, for all practical purpose, the largest distance between first neighbours sets the finest scale that can be resolved in PCNM analysis.

Consider the following example where sites are approximately equally spaced along a transect or time series, except for two sites, at positions 7 and 10, where observations have not been made and, thus, data are missing (Fig. 3a). The largest distance between adjacent observations is 2.006. If no corrective measure is taken, the truncation distance will have to be 2.006 or some larger value.

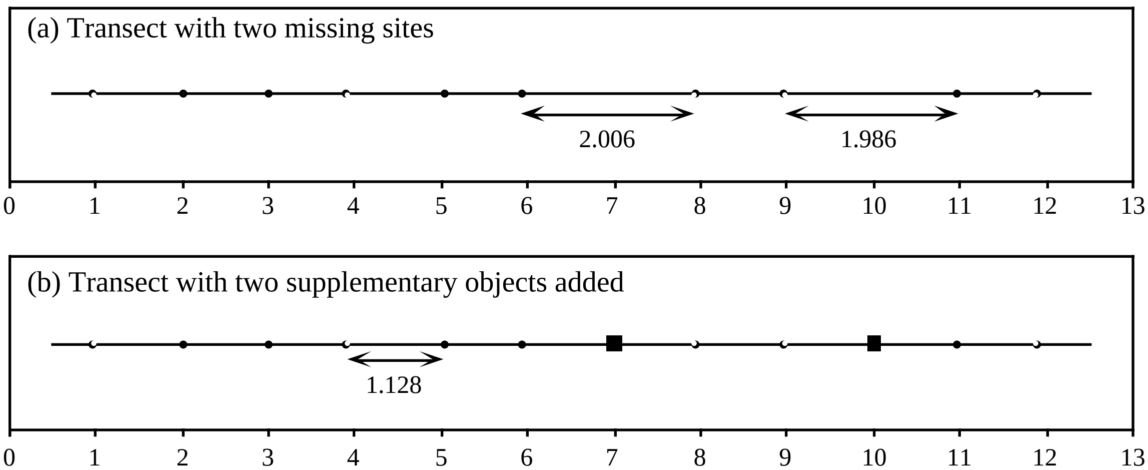

Fig. 3. (a) Transect with 10 observations (open circles). There are two large gaps; they may be due to missing observations. (b) The large gaps are filled by adding supplementary objects (square symbols) to the file of coordinates.

If one wants to investigate spatial structures with periods smaller then 2.006, one can introduce supplementary objects into the file of geographic coordinates to reduce the largest distance between adjacent observations to a smaller value. By adding supplementary objects at geographic positions 7 and 10 along the transect, the largest distance between neighbours is now 1.128. By using these supplementary point coordinates in the construction of the PCNM variables, the analysis will be able to model patterns at the scale of approximately 1 unit, instead of 2. The input file for generation of the PCNM variables would be the following for the sites in Fig. 3b. The *SpaceMaker2* input file is described in more detail in the next section.

10 1 2 ⇐ no. real sites, no. dimensions, no. supplementary sites
0.990 ⇐ second and following lines: coordinates of the real sites along the transect
2.029
3.016
3.932
5.060
5.954
7.960
9.003
10.989

11.905
7.000 ⇐ coordinates of the first supplementary site
10.000 ⇐ coordinates of the second supplementary site
Two supplementary objects were added to the real site coordinates. ⇐ notes
Truncation distance: 1.128 ⇐ notes

The PCNM variables will be created using all sites, real and supplementary. The supplementary sites will then be removed from the analysis since the response variables have not been measured at these sites. Adding supplementary objects comes with a cost: after truncation, the PCNM variables are no longer fully orthogonal to one another. This means that if the PCNM variables are divided into submodels corresponding to broad-scale, medium-scale, and fine-scale patterns, these submodels are no longer linearly independent of one another. For this very small example (10 real sites only), the largest correlation between the PCNM variables was 0.2782; this information is provided by the program when supplementary objects are present in the input file. For larger data sets, the highest correlation between PCNM variables is usually smaller, not exceeding 0.10 if only a few supplementary objects have been added.

Input file

If the file of spatial variables to be generated is based on a linear transect with equispaced sampling units, or on a regular rectangular grid with square mesh, no input file is needed. The program asks for the type of design (transect or grid) and the number of sampling points in each geographic direction.

A file of X or X-Y coordinates is necessary only when the spatial distribution of the sites is irregular and/or if supplementary objects are used. Latitude-longitude or other types of geographic coordinates cannot be used by this program; such data have to be transformed into Cartesian coordinates (with arbitrry origin) before input into *FrameMaker2*. Input files of site coordinates must be formatted as follows.

• Line 1: Number of “real” sites

Number of coordinates: 1 for a transect, 2 for a surface, or 3 for a volume. Volumes are permitted only for PCNM analysis. For technical reasons, polynomial functions are limited by the program to transects or surfaces.

Number of supplementary objects; 0 if no supplementary objects are used.

• Following lines: geographic (X-Y) coordinates of the “real” sites.

• Coordinates of the supplementary sites, if any.

• Notes for the benefit of the user may be written after the last data line, with no consequence. These additional lines are not read by the program.

<u>Example</u>

100 2 2 ⇐ first line: no. real sites, no. dimensions, no. supplementary sites
1.0 3.2 ⇐ second and following lines: coordinates X, X-Y (this example), or X-Y-Z
2.3 4.1
4.3 1.6

5.6 2.9
• •
• •
• • ⇐ coordinates of the last real site
2.0 4.0 ⇐ coordinates of the first supplementary site
4.0 1.5 ⇐ coordinates of the second supplementary site
Blah-blah ⇐ Added comments and notes for the benefit of the author of the file.

Output files

SpaceMaker2 generates two output files; see examples below. File names are provided by the user during the run.

1. The first file gives the general report of the calculations, including the PCoA eigenvalues if PCNM variables have been computed.

2. The second file contains the spatial descriptors:

• PCNM variables — Principal coordinates of a truncated matrix of geographic (Euclidean) distances.

• Polynomial function of the X or X-Y coordinates — The monomials are written in the following order: X, Y, X^2, XY, Y^2, X^3, X^2Y, XY^2, Y^3, X^4, X^3Y, X^2Y^2, XY^3, Y^4, X^5, X^4Y, X^3Y^2, X^2Y^3, XY^4, Y^5. Users can choose the polynomial function to be of orders 2 to 5. Polynomials found in most ecological applications are of orders 2 or 3.

The second output file can be written in three different formats:

(1) A single line per site, whatever the number of output variables (PCNM or monomials).

(2) Folded object vectors, 10 to 12 values per line.

(3) *Canoco* input file written according to the *Canoco FREE* format.

Example 1

The input data file contains the coordinates of 39 site located along the outer rim of a coral reef, Chinchorro Bank, in the Mexican Caribbean (Fig. 4). The data were provided by Prof. Ernesto Arias González, Laboratorio Ecología de Ecosistemas de Arrecifes Coralinos, Departamento de Recursos del Mar, Centro de Investigación y de Estudios Avanzados del Instituto Politécnico Nacional (CINVESTAV, Unidad Mérida), Mérida, México. The coordinates are in metres. The largest distance, 7916 m, is between sites 3 and 25. Any value larger than that, such as 7920 or 8000 m, can be used as truncation distance. The use of PCNM analysis to model the spatial structure of perimeters, such as the littoral zone of lakes or the shore of islands, has been described by Legendre & Borcard (2003).

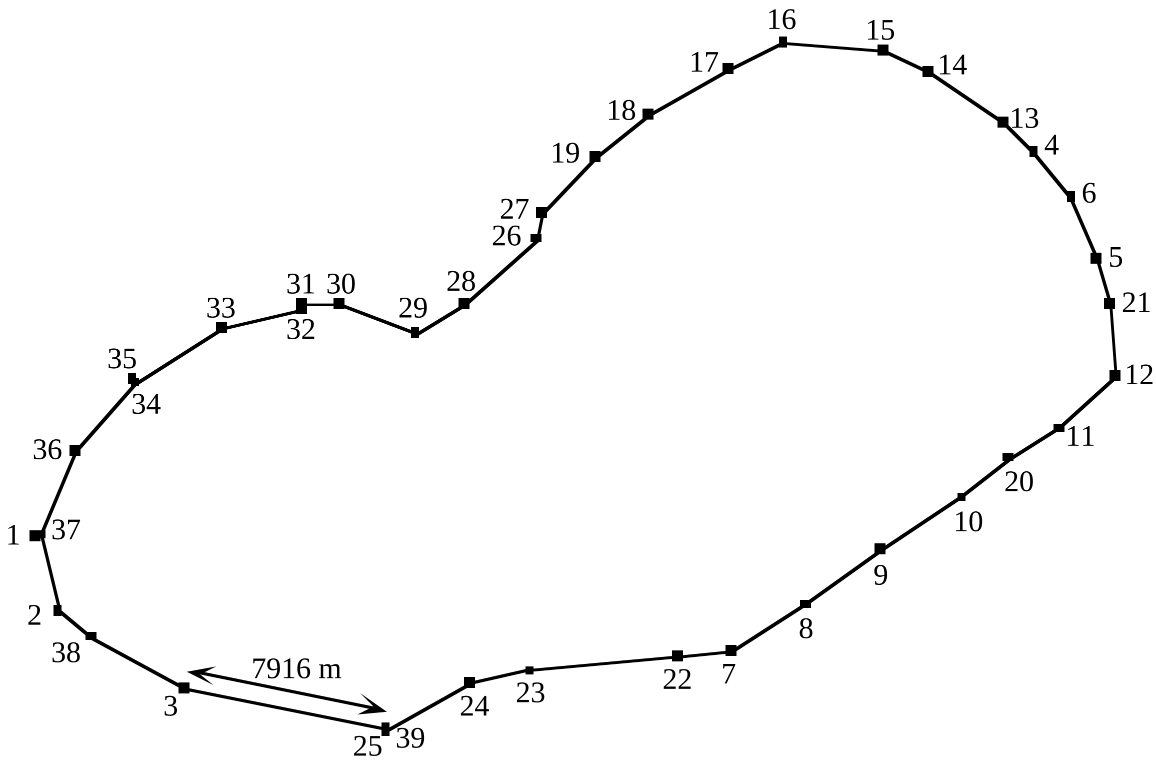

Fig. 4. Map of 39 sampling sites around Chinchorro bank, Mexican Caribbean Sea.

Input file of coordinates — File “Reef_sites.txt”; the coordinates are in metres

```
39 2 0                    ⇐ 39 real sites, 2 geographic dimensions, 0 supplementary site
459986  2033325           ⇐ Beginning the list of site coordinates
457468  2034024
454970  2038992
472501  2071959
469011  2074393
470975  2073478
456200  2060160
457700  2063070
459510  2065977
461220  2069217
463450  2072960
465150  2075120
473446  2070828
475025  2067922
475782  2066123
476073  2062276
475102  2060067
473667  2057008
472337  2054937
462519  2071019
467495  2075010
```

```
456001 2058193
455557 2052423
455141 2050061
453635 2046795
469630 2052720
470400 2052900
467516 2049885
466570 2047985
467504 2044980
467499 2043520
467350 2043480
466671 2040400
464950 2037006
465088 2036926
462760 2034710
459934 2033130
456664 2035320
453611 2046815
The coordinates are in metres.
Truncation distance: 8000 m
```

⇐ Notes for the user's benefit,
⇐ at the end of the file

Dialogue with the program

```
Program "SpaceMaker" creates a file of PCNM
or polynomial spatial variables.

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This program can handle a maximum of   1000 objects.
Name of output file containing the PCoA eigenvalues?
File of PCoA eigenvalues: Reef_out.txt

Name of output file containing the spatial
variables (PCNM or monomials)?
File of spatial variables: Reef_PCNM.txt

Output the file of spatial variables in the following format:
(1) A single line per object
(2) Folded object vectors, 10 to 12 values per line
(3) Canoco input file, FREE format
3

Sampling design:
(1) A transect with equidistant points
(2) A regular grid
(3) File containing X or X-Y coordinates
3

File containing the coordinates?
Input file of coordinates:           Reef_sites.txt
```

```
Do you want to construct
(1) a file of PCNM spatial variables?
(2) a file containing a polynomial of the coordinates?
1

The coordinates were ranged and centred before computing the spatial
variables.

Truncation of the distance matrix --

Highest unmodified value in distance matrix?
Type an integer or a real number, ex. 1 or 65.22.
Use the SAME measurement units as the site coordinates.
8000

Truncation of the distance matrix to the distance    8000.000
yielded   25 positive eigenvalues.

The principal coordinates with positive
eigenvalues (PCNM variables) have been
written out to file Arias_PCNM.txt

Computation time:      4.56 sec.

End of the program.
```

Files of results

The first output file, “Reef_out.txt”, contains a general report of the calculations as well as the PCoA eigenvalues. The list of eigenvalues is written in a format 83 characters wide.

```
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Input file:                 Reef_sites.txt
   39 objects
    2 coordinates
    0 supplementary objects


The coordinates were ranged and centred before computing the spatial variables.
```

```
Matrix of PCNM spatial variables
   Highest unmodified distance value =     8000.000
   Multiplier for "large distances"  =        4.000


Sum of positive eigenvalues              1246.40475
Sum of negative eigenvalues              -301.31295
Trace of Gower-centred matrix             945.09180

Number of positive eigenvalues:  25

Eigenvalues of the PCoA:

  203.696465  172.866781  153.238229  143.291715  121.299409  110.331202   82.202323   70.769783
   47.615413   32.413312   29.006806   26.643821   22.933849   16.203086   11.233476    1.726613
    0.448503    0.202374    0.156998    0.081796    0.025730    0.015904    0.000883    0.000256
    0.000027    0.000000   -0.000277   -0.006714   -0.256261  -10.923364  -16.335104  -18.307547
  -24.323568  -28.748019  -31.282883  -35.833256  -38.135677  -47.134556  -50.025725

Computation time:      4.56 sec.

End of the program.
```

The second output file, “Reef_PCNM.txt”, contains the PCNM variables. The user requested that file to be written in *Canoco FREE* format, ready to be used by the program *Canoco*. A *Canoco* input file starts with 3 heading lines and ends with lists of variable and object names. The file, which is fairly large, is not listed in full; only the PCNM values corresponding to the first and last sites are shown.

```
File of PCNM variables
FREE
        25         39                                           ⇐ 25 PCNM variables, 39 sites
  2.719989   3.889062   0.178854   1.276652   1.443724  -0.033818   0.464347  -0.238400  -0.188884
0.588421  -0.429802
 -0.626545   0.508678  -0.343419   0.221327  -0.016247  -0.074972   0.086739   0.064473  -0.000647
0.011153   0.034976
  0.000907   0.010840   0.000103

[...]
```

On PCs, *Canoco* cannot read files with lines longer than 128 characters; Canoco 3.xx on Macintosh does not have that limitation. So, we limited line lengths in the *Canoco FREE* format to 120 or 121 characters, depending on the size of the numbers to be written. In this output list, physical lines are limited to 90 characters, so that each 121-character record is folded into two physical lines.

```
[...]

  0.106487   0.977757  -2.783199  -1.618244  -2.294036   3.099436  -1.506407   0.374305  -0.967193
0.441178   0.086930
  0.626184   0.080126   0.296258  -0.319414  -0.167187  -0.076110  -0.030150  -0.038051   0.000583
-0.000897  -0.003682
 -0.000164   0.000235  -0.003654
PCNM 1  PCNM 2  PCNM 3  PCNM 4  PCNM 5  PCNM 6  PCNM 7  PCNM 8  PCNM 9  PCNM10
```

```
PCNM11  PCNM12  PCNM13  PCNM14  PCNM15  PCNM16  PCNM17  PCNM18  PCNM19  PCNM20
PCNM21  PCNM22  PCNM23  PCNM24  PCNM25
Site 1  Site 2  Site 3  Site 4  Site 5  Site 6  Site 7  Site 8  Site 9  Site10
Site11  Site12  Site13  Site14  Site15  Site16  Site17  Site18  Site19  Site20
Site21  Site22  Site23  Site24  Site25  Site26  Site27  Site28  Site29  Site30
Site31  Site32  Site33  Site34  Site35  Site36  Site37  Site38  Site39
```

Example 2: Thau marine lagoon

The input data file contains 63 site coordinates. These sites were studied in the Thau marine Lagoon in Southern France (Legendre et al. 1989).

Input file of coordinates — File “Thau_XY.txt”

```
63 2 0                         ⇐ 63 real sites, 2 geographic dimensions, 0 supplementary site
   3 10                        ⇐ Beginning the list of site coordinates
   4 9
   4 10
   5 9
   5 10
   5 11
   6 8
   6 9
   6 10
   7 7
   7 8
   7 9
   7 10
   8 7
   8 8
   8 9
   8 10
   9 7
   9 8
   9 9
   9 10
  10 6
  10 7
  10 8
  10 9
  11 5
  11 6
  11 7
  11 8
  11 9
  12 5
  12 6
  12 7
  12 8
  12 9
  13 4
  13 5
  13 6
  13 7
```

```
  13 8
  14 4
  14 5
  14 6
  14 7
  15.1 1.4
  15 2
  15 4
  15 5
  15 6
  15 7
  16 1
  16 2
  16 3
  16 4
  16 5
  16 6
  17 2
  17 3
  17 4
  17 5
  17 6
  18 4
  19 4
The coordinates are in km.
```
⇐ Note for the user's benefit, at the end of the file

Dialogue with the program

```
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or polynomial spatial variables.

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This program can handle a maximum of   1000 objects.
Name of output file containing the PCoA eigenvalues?
File of PCoA eigenvalues: Thau_out.txt

Name of output file containing the spatial
variables (PCNM or monomials)?
File of spatial variables: Thau_poly.txt

Output the file of spatial variables in the following format:
(1) A single line per object
(2) Folded object vectors, 10 to 12 values per line
(3) Canoco input file, FREE format
1
```

```
Sampling design:
(1) A transect with equidistant points
(2) A regular grid
(3) File containing X or X-Y coordinates
3

File containing the coordinates?
Input file of coordinates:                    Thau_XY.txt

Do you want to construct
(1) a file of PCNM spatial variables?
(2) a file containing a polynomial of the coordinates?
2

The coordinates were ranged and centred before computing the spatial
variables.

Order of the polynomial? 2 to 5
3

The monomials have been written out to file Thau_poly.txt

End of the program.
```

Files of results

The first output file, “Thau_out.txt”, contains a general report of the calculations.

```
Program "SpaceMaker" creates a file of PCNM
 or polynomial spatial variables.

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 Input file:                    Thau_XY.txt
    63 objects
     2 coordinates
     0 supplementary objects


 The coordinates were ranged and centred before computing the spatial variables.

 Constructing a polynomial of order            3

 End of the program.
```

The second output file, “Thau_poly.txt”, contains the 9 monomials forming the third-order polynomial. The user requested all monomials to be written onto a single line per site. The heading line of the file indicates the number of sites (63) and monomials (9).

63 9 ⇐ 63 sites, 9 monomials

-0.530853	0.213889	0.281805	-0.113544	0.045748	-0.149597	0.060275	-0.024286	0.009785
-0.468353	0.151389	0.219355	-0.070903	0.022919	-0.102735	0.033208	-0.010734	0.003470
-0.468353	0.213889	0.219355	-0.100176	0.045748	-0.102735	0.046918	-0.021426	0.009785
-0.405853	0.151389	0.164717	-0.061442	0.022919	-0.066851	0.024936	-0.009302	0.003470
-0.405853	0.213889	0.164717	-0.086807	0.045748	-0.066851	0.035231	-0.018567	0.009785
-0.405853	0.276389	0.164717	-0.112173	0.076391	-0.066851	0.045526	-0.031003	0.021114
-0.343353	0.088889	0.117891	-0.030520	0.007901	-0.040478	0.010479	-0.002713	0.000702
-0.343353	0.151389	0.117891	-0.051980	0.022919	-0.040478	0.017847	-0.007869	0.003470
-0.343353	0.213889	0.117891	-0.073439	0.045748	-0.040478	0.025216	-0.015708	0.009785
-0.280853	0.026389	0.078879	-0.007411	0.000696	-0.022153	0.002082	-0.000196	0.000018
-0.280853	0.088889	0.078879	-0.024965	0.007901	-0.022153	0.007011	-0.002219	0.000702
-0.280853	0.151389	0.078879	-0.042518	0.022919	-0.022153	0.011941	-0.006437	0.003470
-0.280853	0.213889	0.078879	-0.060071	0.045748	-0.022153	0.016871	-0.012849	0.009785
-0.218353	0.026389	0.047678	-0.005762	0.000696	-0.010411	0.001258	-0.000152	0.000018
-0.218353	0.088889	0.047678	-0.019409	0.007901	-0.010411	0.004238	-0.001725	0.000702
-0.218353	0.151389	0.047678	-0.033056	0.022919	-0.010411	0.007218	-0.005004	0.003470
-0.218353	0.213889	0.047678	-0.046703	0.045748	-0.010411	0.010198	-0.009989	0.009785
-0.155853	0.026389	0.024290	-0.004113	0.000696	-0.003786	0.000641	-0.000109	0.000018
-0.155853	0.088889	0.024290	-0.013854	0.007901	-0.003786	0.002159	-0.001231	0.000702
-0.155853	0.151389	0.024290	-0.023594	0.022919	-0.003786	0.003677	-0.003572	0.003470
-0.155853	0.213889	0.024290	-0.033335	0.045748	-0.003786	0.005195	-0.007130	0.009785
-0.093353	-0.036111	0.008715	0.003371	0.001304	-0.000814	-0.000315	-0.000122	-0.000047
-0.093353	0.026389	0.008715	-0.002463	0.000696	-0.000814	0.000230	-0.000065	0.000018
-0.093353	0.088889	0.008715	-0.008298	0.007901	-0.000814	0.000775	-0.000738	0.000702
-0.093353	0.151389	0.008715	-0.014133	0.022919	-0.000814	0.001319	-0.002140	0.003470
-0.030853	-0.098611	0.000952	0.003042	0.009724	-0.000029	-0.000094	-0.000300	-0.000959
-0.030853	-0.036111	0.000952	0.001114	0.001304	-0.000029	-0.000034	-0.000040	-0.000047
-0.030853	0.026389	0.000952	-0.000814	0.000696	-0.000029	0.000025	-0.000021	0.000018
-0.030853	0.088889	0.000952	-0.002743	0.007901	-0.000029	0.000085	-0.000244	0.000702
-0.030853	0.151389	0.000952	-0.004671	0.022919	-0.000029	0.000144	-0.000707	0.003470
0.031647	-0.098611	0.001002	-0.003121	0.009724	0.000032	-0.000099	0.000308	-0.000959
0.031647	-0.036111	0.001002	-0.001143	0.001304	0.000032	-0.000036	0.000041	-0.000047
0.031647	0.026389	0.001002	0.000835	0.000696	0.000032	0.000026	0.000022	0.000018
0.031647	0.088889	0.001002	0.002813	0.007901	0.000032	0.000089	0.000250	0.000702
0.031647	0.151389	0.001002	0.004791	0.022919	0.000032	0.000152	0.000725	0.003470
0.094147	-0.161111	0.008864	-0.015168	0.025957	0.000834	-0.001428	0.002444	-0.004182
0.094147	-0.098611	0.008864	-0.009284	0.009724	0.000834	-0.000874	0.000915	-0.000959
0.094147	-0.036111	0.008864	-0.003400	0.001304	0.000834	-0.000320	0.000123	-0.000047
0.094147	0.026389	0.008864	0.002484	0.000696	0.000834	0.000234	0.000066	0.000018
0.094147	0.088889	0.008864	0.008369	0.007901	0.000834	0.000788	0.000744	0.000702
0.156647	-0.161111	0.024538	-0.025238	0.025957	0.003844	-0.003953	0.004066	-0.004182
0.156647	-0.098611	0.024538	-0.015447	0.009724	0.003844	-0.002420	0.001523	-0.000959
0.156647	-0.036111	0.024538	-0.005657	0.001304	0.003844	-0.000886	0.000204	-0.000047
0.156647	0.026389	0.024538	0.004134	0.000696	0.003844	0.000648	0.000109	0.000018
0.225397	-0.323611	0.050804	-0.072941	0.104724	0.011451	-0.016441	0.023604	-0.033890
0.219147	-0.286111	0.048025	-0.062700	0.081860	0.010525	-0.013741	0.017939	-0.023421
0.219147	-0.161111	0.048025	-0.035307	0.025957	0.010525	-0.007737	0.005688	-0.004182
0.219147	-0.098611	0.048025	-0.021610	0.009724	0.010525	-0.004736	0.002131	-0.000959
0.219147	-0.036111	0.048025	-0.007914	0.001304	0.010525	-0.001734	0.000286	-0.000047
0.219147	0.026389	0.048025	0.005783	0.000696	0.010525	0.001267	0.000153	0.000018
0.281647	-0.348611	0.079325	-0.098185	0.121530	0.022342	-0.027654	0.034228	-0.042367
0.281647	-0.286111	0.079325	-0.080582	0.081860	0.022342	-0.022696	0.023055	-0.023421
0.281647	-0.223611	0.079325	-0.062979	0.050002	0.022342	-0.017738	0.014083	-0.011181
0.281647	-0.161111	0.079325	-0.045376	0.025957	0.022342	-0.012780	0.007311	-0.004182
0.281647	-0.098611	0.079325	-0.027774	0.009724	0.022342	-0.007822	0.002739	-0.000959
0.281647	-0.036111	0.079325	-0.010171	0.001304	0.022342	-0.002865	0.000367	-0.000047

```
0.344147  -0.286111   0.118437  -0.098464   0.081860   0.040760  -0.033886   0.028172  -0.023421
0.344147  -0.223611   0.118437  -0.076955   0.050002   0.040760  -0.026484   0.017208  -0.011181
0.344147  -0.161111   0.118437  -0.055446   0.025957   0.040760  -0.019082   0.008933  -0.004182
0.344147  -0.098611   0.118437  -0.033937   0.009724   0.040760  -0.011679   0.003347  -0.000959
0.344147  -0.036111   0.118437  -0.012428   0.001304   0.040760  -0.004277   0.000449  -0.000047
0.406647  -0.161111   0.165362  -0.065515   0.025957   0.067244  -0.026642   0.010555  -0.004182
0.469147  -0.161111   0.220099  -0.075585   0.025957   0.103259  -0.035460   0.012178  -0.004182
```

Example 3: Regular grid

No input data file is necessary to construct regular transects or regular grids.

Dialogue with the program

```
Program "SpaceMaker" creates a file of PCNM
or polynomial spatial variables.

Daniel Borcard & Pierre Legendre
Departement de sciences biologiques
Universite de Montreal
   (c) Daniel Borcard & Pierre Legendre, 2001, 2003

This program can handle a maximum of   1000 objects.
Name of output file containing the PCoA eigenvalues?
File of PCoA eigenvalues: Grid_out.txt

Name of output file containing the spatial
variables (PCNM or monomials)?
File of spatial variables: Grid_PCNM.txt

Output the file of spatial variables in the following format:
(1) A single line per object
(2) Folded object vectors, 10 to 12 values per line
(3) Canoco input file, FREE format
3

Sampling design:
(1) A transect with equidistant points
(2) A regular grid
(3) File containing X or X-Y coordinates
2

Regular grid:
number of rows and columns of points (two integers)
10 5

Save the file of X-Y coordinates?
(0) No, (1) Yes
0

Do you want to construct
(1) a file of PCNM spatial variables?
(2) a file containing a polynomial of the coordinates?
1
```

```
The coordinates were ranged and centred before computing the spatial
variables.

Truncation of the distance matrix --

Highest unmodified value in distance matrix?
Type an integer or a real number, ex. 1 or 65.22.
Use the SAME measurement units as the site coordinates.
1.42
```

⇐ Truncation distance was chosen to be the diagonal of a square of size 1: √2 = 1.42

```
Truncation of the distance matrix to the distance       1.420
yielded   30 positive eigenvalues.

The principal coordinates with positive
eigenvalues (PCNM variables) have been
written out to file Grid_PCNM.txt

Computation time:      2.43 sec.

End of the program.
```

Files of results

The first output file, “Grid_out.txt”, contains a general report of the calculations as well as the PCoA eigenvalues. The list of eigenvalues is written in a format 83 characters wide.

```
Program "SpaceMaker" creates a file of PCNM
or polynomial spatial variables.

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Universite de Montreal
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Regular grid containing
    10 horizontal points
     5 vertical points


The coordinates were ranged and centred before computing the spatial variables.

Matrix of PCNM spatial variables
   Highest unmodified distance value =        1.420
   Multiplier for "large distances"  =        4.000


Sum of positive eigenvalues              1212.82021
Sum of negative eigenvalues              -356.39445
Trace of Gower-centred matrix             856.42576
```

```
Number of positive eigenvalues:  30

Eigenvalues of the PCoA:

  140.246907  123.968442  112.092609  103.111550   96.254941   88.953797   71.199392   70.766328
   61.419551   52.383709   50.022583   45.590287   38.637719   35.948235   28.403096   25.579667
   14.422341   11.548039   11.266913    8.460799    7.659351    3.938953    3.592394    1.801843
    1.655869    1.425754    1.130142    0.792981    0.441587    0.104426    0.000000   -0.191186
   -0.421301   -0.567275   -2.656268   -5.359652   -9.793036  -10.528118  -12.538399  -14.311698
  -17.117103  -17.208658  -24.358471  -24.685871  -30.531468  -33.299596  -33.666930  -35.479488
  -37.897685  -45.782244

Computation time:      2.43 sec.

End of the program.
```

The second output file, “Reef_PCNM.txt”, contains the PCNM variables. The user requested that file to be written in *Canoco FREE* format, ready to be used by the program *Canoco*. A *Canoco* input file starts with 3 heading lines and ends with lists of variable and object names. The file, which is fairly large, is not listed in full; only the PCNM values corresponding to the first and last sites are shown.

```
File of PCNM variables
FREE
          30          50                                                ⇐ 30 PCNM variables, 50 sites
   0.788104   0.976359  -0.635937  -1.170445   1.098513  -1.519668   1.157035   1.631427  -0.227912
-0.963308  -1.492549
  -1.178521   0.757340   1.342649   1.124678  -1.205501   0.925407  -0.117847  -0.332645   0.189826
-0.536723   0.429422
  -0.176319  -0.080628   0.148324   0.192393  -0.206168   0.187922   0.140234  -0.062670

[...]
```

On PCs, *Canoco* cannot read files with lines longer than 128 characters; Canoco 3.xx on Macintosh does not have that limitation. So, we limited line lengths in the *Canoco FREE* format to 120 or 121 characters, depending on the size of the numbers to be written. In this output list, physical lines are limited to 90 characters, so that each 121-character record is folded into two physical lines.

```
[...]

  -0.788104   0.976359   0.635937  -1.170445  -1.098513   1.519668   1.157035   1.631427  -0.227912
0.963308   1.492549
  -1.178521  -0.757340  -1.342649   1.124678  -1.205501  -0.925407   0.117847  -0.332645   0.189826
0.536723   0.429422
   0.176319   0.080628   0.148324  -0.192393  -0.206168  -0.187922   0.140234   0.062670
PCNM 1  PCNM 2  PCNM 3  PCNM 4  PCNM 5  PCNM 6  PCNM 7  PCNM 8  PCNM 9  PCNM10
PCNM11  PCNM12  PCNM13  PCNM14  PCNM15  PCNM16  PCNM17  PCNM18  PCNM19  PCNM20
PCNM21  PCNM22  PCNM23  PCNM24  PCNM25  PCNM26  PCNM27  PCNM28  PCNM29  PCNM30
Site 1  Site 2  Site 3  Site 4  Site 5  Site 6  Site 7  Site 8  Site 9  Site10
Site11  Site12  Site13  Site14  Site15  Site16  Site17  Site18  Site19  Site20
Site21  Site22  Site23  Site24  Site25  Site26  Site27  Site28  Site29  Site30
Site31  Site32  Site33  Site34  Site35  Site36  Site37  Site38  Site39  Site40
Site41  Site42  Site43  Site44  Site45  Site46  Site47  Site48  Site49  Site50
```

Disclaimer

This program is provided without any explicit or implicit warranty of correct functioning. It has been developed as part of a university-based research program. If, however, you should encounter problems with this program, the authors will be happy to help solve them. Researchers may use this program for scientific purposes, but the source code remains the property of Daniel Borcard and Pierre Legendre. Users of the program may refer to the present user's manual as follows:

Borcard, D. and P. Legendre. 2004. SpaceMaker2 – User's guide. Département de sciences biologiques, Université de Montréal. 20 pages.
Available from the WWWeb site <http://www.fas.umontreal.ca/biol/legendre/>.

Program distribution

Computer programs written by P. Legendre and collaborators are available from our base WWWeb site. They include FORTRAN77 source code, documentation, sample files and executable programs. Versions for MacOS (68k or PowerPC) and 32-bit DOS (suitable for DOS sessions under Windows 95/98/NT) are provided. WWWeb address: <http://www.fas.umontreal.ca/biol/legendre/>.

The programs are written in FORTRAN77 in order to facilitate diffusion. Indeed, there is a compiler, GNU FORTRAN (or g77; see http://www.gnu.org/software/fortran/), that is freely available for this level of FORTRAN, for the DOS/Windows, MacOS X, Unix, and Linux families of operating systems.

Three versions of the program are distributed.

• "SpaceMaker2 n=500" is for a maximum of 500 sites. The Macintosh version of the program requires 13.2 Mb RAM for running.

• "SpaceMaker2 n=1000" is for a maximum of 1000 sites. The Macintosh version of the program requires 51.9 Mb RAM for running.

• "SpaceMaker2 n=2000" is for a maximum of 2000 sites. The Macintosh version of the program requires 206.7 Mb RAM for running.

DOS sessions under Microsoft Windows

For DOS sessions under Windows, the following precautions must be taken:

1. At the beginning of each run, users must provide two file names for the output of the program. The program will not run if the names of these files already exist in the program folder. If this happens, destroy or rename the previously-created files with same names, or use different names for the output files.

2. When typing the name of the file of coordinates, the full name must be given. The name must include any extension, such as ".txt", that the file might possess. *Warning*: some versions of Windows do not show name extensions! If the program does not run, the presence of a hidden extension to the name of the file is the most probable cause. Make sure you can see the extension, or rename the file without any extension. *Hint*: a file that displays a NotePad icon has a (possibly hidden) ".txt" extension.

3. For coordinate input files that do not reside in the program folder, the full path length must be typed. It is often easier to move the coordinate input file to the folder that houses the *SpaceMaker2.exe* program.

4. Coordinate input files names should contain no blanks.

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Legendre, P., M. Troussellier, V. Jarry & M.-J. Fortin. 1989. Design for simultaneous sampling of ecological variables: from concepts to numerical solutions. Oikos 55: 30-42.

Toussaint, G. 1980. The relative neighbourhood graph of a finite planar set. Pattern Recogn. 12: 261-268.

Unix/DOS user's notes prepared by Philippe Casgrain

The Unix (including MacOS X) and DOS versions of this program were compiled using g77, the GNU FORTRAN compiler. They are command-line tools, which means that they must be started from the command line. In Windows 98, Windows NT and derived forms (Windows 2000, Windows XP), simply click on the program icon to start it; the program's dialogue will appear in a black DOS window.

Files created by the program, such as the "Grid_PCNM.txt" file, cannot be overwritten by the FORTRAN program. If, after launching, the program ends abruptly and a message is displayed, such as:

```
open: 'new' file exists
apparent state: unit 9 named Grid_PCNM.txt
lately writing direct unformatted external IO
Abort
```

this means that a file called "Grid_PCNM.txt" already exists in the current directory. Rename or remove that file before running the program again.

Unix instructions

1. Open a new shell.
MacOS X users: open /Applications/Utilities/Terminal

2. At the prompt
(e.g. "[localhost:~] username%") type:
"cd /path/to/the/program/"
where "/path/to/the/program/" represents
the directory where the program is found.
Examples: /Applications, ~/Desktop, etc.

Don't forget that Unix systems are case-sensitive:
upper- and lowercase letters are different.

DOS instructions under Windows 95

1. Open a new shell: from the Start menu,
choose Programs → Accessories → MS-DOS

2. At the DOS prompt (e.g., C:\WINDOWS\>),
type "cd c:\path\to\the\program"
where "\path\to\the\program" represents
the directory where the program is found.

Examples: c:\tmp, c:\windows\desktop, etc.

3. Press the *Return* key.

4. Type the name of the program to start it.

Unix — Example: **.**/SpaceMaker2
(the prefix "**.**/" is essential if the program is not part of your usual path for command-line utilities)

DOS — Example: SpaceMaker2**.**exe

5. Press the *Return* key.

6. Follow the on-screen instructions.

7. If your input file has an extension, like ".txt", you have to type it when you provide the name of the input file, even if the extension does not appear in the file list.
