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AN APPLICATION OF CORRESPONDENCE ANALYSIS, DETRENDED CORRESPONDENCE ANALYSIS AND CANONICAL CORRESPONDENCE ANALYSIS WITH REFERENCE TO THE VEGETATION AND ENVIRONMENT OF CALCAREOUS HILLS AROUND KARACHI

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ABSTRACT

Thirty stands on the slopes of calcareous hills around Karachi and its vicinity were sampled by point-centered quarter method. Sampling was restricted to trees, shrubs and perennial herbs. Soil samples were collected from each stand and were analyzed physically and chemically. The vegetational and environmental (soil) data sets were subjected to various multivariate data exploratory techniques including principal component analysis (PCA), correspondence analysis (CA), detrended correspondence analysis (DCA), and canonical correspondence analysis (CCA). The results of the different techniques were compared. Each technique provided useful, often unique, information pertaining to the ecosystem. In general, information on compositional variation was helpful in the interpretation of the vegetational dynamics of the hills. Canonical correspondence analysis was able to expose the underlying environmental gradients associated with the vegetational variation. The merits and demerits of the techniques are discussed.

Key-words: Correspondence analysis, detrended correspondence analysis, Canonical correspondence analysis

INTRODUCTION

Multivariate methods are now widely used by ecologist, both because of their ability to detect and describe inherent patterns of a group of variables and because of an increased acceptance that univariate tests are inappropriate in multivariate situations (Green, 1980). The analysis of correlation between ecological factors and the trend of variation between communities and species can be performed by the application of ordination methods. Numerous techniques for ordinating ecological data and exposing underlying ecological relationships have been devised over the past four decades and have often been reviewed (Orloci, 1978; Greig-Smith, 1983; Shaukat and Uddin, 1989). The methods are mainly based on the extraction of eigenvalues and eigenvectors from symmetric resemblance or correlation matrices. Basically two types of ordinations can be distinguished, *i.e.*, direct and indirect ordination. Direct ordination arranges samples along one or more ecologically important environmental gradients (Whittaker, 1973) and should only be used where the effects of specific environmental gradients are of primary concern (Beals, 1973). On the other hand, indirect ordination arranges samples or species along one or more abstract axes which may or may not be related to environmental variables or complexes (Austin, 1976). Additionally, this technique provides reduction in dimensionality by identifying groups of similar species (Orloci, 1978). Historically, the first effective indirect ordination technique was polar ordination (Bray and Curtis, 1957), and despite several drawbacks, it is still used by some ecologist (Beckett, 1977; Nicholson et al., 1979). The major disadvantage of this technique is the subjective choice of the end points for the axes (Culp and Davies, 1980).

Correspondence analysis (CA) is now a widely used ordination technique that is preferred over the principal component analysis (PCA). One major advantage is that corresponding site and species ordinations are obtained simultaneously, allowing the ecologist to explore the ecological interrelationships between sites and species in a single analysis. CA is derived through an eigenanalysis (similar to PCA) or through a series of weighted-average operations. Hill (1973) named the latter procedure as reciprocal averaging (RA). Hill (1974) advocates that RA is equivalent to Fisher's contingency table analysis, is a generalization of Whittaker's gradient analysis and is a refinement of Kendall's serration. French School that originally developed the correspondence analysis maintain that a deference exits between CA and RA. Theoretically the methods are the same, apart possibly from scaling of axes, but correspondence analysis has been developed for wider practical application (Greenacre, 1984).

Detrended correspondence analysis (DCA) is also an eigenvector technique which ordinates simultaneously both the species and the sites by a re-iterative weighting procedure but differs from CA in the trend removal in successive axes with optimal re-scaling of axes to remove compression of points at either end (Hill and Gauch, 1980). Axes subsequent to the first are derived by the weighted-averages procedure but, at the end of each iteration regression is taken out in the first axis so that the new axes are orthogonal with those of the first axis. Detrending is basically achieved by the division of the first axis into segments, within which the samples are adjusted to have zero means. Another attractive feature is that the axes are re-scaled by expanding the local scaling in proportion to the reciprocal of the local mean square deviation with the practical implication that equal distances in the ordination space tend to correspond to equal differences in species composition (Hill and Gauch, 1980). The robustness, freedom from distortion and the meaningful axis units of DCA render it a powerful tool for subsequent environmental interpretation (Whittaker, 1987).

Canonical correspondence analysis (CCA), an extension of correspondence analysis (CA), was developed to relate community composition to known variation in the environment (ter Braak, 1986). In CA ordination axes are typically interpreted with the help of external knowledge regarding the environmental variables. Such two-step approach has been termed as indirect gradient analysis. In CCA the axes are constructed in the light of the environmental measurements with the added constraint that the axes be the linear combinations of environmental variables. This allows relating the compositional characteristics directly with the environmental variables or group of variables as environmental gradients. In terms of a linear model, CCA is based on a weighted multivariate regression of transform species data on the covariable data as well as the environmental data set (Sabatier et al, 1989). Detrending can also be introduced in this technique to achieve the removal of horseshoe effects. Detrending is particularly necessary in CCA when the species response is Gaussian with respect to environmental gradients. The principal advantage of CCA is that triplots can be obtained in which the points represent species and sites while vectors represent the environmental variables.

MATERIALS AND METHODS

Correspondence Analysis

In correspondence analysis, we have only displayed the data along a one-dimensional axis and the reciprocal averaging procedure can be easily extended to a second dimension by removing the first solution from the data, as we did with the trivial solution, and repeating to find an additional RA solution. This process can be repeated and giving an extra solution each time. However, rather than adopt this computational approach, we prefer to proceed via matrix algebra and find the full set of solutions; this is more in the theme of correspondence analysis.

According to the matrix algebra, the transition formulae

$$a_i = \rho^{-1} \sum\nolimits_j x_{ij} \frac{b_j}{r_i} \quad ; \; i = 1,2,3,\ldots\ldots,n, \quad \ldots.[1]$$

$$b_j = \rho^{-1} \sum\nolimits_i x_{ij} \frac{a_i}{c_j} \quad ; \; j = 1,2,3,\ldots\ldots,p, \quad \ldots.[2]$$

are

$$a = \rho^{-1} R^{-1} X'b \quad \ldots\ldots\ldots\ldots\ldots..[3]$$

and

$$b = \rho^{-1} C^{-1} X'a \quad \ldots\ldots\ldots\ldots\ldots..[4]$$

Where **R** and **C** are diagonal matrices with elements r_i and c_j representing species and site totals. Substituting the value of **a** from equation [3] into equation [4] we have

$$b = \rho^{-2} C^{-2} X'R^{-1} Xb \quad \ldots\ldots\ldots\ldots\ldots..[5]$$

and after some manipulation

$$\rho^2 C^{\frac{1}{2}} b = \left[R^{-\frac{1}{2}} X C^{-\frac{1}{2}} \right]' \left[R^{-\frac{1}{2}} X C^{-\frac{1}{2}} \right] \left[C^{\frac{1}{2}} b \right]$$

Where $\mathbf{R}^{½}$ and $\mathbf{C}^{½}$ are obtained from **R** and **C** by taking the square roots of their diagonal values. Now writing $\mathbf{Z} = \mathbf{R}^{-½} \mathbf{X} \mathbf{C}^{-½}$, equation [5] is seen to be merely the latent roots and vectors equation $\lambda \mathbf{v} = (\mathbf{Z'Z})\mathbf{v}$, with $\lambda = \rho^2$ representing the latent roots and $\mathbf{v} = \mathbf{C}^{½}\mathbf{b}$ the latent vectors of the sum of squares and products matrix $\mathbf{Z'Z}$.

Spectral decomposition of $\mathbf{Z'Z} = \mathbf{V \Lambda V'}$ is related to the singular value decomposition (SVD) $\mathbf{Z} = \mathbf{USV'}$ with $\Lambda = \mathbf{S}^2$, shows that the values of ρ for all the solutions are the singular values of $\mathbf{Z} = \mathbf{R}^{-½} \mathbf{X} \mathbf{C}^{-½}$ and the corresponding scores **b** are the columns of $\mathbf{B} = \mathbf{C}^{-½}\mathbf{V}$. By a similar argument we get $\mathbf{A} = \mathbf{R}^{-½}\mathbf{U}$, whose columns give the scores **a,** again for all the solutions.

As we obtained **Z** from **X**, rather than from **Y**, the first column of **A** and **B**, and the first singular value, will correspond to the trivial solution found by the RA process. Thus we must remove the first column of **A** and **B.** Now the scores for the first (non-trivial) solution are given in the first column of the two reduced matrices **À** and **B** and the first pair of solutions contains the points (a_{i1}, a_{i2}).

Detrended Correspondence Analysis

The default version of detrended correspondence analysis (DCA) involves detrending by segments and nonlinear rescaling of axes. DCA is designed to correct for two major defects, which are (i) the ends of the first axis are compressed compared to the middle part, and (ii) the scores of the second axis usually bear a quadratic relationship with the first axis, i.e., the horseshoe (or arch) effect (Hill, 1974). DCA can be improved by one additional step involving log-linear regression. For each species with ample presences, a log-linear regression of species data on the first two ordination axes employing the following model:

$$Log_e E_{yki} = b_0 + b_{1k}x_{i1} + b_{3k}x_{i2} + b_{4k}\left(x_{i1}^{\ 2} + x_{i2}^{\ 2}\right)$$

Where x_{i1} and x_{i2} represent the scores of site i on the first two DCA axes.

Canonical Correspondence Analysis

In canonical correspondence analysis (CCA) we proceed by maximizing the equation

$$\delta = \frac{u'Mu}{x'Nx} = \frac{x'Y'M^{-1}Yx}{x'Nx} \quad .... [6]$$

subject to the equation

$$x_i = c_0 + c_1 z_{1i} + c_2 z_{2i} + ... + c_q z_{qi} \quad ....[7]$$

where x_i is the value of the resulting compound environmental variable at site i, z_{ij} is the value of environmental variable j at site i and c_j are the corresponding weights, provided **x** is centered. Matrix **Z** is extended with a row of ones, equation [6] becomes,

$\mathbf{x} = \mathbf{Z'c}$, with $\mathbf{c} = (c_j)$; [j = 0, 1, ...q]

By substituting the value of $\mathbf{x} = \mathbf{Z'c}$ in equation [6] and (re) defining, with **Y** non-centred,

$$\left.\begin{aligned} S_{12} &= YZ' \\ S_{11} &= M = diag\left(y_{k+1}\right) and \\ S_{22} &= ZNZ' \end{aligned}\right\} \quad ....[8]$$

The following equation is obtained

$$\delta = \frac{c'S_{21}S_{11}^{\ -1}S_{12}c}{c'S_{22}c} \quad ....[9]$$

Therefore, the solution of CCA can be obtained from the eigenvalue equation.

$$S_{21}S_{11}^{\ -1}S_{12}c = \lambda S_{22}c \quad ....[10]$$

With S_{12} , S_{11} and S_{22} defined as in equation [8]. CCA has a trivial solution $c' = (1, 0, 0, ..., 0)$, $x = 1$ and the first non-trivial eigenvector maximizes δ subject to $\mathbf{1'Nx} = \mathbf{1'NZ'c} = 0$ and the maximum δ equals the eigenvalue. Trivial solution is readily excluded by subtracting from each environmental variable its weighted mean

$$\bar{Z}_j = \frac{\sum_i y_{+i} z_{ji}}{y_{++}}$$

subsequently, the matrix **Z** contains weighted row means equal to 0:
$\Sigma_i y_{+i} z_{ji} = 0$. The species scores and the canonical coefficients of the environmental variables can be obtained from the following equation [11] and [12].

$$S_{11}^{-0.5} S_{12} S_{22}^{-0.5} = P\Lambda^{0.5} Q' \ldots\ldots\ldots\ldots\ldots\ldots[11]$$

$$B = S_{11}^{-0.5} P\Lambda^{0.5} \ and \ \ C = S_{22}^{-0.5} Q \ldots\ldots[12]$$

The biplots for species and environmental variables are derived as weighted least-squares approximation of the elements of a ***m* x *q*** matrix as follows:

$$W = M^{-1} Y Z'$$

The triplots are simply the extensions of biplots.
Analyses were conducted using CANOCO Version 4.5 (ter Braak and Smilauer, 2002).

RESULTS

Ordination seemed to be the most effective approach for processing the large set of phytosociologyical data obtained during the survey. The results of different ordination methods used are presented below:

Correspondence analysis (CA)

The eigenvalues were 0.382 for CA1 and 0.262 for CA2 and the sum of all eigenvalues was 1.508. The first two CA axes explained 42.7% of the total variance while the first three axes accounted for 51.6% of the variation in species distribution (Table 1). Although the results of PCA are not presented in detail it is pertinent to compare these with CA. The first two PCA components explained only 30.7% while the first three components explained 43.3% of the total variation in species density. In case of PCA the sum of all eigenvalues was 1.00 while the eigenvalues corresponding to the first three components were 0.161, 0.146 and 0.126:

The stand scores and species scores of the CA ordination are displayed graphically as biplot in Fig.1. Although many stands are aggregated in the lower-left portion of the ordination, a clear-cut trend of the successional sequence related to the axis 1 can be identified. The axis 2 could not be analogized with any of other major gradient (Fig.1). However, the axis 2 seems to be a function of disturbance factor with stands having greater disturbance located at lower positions on axis 2 and those with lesser disturbance taking high positions on axis 2. An examination of the distribution pattern of species in the ordination plane reveals that the pioneer species are generally distributed to the right of the ordination (e.g. *Pulicaria hookeri*), the dominant species of the middle part of the successional sequence are distributed in the middle and middle-to-left part of the axis 1 while the climax or terminal species are located towards the left-side of the ordination configuration. Thus the arrangement of species along the first axis reflect the successional sequence. Fig. 2a. shows species distribution on the first two axes of CA ordination. *Pulicaria hookeri* shows an increasing trend from left to right on the first axis. *Barleria acanthoides* and *Ruellia patula* (Fig. 2b,c) shows lower values below and to the left of the ordination plane and trend to increase in the upper and left-portions of the ordination. *Vernonia cinerascens* (Fig. 2d) is mostly distributed towards the left of the ordination with low densities. Likewise, *Grewia tenax* is depicts on increasing trend towards the upper left of the configuration (Fig. 2e). *Grewia* sp. is widely distributed (Fig.2f), occurring in pioneer, intermediate and climax stands though with greater density in the intermediate stands located in the center of the ordination plane remarkably, *Grewia* sp. also shows a trend of decreasing density in relation to the second axis of CA ordination. *Commiphora wightii*, a widely distributed species on the calcareous hills, depicts an increasing trend from lower-right to upper-left of the ordination plane. *Euphorbia caducifolia* and *Acacia senegal* both representing the edaphic-topographic climax of the hills are represented with high density in the left portion of the ordination configuration (Fig.2g,h,i).

Table 1. Results of canonical analysis. Eigenvalues, corresponding variances and cumulative explained variance.

Axes	1	2	3	4	Total inertia
Eigenvalues	0.382	0.262	0.134	0.121	1.508
Percentage variance	25.3	17.4	8.9	8.0	
Cumulative percentage variance of species data	25.3	42.7	51.6	59.6	
Sum of all eigenvalues	1.508				

Table 2. Results of canonical correspondence analysis. Eigenvalues, species-environmental correlations, cumulative percentage variance of species data and cumulative percentage variance of species-environment relations.

Axes	1	2	3	4	Total inertia
Eigenvalues	0.236	0.124	0.107	0.077	1.508
Species-Environmental correlation	0.876	0.773	0.931	0.850	
Cumulative percentage variance of species data	15.7	23.9	31.0	36.1	
Cumulative percentage variance of species-environmental relation	32.7	49.9	64.8	75.5	
Sum of all eigenvalues	1.508				
Sum of all canonical eigenvalues	0.722				

Table 3.Weighted correlations between vegetation (species) axes and environmental (soil) axes obtained in CCA.

	Species AX1	SpeciesA X2	Species AX3	Species AX4	Env. AX1	Env. AX2	Env. AX3	Env. AX4
Species AX1	1.0							
Species AX2	-0.0992	1.0						
Species AX3	0.0553	-0.0792	1.0					
Species AX4	0.0293	0.0527	0.0436	1.000				
Env. AX1	0.8764	0.000	0.000	0.000	1.000			
Env. AX2	0.000	0.7731	0.000	0.000	0.000	1.000		
Env. AX3	0.000	0.000	0.9312	0.000	0.000	0.000	1.000	
Env. AX4	0.000	0.000	0.000	0.8499	0.000	0.000	0.000	1.000

1. Detrended correspondence analysis (DCA)

The trend of stand and specie distribution along the first DCA axis is similar to that of CA1 except that the direction of the axis is reversed (Fig. 3). Again it is easy to detect a tendency of floristic variation expressible in terms of ecological succession. The second axis appears to represent the magnitude of disturbance with relatively greater disturbance (e.g. grazing) in the stands associated with those located at lower positions on DCA axis 2 and lesser perturbation in those taking higher positions on axis 2. The eigenvalues for DCA axis 1 and axis 2 were 0.382 and 0.114 respectively while the sum of all eigenvalues was 1.50. The first axis explained 25.3% of the total variance while the first two and the first three axes cumulatively accounted for 32.9% and 38.0% of the total variance contained in the species density data.

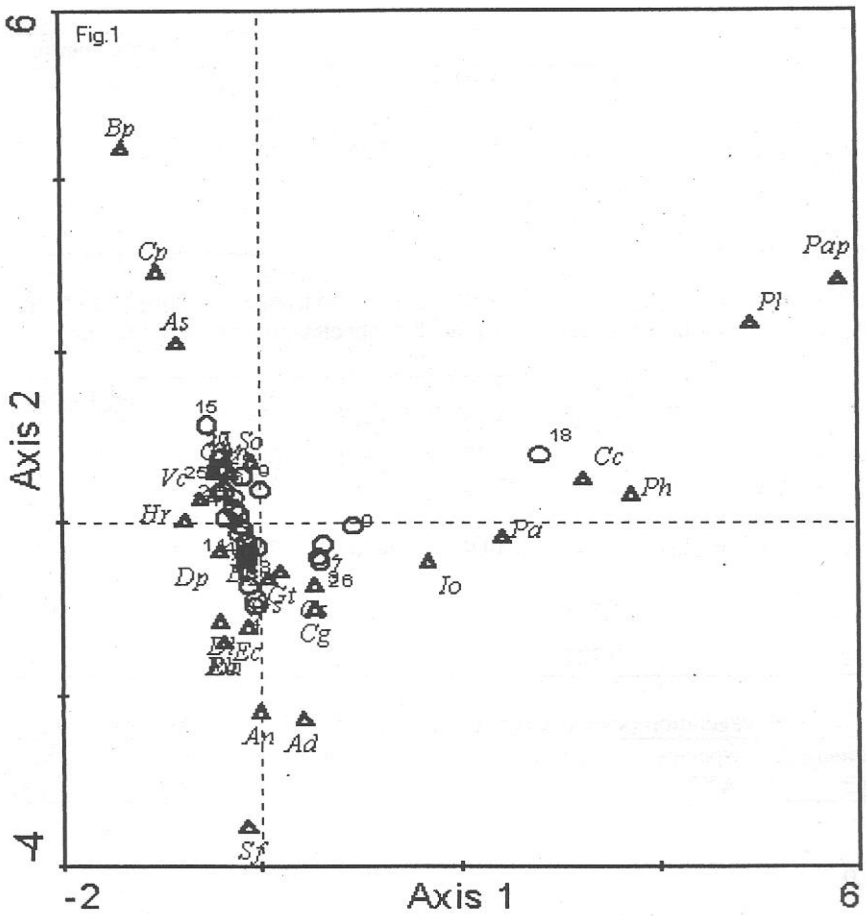


Fig.1. Correspondence analysis ordination showing stands as well species positions on the first two axes. Key to symbols is as follows: Ad, *Asperagus dumosus*; An, *Acacia nilotica*; As, *Acacia senegal*; Ba, *Barleria acanthoides*; Bp, *Barleria prionitis*; Cc, *Capparis cartilaginea*; Cg, *Cordia gharaf*; Cm, *Commiphora mukul*; Cp, *Clerodendron phlomoides*; Cs, *Commiphora stocksiana*; Dl, *Dipteracanthus longifolius*; Dp, *Diptercanthus patulus*; Ec, *Euphorbia caducifolia*; Gs, *Grewia species*; Gt, *Grewia tenax*; Gv, *Grewia villosa*; Hr, *Haloxylon recurvum*; Io, *Indigofera oblongifolia*; Le, *Lycium europeum*; Pa, *Pluchea arguta*; Pap, *Periploca aphylla*; Pb, *Physorhynchus brahvicus*; Ph, *Pulicaria hookeri*; Rm, *Rhus mysurensis*; So, *Salvadora oleoides*; Sf, *Suaeda fruticosa*; Tl, *Taverniera lappacea*; Vc, *Vernonia cenarescens*.

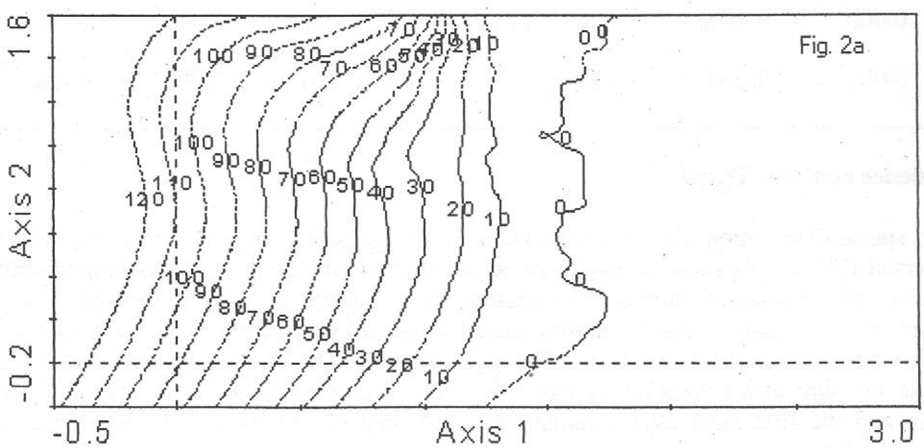
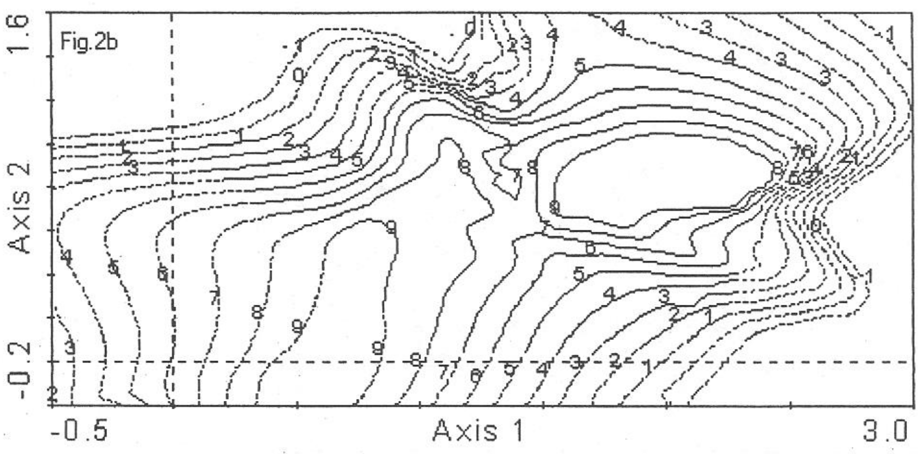


Fig.2a. Species distribution of correspondence analysis ordination of *Pulicaria hookeri* shows an increasing trend from left to right on the first axis.



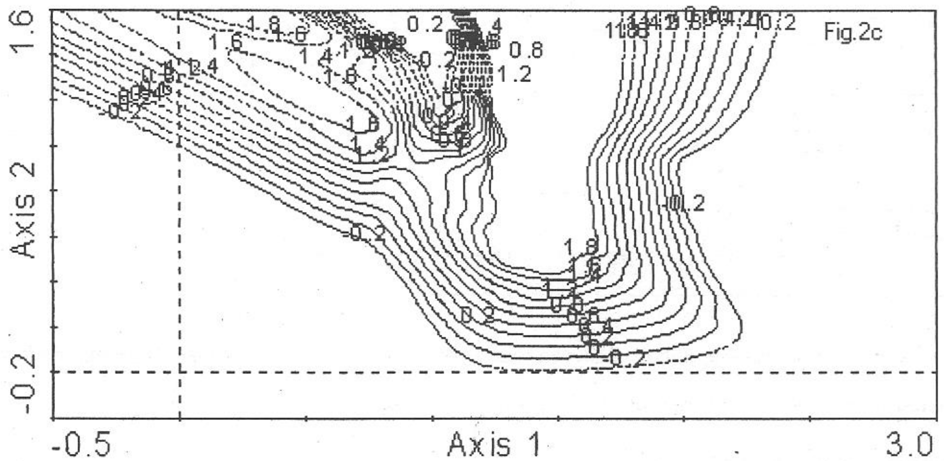


Fig.2b,c.Species distribution of correspondence analysis ordination of *Barleria acanthoides* and *Ruellia patula* shows lower values below and to the left of the ordination plane and trend to increase in the upper and left-portions of the ordination.

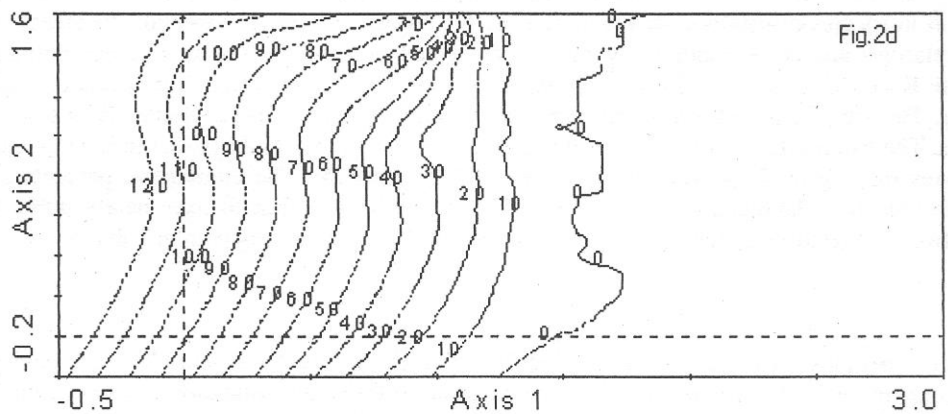
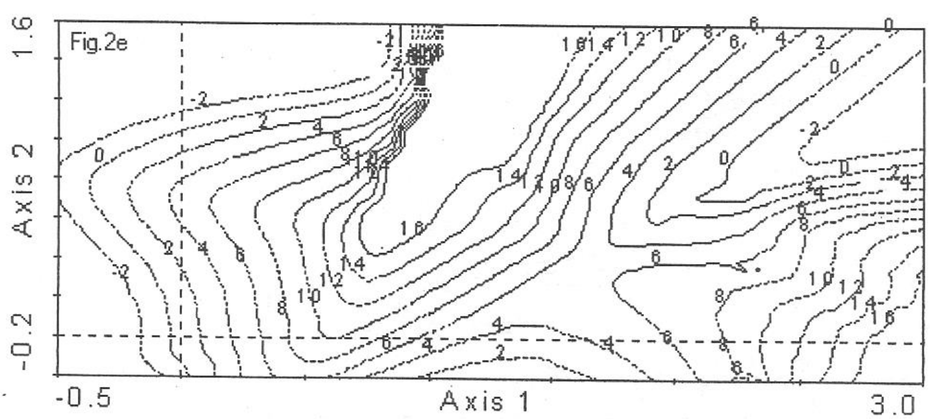


Fig.2d. Species distribution of correspondence analysis ordination of *Vernonia cinerascens* is mostly distributed towards the left of the ordination with low densities.



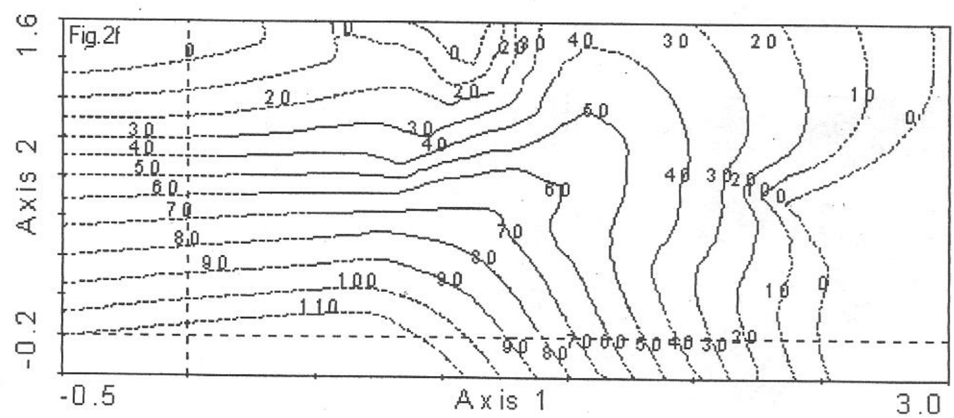


Fig.2e. Species distribution of correspondence analysis ordination of *Grewia tenax* is depicts on increasing trend towards the upper left of the configuration.
Fig.2f. Species distribution of correspondence analysis ordination of *Grewia* sp. is widely distributed.

2. Canonical correspondence analysis (CCA)

A perusal of CCA ordination discloses the existence of the successional gradient observed in CCA and DCA (Fig. 4). The successional trend is associated with CCA axis 1 running from left to right along the axis 1. The axis 2 again depicts an association with the disturbance regime with stands having greater disturbance occupying lower positions on axis 2 and stands with lower disturbance intensity falling at higher position on axis 2. The eigenvalues were 0.236, 0.124 and 0.107 for axis-1, 2, 3 respectively and the sum of all canonical eigenvalues was 0.722 (i.e.72.2% of the variation in species distribution was explained by the eleven soil (environmental) variables). The results of canonical correlations and corresponding eigenvalues are given in Table 2. The species-environmental canonical correlation were R_1=0.876 and R_2=0.773 that are high indicating high degree of environmental control of vegetational composition. The significance of canonical correlations were checked using a Monte Carlo test with 499 random permutations. The F-ratio for the first canonical axis (eigenvalues 1) was 3.347 (p=0.1060) while the F-ratio for all canonical axes (all eigenvalues, trace=0.722) was 1.504 (p=0.0120). The cumulative percentage of variance of species-environmental relations for first axis was 32.7% and for the first to axes nearly 50%. The weighted correlations between vegetation (species) axes and environmental (soil) axes are given in Table 3.

DISCUSSION

A variety of ordination methods were used and compared including PCA, CA, DCA and CCA, although the results of PCA are not given in detail. PCA performed poorly compared to the other ordination methods used. All methods of data analysis offered information of some potential utility. The cumulative percentage variance accounted for by the first three axes of PCA was considerably lower than that of CA but the least value was obtained for DCA. In general, the ordination methods were able to disclose the compositional patterns, differential species distributions along gradients and the successional trend inherent in the vegetational data. The first ordination axis of the various ordinations exhibited the underlying dynamical trend in the vegetation. The second axis invariably accounted for perturbations in vegetation. The perturbations were mostly the result of grazing, cutting and the consequent vegetation denudation. Although, grazing was mild, it should be remembered that at this intensity, grazing is selective and many plant species that are palatable are consumed by the herbivores to a greater extent than the unpalatable species.

The degree of relationship between vegetational and the environmental variables is disclosed by the canonical correlations obtained in CCA. These correlations were appreciably high for the first and canonical axis, indicating the preeminent role of the edaphic characteristics in the control of the vegetation. The vegetational axis 1 of CCA was strongly correlated with water retaining capacity of soil, humus content, clay percentage, and potassium, magnesium and phosphorus contents. Of all the soil variables, water-holding capacity of soil was readily correlated with the first vegetational axis of all the ordinations. On the other hand, the second vegetational axis did not exhibit significant relationship with any of the soil properties. However, it is conjectured that it might be correlated with some extrinsic factors that were not taken into account, e.g., the intensity of grazing or the degree of disturbance.

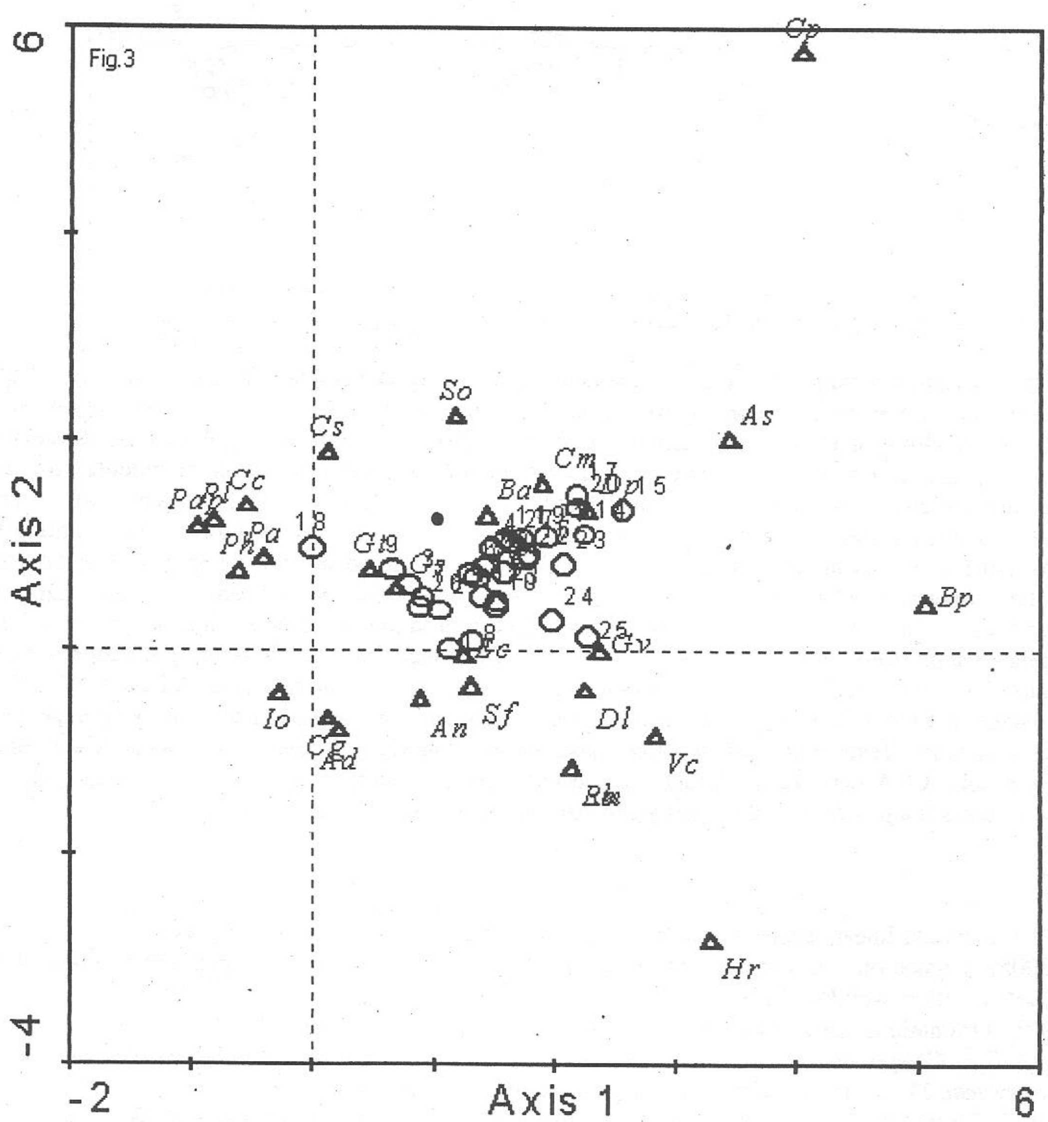


Fig.3. Detrended correspondence analysis ordination showing the trend of stand and specie distribution along the first DCA axis is similar to that of CA1 except that the direction of the axis is reversed.

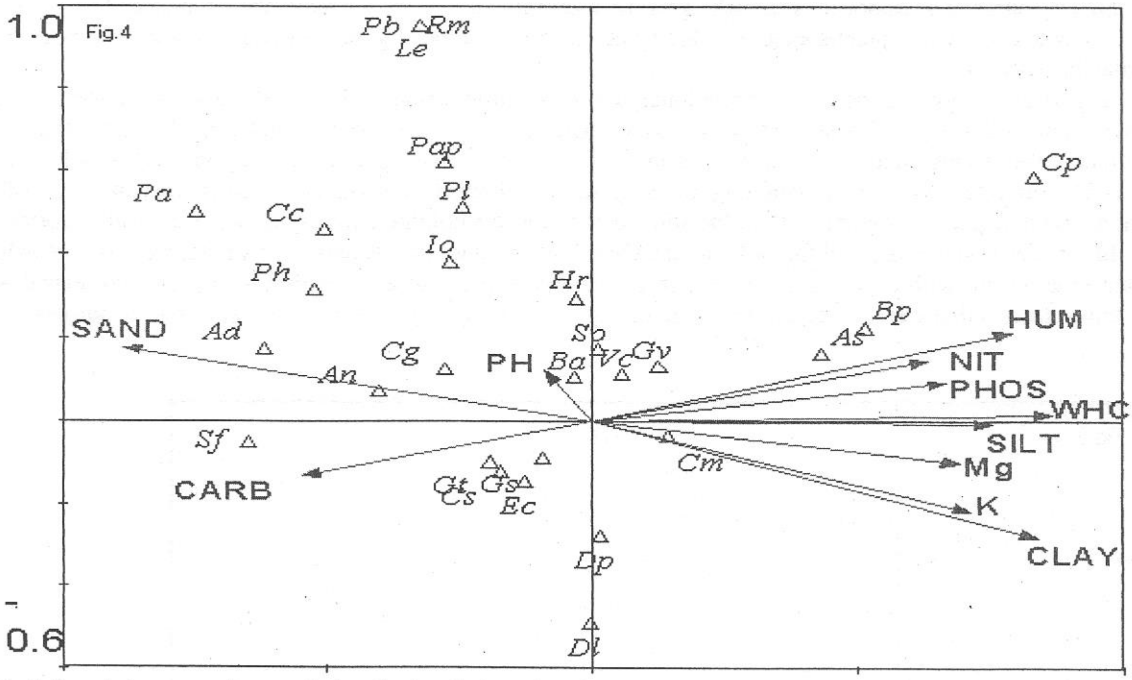


Fig.4. Canonical correspondence analysis ordination discloses the existence of the successional gradient observed in CCA and DCA.

Comparing the ordination methods briefly, PCA has a number of drawbacks, i.e., horseshoe effect, inability to cope with Gaussian or other non-linear responses, involution of gradients' ends and so on (Swan, 1970; Gauch *et al.*, 1977). The principal drawback of DCA is that detrending is regarded as artificial, i.e., the technique removes the trend for a non-linear axis, rendering it into a linear one artificially. The shortcomings of the detrending procedure become more serious at higher dimensions (Okasanen, 1983; Odd *et al.*, 1990). Furthermore, in our study it gave a lower cumulative explained variance for the first three axes. CA yielded some useful information regarding the compositional pattern and the dynamical trends. CA is relatively less affected by non-linearity in the data sets, involution and beta diversity. However, CA is unable to deal with species and environmental data sets simultaneously and thus cannot expose the combined underlying pattern in the vegetational and environmental data sets. Such interrelationships were conveniently disclosed by the CCA technique. In CCA the ordination axes are constrained to maximize their relationships with a nominated set of environmental variables (Austin, 2005). Thus, the primary advantage of CCA is that it provides triplots, which facilitate the exposition of underlying vegetation-environmental relationships. Tests with real data sets have shown that CCA is extremely robust when certain assumptions do not hold. CCA permits the number of species to exceed the number of sites. The flexibility and robustness of CCA makes it a powerful tool for analysing species-environmental relationships.

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