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World climate patterns in grassland and savanna and their relation to growing seasons

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ABSTRACT

The climate at eleven IBP savanna or grassland study sites from five continents are described and principal components analysis is used to compare them. A multivariate linear discriminant function based on mean monthly precipitation, mean monthly temperature, latitude and altitude, is used to predict the length of the growing season at each site. At most sites, the actual and predicted start and end of the growing season agreed closely. It is concluded that growing season on a world-wide basis may be predicted fairly reliably from a small number of abiotic variables by means of a multivariate discriminant function.

RESUME

CYCLES CLIMATOLOGIQUES MONDIAUX EN PRAIRIE ET SAVANE ET LEUR RELATION AVEC LES SAISONS DE CROISSANCE

Les climats en onze points d'étude de la savane ou de la prairie, choisis par le Programme Biologique International sur les cinq continents, sont décrits et comparés par le moyen de l'analyse des principaux composants. Une fonction discriminante linéaire multivariée, basée sur les moyennes mensuelles de la précipitation et de la température, sur la latitude et l'altitude, est utilisée pour prédire la longueur de la saison de croissance en chaque endroit. Dans la plupart des cas, il y a un excellent accord entre le calcul et l'observation pour le début et la fin de la saison de croissance. On en conclut que cette saison peut, à l'échelle mondiale, faire l'objet d'une prévision assez sûre à partir d'un petit nombre de données abiotiques et en utilisant une fonction discriminante multivariée.

INTRODUCTION

In this article we consider a variety of savanna and grassland sites and one tundra site, characterize their climates and relate climate to the conditions for growth of the natural vegetation of the sites. By so doing, we hope to better understand the factors involved in growing season determination. By growing season, we mean that period of the year from the time when environmental factors cease to limit growth, usually in spring, until they limit it again, usually in autumn.

With the present world population and limited food supplies it is important that we use all available land in an efficient manner for either agriculture, grazing, wood production, or conservation. As recently pointed out by Newman & Pickett (1974), the one uncontrollable factor which limits land productivity is weather. Success or failure of crops and of forage production are dramatically affected by whims of weather. Newman & Pickett suggest that knowledge of world climate will enable us to predict productive uses for each area. To apply this strategy, however, knowledge of how crops and other vegetation respond to climatic factors is required. For crops, and monospecific communities in general, physiological studies give us the required information concerning responses to light, temperature, precipitation, and other factors. For savanna, grassland, or tundra communities of many species, physiological studies give us no single answer. Another solution is required if we are to utilize such communities efficiently on a world-wide basis for grazing or fodder production.

The International Biological Program (IBP) gives us a unique opportunity to study these communities of many species. In this paper we include data from IBP grassland sites and one tundra site (eutrophic mire) falling in a range from 6° to 60° latitude, north and south of the equator from five continents (Table 1). Each site represents typical savanna, grassland or tundra vegetation under grazing, haying, or fallow conditions. The data include short-term specific weather records on at least a monthly basis and the associated growing seasons as determined subjectively by the investigators at each site. In order to predict conditions for growth of the local vegetation, we consider monthly precipitation and average temperature along with latitude and altitude.

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TABLE 1.—Study sites and sources of data

Site	Latitude	Period of data measurement (month and year)	Contributor	Source
Australia, Armidale	30,5° S	10/69—9/70	K. J. Hutchinson & A. R. Till	Personal Communication
Czechoslovakia, Lanzhot	49° N	1/69—12/69	M. Rychnovská	Smid (1972)
India, Kurukshetra	30° N	1/70—12/71	J. S. Singh	Singh & Yadava (1974)
India, Rajkot	22° N	1/71—12/71	S. C. Pandeya	Pandeya, *et al.* (1972)
Ireland, Glenamoy	54° N	1/70—12/71	J. J. Moore	Personal Communication
Ivory Coast, Lamto	6° N	1/69—12/70	M. Lamotte	Lamotte (1967), César & Menaut (1974), Lecordier (1974)
Netherlands, Terschelling	53° N	1/67—12/70	P. Ketner	Ketner (1972)
Norway, Hardangervidda	60° N	7/69—9/71	F. E. Wielgolaski	Skartveit, *et al.* (1975)
South Africa, Welgevonden	24° S	1/70—12/70	J. J. P. van Wyk	Personal Communication
United Kingdom, Moor House	54° N	1/68—12/68 and 1/71—12/71	O. W. Heal	Personal Communication
United States, Pawnee	41° N	1/69—12/71	U.S./IBP Grassland Biome	Biome data bank

CHARACTERIZATION OF CLIMATE TYPES BY PRINCIPAL COMPONENTS ANALYSIS

There is a wide range of climates, both tropical and temperate, represented in the sites included in the study. Of the tropical climate sites, Lamto, Ivory Coast, has uniform temperatures with heavy precipitation from March to October with a brief respite in mid-summer. The two Indian sites have three seasons; a rainy season from mid-June to September, a cool dry season from October to February, and a hot dry season from March to mid-June. Welgevonden, South Africa, is a dry sub-tropical savanna site with summer rainfall. The temperate sites range from 30 to 60° from the equator. They have seasons dictated by the angle of the sun's incoming rays. Armidale, Australia, is a cool temperate rangeland with moderate precipitation, which is fairly uniform but heaviest in summer. Temperate sites which are relatively humid are Lanzhot, Czechoslovakia; Glenamoy, Ireland; Terschelling, Netherlands; Hardangervidda, Norway; and Moor House, U.K. The season of rainfall varies greatly among temperate sites. For example, Ireland's heavy precipitation occurs in November, December and January, whereas Terschelling has uniform rainfall throughout the year. The Pawnee Site in the United States is very dry relative to the other sites.

A number of these sites have climates which are influenced by geographical features. The Netherlands, Norway, Ireland, Ivory Coast and United Kingdom sites are influenced by proximity to the ocean. Both the Czechoslovakian and the United States sites are continental. The Pawnee (U.S.) site's weather is furthermore modified by the north-south Rocky Mountain Range, a few kilometres to the west. Czechoslovakia on the other hand is bounded by the major east-west mountain ranges of Europe. Another site affected by mountains is the northern India site (Kurukshetra), whose climate is influenced to some extent by the Himalayas.

All in all, these sites have a fairly predictable pattern of monthly temperature based on incoming radiation, but they present a mosaic of precipitation regimes. Principal component analysis (PCA) (Seal, 1964) was used to illustrate this contrast. For temperature, using the twelve monthly values as attributes over the eleven sites (entities), the first component (an average temperature component) accounts for 94% of total variability in the data and the second component brings the cumulative per cent to 99%. The second component contrasts summer and winter temperatures, yielding a range from very uniform monthly temperatures (Ivory Coast, Ireland and U.K.) to strongly seasonal ones, including U.S.A. and Czechoslovakia (Fig. 1). The first component separates warm sites, such as the Indian and the Ivory Coast sites, from cold ones such as U.K. and Norway. As a hierarchical cluster analysis (Johnson, 1967) on temperature correlation or seasonal patterns grouped the sites in the same manner as component two of the PCA, except for the U.S. site which, for these data, showed a monthly temperature pattern similar to the Moor House site, these results are not presented. A hierarchical cluster analysis using euclidian distance, that is, temperature magnitudes rather than patterns, yielded clusters predictably similar to the first component of the PCA and is also not presented.

For mean monthly precipitation values over the eleven sites, the first three principal components account for only 52%, then 75%, then 86% of the total variability. There is no discernable pattern of rainfall along latitudinal or altitudinal gradients. This result follows from the above characterization of climate types since the precipitation at these sites is variously affected by oceans, mountains, and other non-regular causes. In contrast to the sun's orbit, which is the principal regulator of temperature, there is no single unifying phenomenon that controls precipitation.

DETERMINATION OF GROWING SEASON BY DISCRIMINANT ANALYSIS

If one were to take a plant physiological approach to the specification of conditions for growth, one would consider available solar radiation, maximum and minimum air temperature, soil temperature, number of daylight hours (related to latitude), available moisture and phenological stage. We have taken four variables as integrators of all these factors, namely: mean monthly temperature, monthly precipitation, latitude and altitude. The growing seasons for the 11 sites do not simply commence and end as the sun progresses to and from the equator. If this were so, either average monthly temperature or latitude would suffice to predict growing seasons.

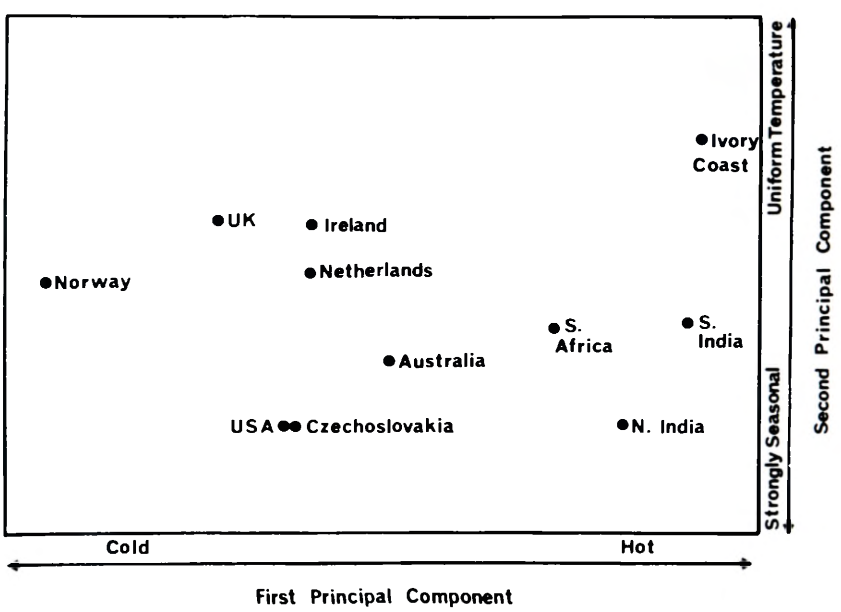

FIG. 1.—First and second principal components of monthly mean temperature data for the eleven sites.

A step-wise discriminant algorithm (Dixon, 1971) was applied to determine if some combination of these four variables was a good indicator of growth. Each month, at each site, was classified as either a growing- or non-growing-season month according to the dates defining the length of the growing season supplied by each investigator. The means for the four response variables are given in Table 2, and the pooled covariance matrix is given in Table 3.

TABLE 2.—Mean values (F) over the eleven sites for the four responses

Variable	Growing season months	Non-growing season months	All months
Precipitation (mm)....	89,96	43,98	68,36
Temperature (°C)....	16,55	9,99	13,67
Latitude (degrees N or S)................	38,86	38,09	38,50
Altitude (m)..........	483,61	569,02	523,73

TABLE 3.—Pooled covariance matrix($\hat{\Sigma}$) of variances and covariances among the four responses

	Precipitation	Temperature	Latitude	Altitude
Precipitation.	4227,66	—	—	—
Temperature.	−47,66	110,05	—	—
Latitude.....	114,23	−139,94	271,65	—
Altitude.....	−6254,53	−1872,56	1284,00	254708,75

Data from South Africa and Australia were displaced by six months for the calculations so that "summer" and "winter" seasons would coincide with northern hemisphere seasons. Growing season months clearly have more rainfall and are warmer (Table 2). The latitude and altitude means differ in the two groups only in so far as the sites at different latitudes or altitudes have greater than or less than 6 months of growth. Curiously, there are relatively more growing season months at greater latitudes than non-growing months at those latitudes (group means of 38,9 and 38,1 respectively), although the difference is not significant.

The most important single variable is precipitation (t-test between growing and non-growing groups yield a significance of $p<0{,}0005$). However, when used as an indicator of growth, this variable by itself incorrectly labels 35 growing season months as non-growing months while correctly categorizing 84 months. The remaining 13 months were non-growing months mis-specified as growing months. The best discriminant function uses either all four variables, in which 29 of 132 months are mis-specified, or all variables excluding altitude for which 29 of, 132 months are also mis-specified. Latitude is needed in addition to precipitation and temperature in order to predict growth more accurately for some cool sites. Using all four variables, the multivariate t-test for groups yields a significance of $p<0{,}0005$. While it is clear that the largest difference between the growing and the non-growing months is their precipitation, precipitation alone is not sufficient to predict suitable conditions for growth.

Using all four variables the discriminant function for group i is

$$-\tfrac{1}{2}\hat{\mu}^1_i\ \hat{\Sigma}^{-1}\hat{\mu}_i+\hat{\mu}^1_i\ \hat{\Sigma}^{-1}x=a_i+b^1_i x$$

where μ_i is the four-variate mean for group i in Table 2, $\hat{\Sigma}$ is the pooled estimate of the variance-covariance matrix (Table 3), and x is the four variate response for a particular site and month. For the growing season group, $a_1=-27{,}6731$ and $b^1_1=(0{,}02709,\ 1{,}20478,\ 0{,}71537,\ 0{,}00781)$; for the non-growing season months one obtains $a_2=-19{,}60077$ and $b^1_2=(0{,}01511,\ 0{,}99297,\ 0{,}61318,\ 0{,}00681)$. After cancelling constant terms the posterior probability of being in group i is:

$$\frac{\pi_i e^{a_1+b^1_i x}}{\pi_1 e^{a_1+b^1_1 x}+\pi_2 e^{a_2+b^1_2 x}}$$

where π_1 and π_2 are the prior probabilities of being in the growing and non-growing groups, respectively (Dixon, 1971). Both π_1 and π_2 are taken to be one-half in this case. Prior probabilities are those based on the assumption or hypothesis under investigation, in this instance, that a month has an equal chance of being either a growing or a non-growing month. The two posterior probabilities, in this instance, are the chances of a month being a growing and non-growing month, calculated by substitution in the above equation of the month's precipitation, temperature, latitude and altitude values using (a_1, b^1_1) and (a_2, b^1_2), respectively. Posterior probabilities were calculated for each month at each site and each month as classified as growing or non-growing, depending on which posterior probability was greatest.

In Fig. 2 the growing seasons as given by the investigators are compared with the calculated growing seasons from the four-variable discriminant analysis. There are a total of 103 of 132 months correctly specified, whereas 17 growing season months were incorrectly classified as non-growing months and 12 non-growing season months were specified as suitable for growth. Half of the misclassified months were for tropical countries where growth would appear to be regulated by something in addition to rainfall and temperature. Predictions for both Indian sites and the Ivory Coast were particularly poor while those for South Africa and Australia are acceptable. On the other hand, the growing season was precisely predicted at Hardangervidda. Other temperate locations were treated relatively well, except that the linear discriminant technique was not able to accurately predict initiation of growth at Glenamoy, Ireland.

DISCUSSION AND CONCLUSIONS

Although the 11 sites represent vastly differing climates, including various combinations of temperature and moisture regimes, use of multivariate linear discriminant analysis suggests that, over a large portion of the globe, growing season is basically a function of precipitation and temperature with some modification due to latitude. Given these three variables, altitude may be of slight additional significance. Growth in tropical areas is dependent upon other or additional factors, including possibly mean monthly minimum temperature. The unsatisfactory predictions could also be accounted for by the use of one or two years' records instead of long-term averages in the calculations. The success in correctly classifying conditions conducive to growth using a multivariate linear function of three or four variables suggests that a plant community approach, as opposed to species-specific physiological approaches, can be successful.

It is possible to predict conditions suitable for growth at the community level on a global basis using a few abiotic variables. Future research can be directed at finding particular response curve relationships between initiation and termination of growth and

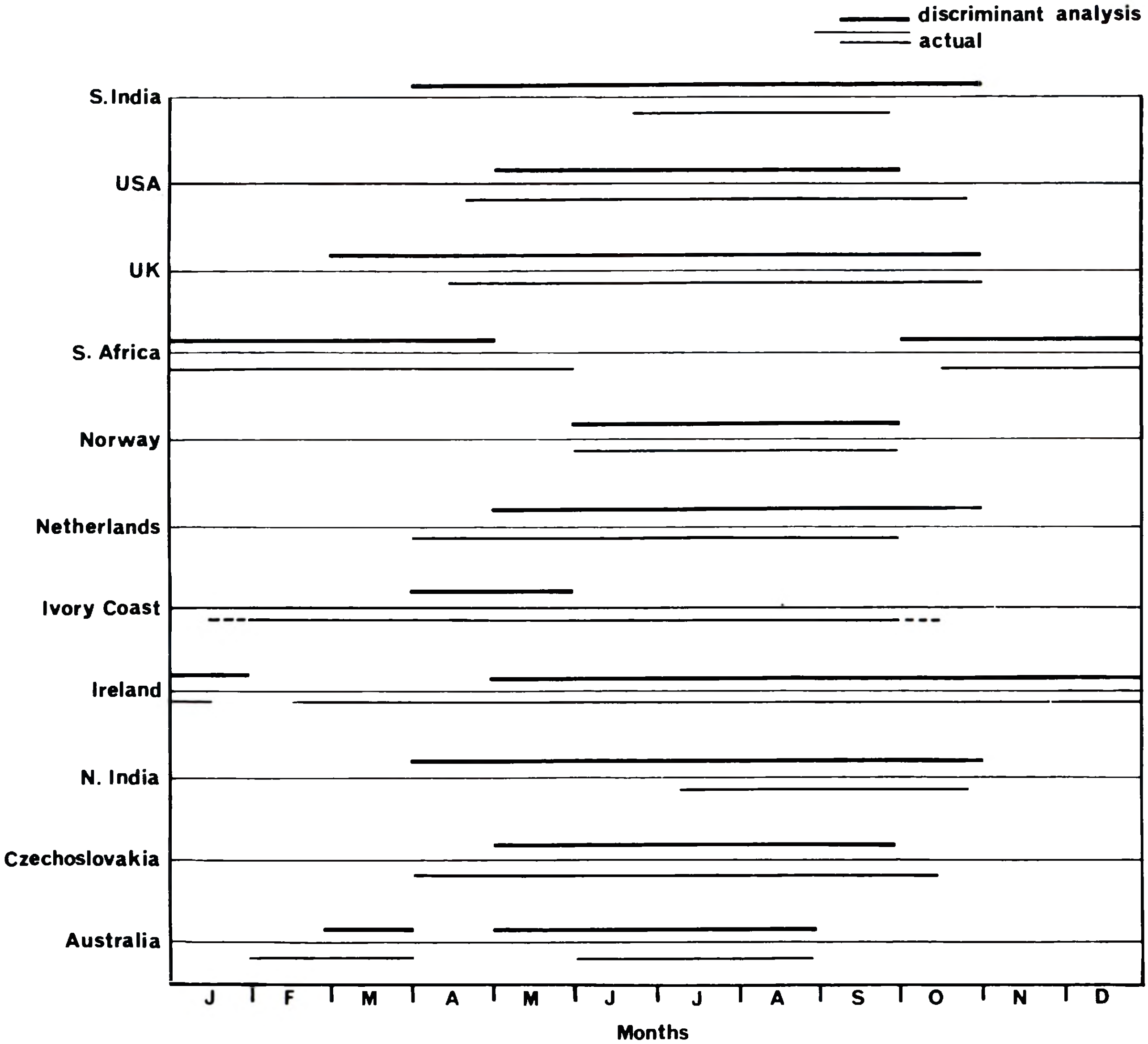

FIG. 2—Comparison of actual and predicted length of growing season at each site.

these factors. Until such research is done, the discriminant function used here gives us a reasonable tool for determining growing season. Management strategists can use this function to predict the possible outcomes of various strategies under conditions which have not occurred previously. For example, if one anticipates a cool wet spring, representative precipitation and temperature figures can be supplied and the effect on the start and end of the growing season may be predicted.

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UITTREKSEL

Elf IBP savanne- en grasveldstudiegebiede (vanaf vyf vastelande) se klimaat word beskryf en met behulp van hoofkomponentanalise vergelyk. 'n Veelvoudige lineêre diskriminantfunksie word gebruik om die lengte van die groei-seisoen vir elke gebied te bereken. Die gemiddelde maandelikse reënval, gemiddelde maandelikse temperatuur, lengtegraad en hoogte bo seespieël word gebruik om hierdie funksie te bereken. Vir die meeste van die gebiede was daar min verskil tussen die werklike en die berekende aanvang en einde van die groeiseisoen. Daar word tot die gevolgtrekking gekom dat die groeiseisoen redelik betroubaar, wêreldwyd bereken kan word met behulp van 'n veelvoudige diskriminantfunksie en 'n klein aantal abiotiese gegewens.

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