Ecology, 67(6), 1986, pp. 1568–1575

MULTIVARIATE ANALYSIS OF PLANT COMMUNITIES AND ENVIRONMENTAL FACTORS IN NGARI, TIBET[1]

D. H. S. CHANG[2] AND H. G. GAUCH, JR.
Section of Ecology and Systematics, Cornell University, Ithaca, New York 14853 USA

Abstract. Ngari is the driest, coldest, and highest region on the Tibetan Plateau. During the 1976 Interdisciplinary Scientific Expedition of the Chinese Academy of Sciences to the Qinghai-Xizang (Tibetan) Plateau there was a rare opportunity to study this area. Sampling of 163 sites was done, recording abundances of 241 vascular plant species, along with basic environmental information. The purposes of this study were (1) to analyze these data statistically despite their complexity and limitations, and (2) to produce a quantitative description of the vegetation of Ngari and of its relationship to environmental factors. The principal analysis of these data involved two steps: first the vegetation matrix was summarized in two vectors of ordination scores produced by detrended correspondence analysis (DCA), and then these scores were related to environmental and geographical parameters by multiple regression analysis. This analysis successfully handled the extreme diversity of plant communities, from low montane warm desert to high mountain periglacial communities, and from intrazonal saline meadow and bog to zonal montane desert and steppe. The plant community pattern in Ngari is largely determined by thermal and moisture gradients, as determined by geographical position and soil conditions.

Key words: climatic factors; correlation; detrended correspondence analysis; direct gradient analysis; multiple regression; multivariate analysis; Ngari; ordination; plant community types; reciprocal averaging; Tibetan Plateau.

INTRODUCTION

Ngari is the driest, coldest, and highest region on the Tibetan Plateau, and has been called the "arid core" of the Asiatic Plateau (Troll 1972). It is also the least studied and understood Tibetan region. Gradient and correlation analyses relating its unique plant communities to the unusual combination of extreme ecological conditions are of inherent interest. Temperature, moisture, and available nutrients are often near the limits for survival of plants. Consequently, plant populations are extremely sensitive to and strongly fluctuate with small changes in environmental factors. The implied close relationship between environment and plant communities is advantageous for this study. The purposes of this analysis involve quantifying Ngari vegetation and testing the multivariate methodology required to correlate community variation with significant environmental factors and geographical parameters.

STUDY AREA

The geographical position of the Ngari region is between 30° and 35.5° N and from 78.3° to 86° E (Fig. 1). The area is ≈350 000 km². Apart from mountains on the north and west, the central and eastern Ngari is the western part of the Qiangtang Plateau. Its average elevation is 5000 m in the south and 5200 m in the north. The Gandise Mountains extend across the mid-southern part of Ngari and separate the high mountain, valley, and lake basin parts of western and southern Ngari from the plateau. The average elevation of these valleys and lake basins is 3900 m in the south and 4300 m in the north. The lowest point in Ngari is 2900 m in the southwestern corner of the region, the gorge of the Xiangquanhe River.

The three principal geographical gradients of Ngari are: (a) latitudinal extent of 600 km or 5.5° latitude; (b) longitudinal extent of 720 km or 7.7° longitude; and (c) altitudinal range of 4100+ m (from 2900 to 7000+ m).

Climate

Ngari is characterized by an extremely continental plateau climate. The annual precipitation (P) of Tibet decreases from east to west and from south to north. Ngari is situated at the driest end of both gradients. Precipitation on the Qiangtang Plateau to the east is 180 mm at Gerze. It decreases to ≈50 mm at the western boundary of Ngari in the Bangong Lake Basin, but increases towards the west to 115 mm at Leh, Ladakh. At Pulan, in the inner valley of the Western Himalaya, P is 172 mm. It sharply decreases towards the north: 88 mm in the mid-south (Shiquanhe), 54 mm in the mid-north (Shanhe), and, finally, only 21 mm in the inner Kunlun Mountains (Tianshuihai). The regression equation for P on elevation (H), latitude (L), and longitude (G) in Ngari (Chang 1985) is:

$$P = -210.6 + 0.05475H - 35.065L + 15.111G$$
$$(r^2 = 0.993)\ (n = 11)$$

From the above equation, the vertical precipitation gradient is ≈+5.5 mm/100 m altitude, the latitudinal

[1] Manuscript received 29 October 1985; revised 14 February 1986; accepted 21 February 1986.

[2] Present address: Section of Ecology and Geobotany, Institute of Botanical Research, Chinese Academy of Sciences, Beijing, China.

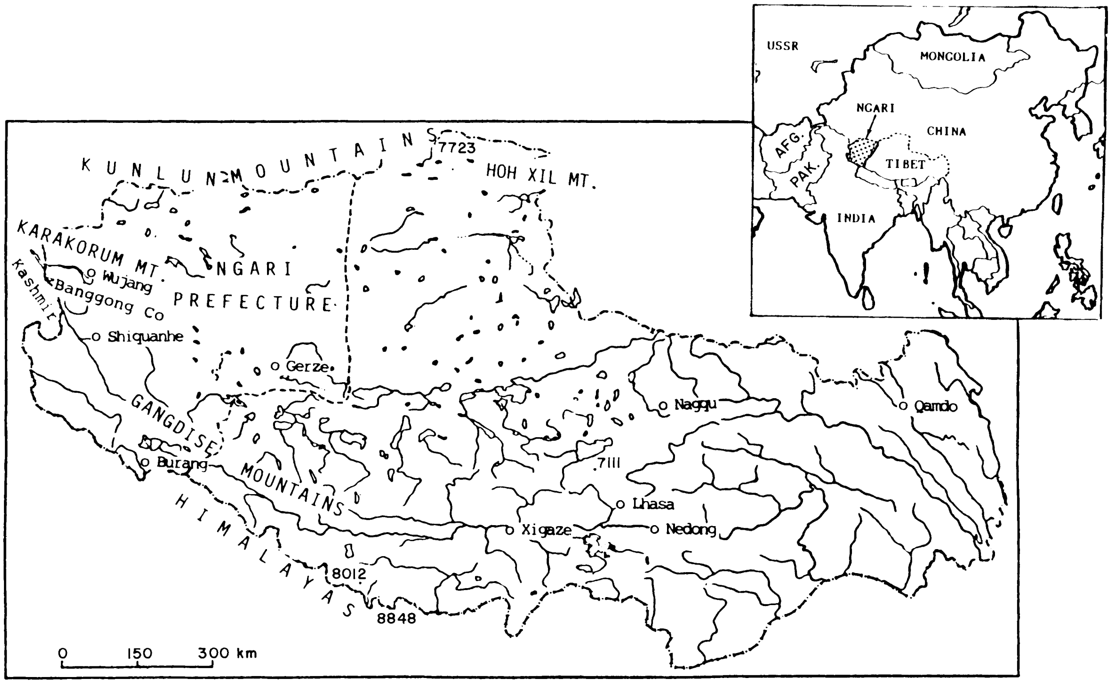

FIG. 1. Geographic position of Ngari Prefecture in Tibet, China.

gradient is −35 mm/degree of latitude, and the longitudinal one is +15 mm/degree of longitude.

Due to the high elevation of Ngari, its annual mean temperature (T) is quite low: 3°C to the south, −0.1° in the central part, and as low as −10° to the north. The regression equation for T (Chang 1985) is:

$$T = 33.7 - 0.00676H - 0.7535L + 0.2372G$$
$$(r^2 = 0.985)\ (n = 11)$$

T is determined mostly by elevation. The lapse rate of T on elevation in Ngari is −0.68°/100 m, −0.75°/degree of latitude, and +0.24°/degree of longitude.

It is evident that P and T are strongly related to elevation, latitude, and longitude in Ngari. This provides a strong basis for gradient analysis of plant communities and species. The site parameters (H, L, and G) can also be transformed to climatic indexes (P, T, etc.) for use in ordination and classification of the plant species and communities. The climatic indexes give the simplest and cleanest environmental interpretation for modelling the distribution of the plant communities and species.

Floristic features and vegetation types

There are ≈60 families, 200⁺ genera, and 450⁺ species of seed plants in Ngari (D. H. S. Chang, J.-t. Wang, and B.-s. Li, *personal observations* and S.-w. Liu, J.-t. Pan, and H.-z. Zhang, *personal communication*). Plant families containing 20 or more species are Compositae (54 species), Gramineae (37 species), Leguminosae (22 species), Cruciferae (22 species), Cyperaceae (20 species), Caryophyllaceae (20 species), and Chenopodiaceae (20 species). This floristic composition is similar to the Central Asiatic Desert (Grubov 1963). We collected 242 species in Ngari, and they include most of the dominant and significant companion species. The specimens are deposited in the Section of Ecology and Geobotany, Institute of Botanical Research, Chinese Academy of Sciences, Beijing, China.

The distribution of vegetation zones in Ngari has a prominent three-dimensional zonality. The latitudinal vegetation zonation is related to the decreasing gradient of precipitation and temperature towards the north and presents the following vegetation zones: xeric shrubland and desert steppe in southern mountains; on the Qiangtang Plateau, the subhigh-cold steppe of *Stipa purpurea* in the southern part and the high-cold steppe of *Carex moorcroftii* and *Stipa purpurea* in the northern part; and high-cold desert dominated by cushionlike *Ceratoides compacta* communities interspersed with high-cold steppe of *Carex moorcroftii*. The longitudinal vegetation zonation, related to the gradient of decreasing precipitation from the east to the west, presents the following zones: subhigh-cold steppe of *Stipa purpurea* in the western Qiangtang Plateau; temperate montane desert of *Ceratoides latens* and *Ajania fruticulosa* in the western mountain region of Ngari; and Kashmiri warm-temperate montane steppe desert of *Artemisia maritima* and *Scrozonera divaricata* in the southwestern corner of Ngari (Chang 1985).

TABLE 1. Description of climatological stations in Ngari, Tibet and Kashmir.

Station	Lat. N	Long. E	Elevation (m)	Recording years	Annual P (mm)	Annual mean T (°C)
Pulan	30°17′	81°15′	3900	73–80	171.8	3.1
Shiquanhe	32°30′	80°05′	4278	71–80	87.8	−0.1
Shanhe	33°38′	79°53′	4267	65–70	53.8	···
Gerze	32°09′	84°25′	4415	73–79	180.3	−0.1
Wusangaodi	34°43′	79°18′	5278	65–70	51.0	−9.8
Tianwendian	35°18′	78°16′	5500	65–70	42.8	−10.9
Tianshuihai	35°21′	79°33′	4900	65–70	20.6	−8.2
Leh*	34°09′	77°34′	3514	31–60	115.0	5.5
Kargil†	34°30′	76°05′	2680	···	240.0	9.1
Skardu†	35°15′	75°35′	2288	···	160.0	11.3
Gilgit†	35°55′	74°18′	1490	···	132.0	16.4

* Rao 1981.

† Ogino et al. 1964; recording years are not stated in this publication.

SAMPLING METHODS

Plant community data used for the analysis were obtained during May–September of 1976 by the Interdisciplinary Scientific Survey Expedition on the Qinghai-Xizang (Tibetan) Plateau, Chinese Academy of Sciences. Because of limited time and manpower, difficult travel, and severe living conditions, sampling for plant communities could be done only along several previously determined observation routes and at subjectively determined "typical" or "representative" points. There were 163 formal plant community samples and some supplemental samples. That is certainly not enough sampling for such an extensive area as Ngari. However, there were repeated selections of samples in the same type, and the samples were placed within a wide variety of topographic and hydrological conditions. Therefore, the selection and placement of samples (n = 163) were suitable for gradient analysis and hierarchical classification.

Quadrat size of the samples was 10 × 10 or 5 × 20 m in desert and shrubland vegetation and 1 × 1 or 2 × 1 m in steppe and meadow vegetation. Certain environmental conditions, species coverage percentage and abundance, community structure and height of layers, and phenological phases were recorded for each sample. The plant community type was primarily determined in the field by the dominant plants.

Environmental factors measured or noted included: altitude (H), latitude (L), longitude (G), annual mean temperature (T), the warmest monthly mean temperature (WMT), coldest monthly mean temperature (CMT), annual mean precipitation (P), Thornthwaite's moisture index (IM) and thermal efficiency (TE, Thornthwaite and Mather 1955), Kira's moisture index (K) and coldness index (CI, Kira 1976), and Holdridge's potential evapotranspiration rate (PER) and biotemperature (BT, Holdridge 1967).

Climatological data could not be obtained directly for each community sample. They were recorded at only seven Ngari stations and four additional stations in nearby Ladakh (Table 1). Climatic factors were correlated with the geographical site parameters (latitude, longitude, and altitude) for all the weather stations. Multiple regressions of individual climatic factors onto the site factors were calculated to estimate climatic indexes for each sample in Ngari, thus providing climatic and geographical interpretation of the distribution of plant community types.

STATISTICAL METHODS

Multivariate analysis of community data and of environmental factors of Ngari in this paper included the following steps:

A) Ordination of plant community data by multivariate analysis: detrended correspondence analyses (DCA), reciprocal averaging (RA), and additive main effects and multiplicative interaction (AMMI, also named the "biplot" analysis);

B) Correlation analysis and multiple regression of environmental factors;

C) Correlation analysis and multiple regression of community ordination axes (DCA) on dominant environmental factors.

The community data consist of species abundances, community types, and environmental factors. In order to assure the objectivity of the gradient analysis, only the species abundance data were used for ordination (Gauch 1977, 1982, Hill 1979*a,b*). RA and DCA provided effective results, but principal components analysis (PCA) and AMMI (H. G. Gauch, *personal observation*) were also compared. The effectiveness of the analyses was judged by four criteria: (1) ecological interpretability; (2) effective spreading out of the points, in contrast to all the points in a clump except for a few outliers; (3) avoidance of the arch distortion; and (4) effectively revealing minor community gradients (Hill and Gauch 1980). As described later, the DCA ordination met all four criteria of effectiveness almost perfectly. It offered two significant ordination axes (gradients) for communities and species that could be used subsequently for correlation analysis with environmental factors.

The next step, after ordination and classification of the plant community data, was to seek environmental interpretation. There were four categories of abiotic environmental factors for the plant communities: climatic factors (monthly mean temperature, accumulated temperature, monthly mean precipitation, relative humidity, solar radiation, wind velocity, potential evapotranspiration, aridity), soil factors (soil texture, organic matter, pH), topographical factors (slope, orientation, slope form, and position), and geographical site factors (latitude, longitude, and elevation).

Correlation analysis was used to provide an initial, preliminary understanding regarding which environmental factors are dominant in determining the distributions of communities and species. Then, multiple or stepwise regression was used to obtain regression equations for quantitative correlations between the DCA axes and dominant environmental factors. By incorporating the geographical site parameters of samples into these multiple regression equations, quantitative environmental interpretation of samples or species is possible. A pattern or model for the community types and species distributions could be objectively established by plotting samples or species in the DCA ordination.

Results and Discussion

DCA ordination

DCA was clearly indicated as the method of choice, in comparison to RA ordination (Chang 1985), PCA, and biplot or AMMI ordination. DCA produced an excellent ordination for the Ngari data, successfully handling the extreme diversity of plant communities, from low montane warm desert to high mountain periglacial communities, and from saline meadow and bog to montane desert and steppe. The gradients encountered here appear to be longer (10 and 6.5 half-changes) than those of any previously published field data ordination, so these results extend the established capability of DCA (Hill and Gauch 1980, Gauch 1982). (A half-change, as defined in Gauch [1982], is a 50% change in species abundances.)

The first two axes of DCA ordination have significant ecological meaning (Fig. 2). Its first axis (AX1) is an elevation (high-to-low) gradient. It presents an ecological series from high-altitude, cold-resistant, alpine plant communities, through subalpine and middle montane to low montane warm plant communities (see also Table 2).

Generally speaking, the plant communities with AX1

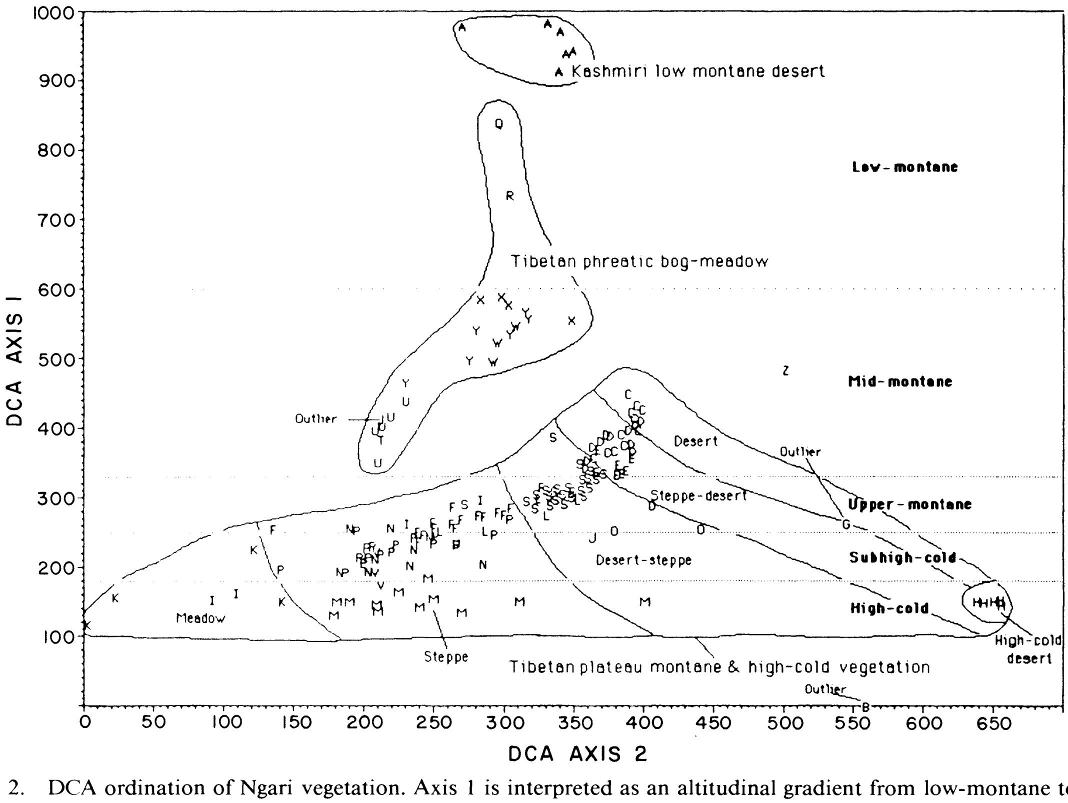

FIG. 2. DCA ordination of Ngari vegetation. Axis 1 is interpreted as an altitudinal gradient from low-montane to high-cold. The outliers are samples with low similarity to all other samples. The 26 plant community symbols are defined in Table 2.

TABLE 2. Dominance-types of plant communities in Ngari, Tibet (from D. H. S. Chang, J.-t. Wang, and B.-s. Li, *personal observations*).

A—Kashmiri warm desert & steppe-desert dominated by *Artemisia maritima, Ephedra intermedia*
B—Pioneer desert community of *Bassia dasyphylla*
C—Montane suffrutescent desert of *Ceratoides latens*
D—Montane suffrutescent-grass steppe-desert of *Ceratoides latens, Caragana versicolor,* and either *Stipa glareosa* or *Stipa subsessiliflora* var. *basiplumosa*
E—Montane suffrutescent-grass steppe-desert of *Ajania fruticulosa* and *Stipa glareosa*
F—Montane steppe-shrubland of *Caragana versicolor*
G—Montane desert-shrubland of *Caragana gerardiana*
H—High-cold cushionlike desert of *Ceratoides compacta*
I—High-cold cushionlike plant communities of: *Arenaria monticola,* or *A. musciformis,* or *Thylacospermum caespitosum*
J—Periglacial plant communities
K—High-cold meadow of *Kobresia pygmaea*
L—Montane desert steppe of *Artemisia wellbyi*
M—High-cold steppe or desert-steppe of *Carex moorcroftii*
N—Subhigh-cold steppe of *Stipa purpurea* and *Carex moorcroftii*
O—Montane desert-steppe of *Orinus thoroldii*
P—Subhigh-cold steppe of *Stipa purpurea*
Q—Saline meadow of *Phragmites communis*
R—Valley shrubland of *Hippophae rhamnoides*
S—Montane or subhigh-cold grass desert-steppe dominated by *Stipa glareosa*
T—Fluvial meadow of *Trikeraia hookeri*
U—Fluvial meadow of *Aneurolepidium dasystachys*
V—Fluvial meadow of *Carex moorcroftii* and *Aneurolepidium dasystachys*
W—Bog-meadow of *Kobresia royleana*
X—Bog-meadow of *Kobresia pamiraalaica*
Y—Bog-meadow dominated by *Blysmus sinocompressus* and *Carex* spp.
Z—Saline meadow of *Suaeda corniculata* var. *olufsenii* or *Polygonum sibiricum* var. *thompsonii*

scores <180 units belong to the alpine or high-cold layer, with elevations >5100 m. The scores of AX1 between 180 and 250 are subalpine or subhigh-cold plant communities, with elevations of 4530–5200 m. AX1 scores between 250 and 600 are upper and middle montane plant communities, and between 600 and 900 are low montane. The Kashmiri low montane warm-temperate plant communities are located between AX1 900 and 980, with elevations <3550 m. Usually a given plant community type occurs at higher elevation on the mountains at lower latitudes.

The second ordination axis of DCA (AX2) reflects a moisture gradient. The ordination of samples along this gradient goes from the meadow type at the low end, passes through a series of transitional steppe and desert types, then reaches to the high-cold desert type at the high end. The ordination scores of alpine meadow are approximately 20–110, meadow-steppe 120–180, steppe 180–270, desert-steppe 270–380, steppe-desert 330–390, desert 350–400, and high-cold desert >640. The overlapping sections between adjacent types are due to the interacting effects of thermal conditions and altitude. The same score on AX2 for lower altitudes or warmer sites may indicate drier plant community types there.

The analysis of DCA AX2 shows that the edaphic or soil characteristics are the second most significant factors for the structure and distribution of communities and species. This has also been noted by other researchers (Marks and Harcombe 1981, Christensen and Peet 1984, Olsvig-Whittaker et al. 1984). However, the soil characteristics used for the present analysis are organic content and pH, which are conjugate factors of soil moisture, instead of the basic characteristics such as soil texture, soil depth, slope orientation, form, position, etc., which directly determines the soil texture. Future research on these characteristics should be of great importance. Both AX1 and AX2 are needed to characterize plant community distributions adequately.

The mathematical relation between the elevation (AX1) and moisture (AX2) axes is not a simple straight line, but a logarithmic curve. The desert communities are located in the low montane belt at the center of DCA axis 2 (vegetation type A in Fig. 2), the mid-montane deserts are beneath and slightly to the right (higher elevation types: C, D, and E), and, finally, the cold and dry deserts (type H) are situated at the rightmost end in the high-cold belt of the pattern. The distribution of the phreatic plant communities in the pattern does not show their real moisture condition. They are displaced on the third DCA ordination axis, which was not presented here in our two-dimensional graph.

The 163 samples in the ordination diagram distinctly aggregate into three groups. The group consisting of the uppermost six samples are lower montane steppe-desert, which belong to the vegetation type in the warmest Kashmir Valley. The group of 22 samples in the middle left is the saline meadow and bog; these are located in lake basins and wide valleys and are dominated by phreatophytes, which are supported by the groundwater, rivers, and lakes. The third and largest group on the bottom consists of all the zonal vegetation types on mountains and plateau of Ngari. It contains a series of plant communities from the moist (left) to the dry (right): meadow, steppe, desert, and the high-cold desert in the lowest and furthest right area.

Multiple regression of environmental factors

The correlation coefficients between various climatological and geographical site factors have been calculated (Table 3) in order to find the significant site factors for each climatological factor. For example, T correlates highly with H and L (but not G). The correlation coefficients are -0.94 and -0.68, respectively. P has significant correlations with L and G (-0.75 and 0.66), but not with H, because the relationship between P and H is not a simple linear correlation but rather a nonlinear one. P increases with H between 3900–5500 m, but at a certain limit of elevation (>5500 m) it decreases. Therefore, H is the most significant independent variable for P in the nonlinear multiple regression analysis.

The linear regression equations are as follows:

$$T = 33.7 - 0.0068H - 0.75L + 0.24G \quad (r^2 = 0.985)$$

$$WMT = 39.74 - 0.0075H - 0.04L + 0.08G \quad (r^2 = 0.973)$$

$$CMT = 51.84 - 0.0016H - 1.92L + 0.05G \quad (r^2 = 0.990)$$

$$P = -210.6 + 0.055H - 35.06L + 15.11G \quad (r^2 = 0.993)$$

The nonlinear regression equation for P is:

$$P = 669.1 - 0.452H + 5.91 \times 10^{-5}H^2 - 0.35L^2 + 0.123G^2 \quad (r^2 = 0.999)$$

From the linear regression, note that T decreases 0.75°C for 1° increase in L. The lapse rate of T on H is 0.68°/100 m, but the longitudinal gradient of T is small, only 0.11°/1° G, with T increasing towards the east in Ngari. These results from Ngari agree well with general world geographical patterns (Strahler 1968, Rao 1981). Ngari exhibits the powerful heating effect of the Tibetan Plateau (Ye and Gao 1979). WMT is mainly affected by H. Its altitudinal lapse rate is −0.75/100 m and there is almost no effect of L and G on it. CMT is mainly affected by L and H.

According to the linear regression, the latitudinal gradient of P in Ngari is −35.1 mm/1°L. It shows that the latitudinal gradient of P is caused by the rain-shadow effect of multiple east-west orographic barriers. The longitudinal gradient of P is ≈15 mm/1°G. The altitudinal gradient of P is ≈5.5 mm/100 m in H within the vertical range 3900–5500 m.

The regression equations for several additional climatological indices are:

$$IM = -1065.5 - 0.20H + 2.23 \times 10^{-5}H^2 + 62L - 0.99L^2 + 5.91G \quad (r^2 = 0.996)$$

$$K = -82.7 - 0.02H + 0.218 \times 10^{-5}H^2 + 5.05L - 0.08L^2 + 0.60G \quad (r^2 = 0.991)$$

$$PER = 32.2 + 0.02H - 0.201 \times 10^{-5}H^2 - 2.81L + 0.05L^2 - 0.28G \quad (r^2 = 0.990)$$

$$TE = -1062.3 - 0.13H + 1.07 \times 10^{-5}H^2 + 86.77L - 1.37L^2 + 1.03G \quad (r^2 = 0.997)$$

$$BT = -63.06 - 0.01H + 0.128 \times 10^{-5}H^2 + 6.64L - 0.10L^2 \quad (r^2 = 0.998)$$

$$CI = -1929 - 0.18H + 1.18 \times 10^{-5}H^2 + 119.04L - 1.90L^2 + 2.71G \quad (r^2 = 0.997)$$

It is clear that there are significant correlations between climatological and site factors, and these make it possible to predict climatological indexes accurately from site data (H, L, and G) by using regression equations.

Multiple regression of DCA axes on dominant environmental factors

Correlation of DCA sample ordination scores with environmental indexes provides objective, quantitative environmental interpretation for vegetation types. According to the correlation analysis (Table 4), DCA AX1 is significantly correlated negatively with altitude and positively with all thermal indexes. Because these thermal indexes are conjugate factors, only WMT was selected with site parameters as the independent variables in the regression for predicting AX1:

$$AX1 = -2725.2 + 1.68WMT^2 - 29.34WMT + 178393/G + 4226833H \quad (r^2 = 81.7)$$

AX2 appears to reflect a soil moisture gradient, and it does not correlate with any of our thermal data (Table 4). P and various moisture indexes have only low or

TABLE 3. Correlation coefficients between environmental and site factors (n = 135).

Environmental factor	Site factors† Elevation (H)	Latitude (L)	Longitude (G)
Organic matter % (ORG)	0.372**	−0.015	0.276*
pH (PH)	−0.397**	0.036	−0.320**
Annual mean temperature (T)	−0.398***	−0.679***	−0.121
Annual mean precipitation (P)	−0135	−0.748***	0.664***
Warmest monthly temperature (WMT)	−0.990***	−0.403**	−0.262*
Coldest monthly temperature (CMT)	−0.900***	−0.652***	−0.139
Moisture index, IM (Thornthwaite)	−0.081	−0.376**	0.574**
Moisture index, K (Kira)	0.132	−0.237*	0.628***
Evapotranspiration rate, PER (Holdridge)	−0.628***	0.062	−0.456**
Thermal efficiency, TE (Thornthwaite)	−0.976***	−0.502**	−0.176
Biotemperature, BT (Holdridge)	−0.961***	−0.415**	−0.255*
Index of coldness, CI (Kira)	−0.977***	−0.546**	−0.125

† Correlation coefficient (r) is significant at * $P < .05$, ** $P < .01$, *** $P < .001$.

TABLE 4. Correlation coefficients of DCA axes with environmental and site factors ($n = 135$).

Environmental factor	Axis 1†	Axis 2†
Elevation (*H*)	−0.812***	−0.209*
Latitude (*L*)	−0.170	0.310**
Longitude (*G*)	−0.430**	−0.160
Slope index	0.062	0.142
Soil texture	0.208*	0.031
Organic matter % (ORG)	−0.384**	−0.848***
pH	0.348**	0.889**
Annual mean temperature (*T*)	0.705***	0.031
Annual mean precipitation (*P*)	0.013	−0.344**
Warmest monthly temperature (*WMT*)	0.801***	0.173
Coldest monthly temperature (*CMT*)	0.772***	0.017
Moisture index, *IM* (Thornthwaite)	0.119	−0.267*
Moisture index, *K* (Kira)	0.047	−0.279**
Evapotranspiration rate, *PER* (Holdridge)	0.410**	0.383**
Thermal efficieny, *TE* (Thornthwaite)	0.817***	0.105
Biotemperature, *BT* (Holdridge)	0.860***	0.122
Index of coldness, *CI* (Kira)	0.786***	0.100

† Correlation coefficient (r) is significant at * $P < .05$, ** $P < .01$, *** $P < .001$.

moderate significance for AX2, as do the site factors, because the soil moisture or environmental moisture gradient is not a simple consequence of P or evapotranspiration. The effect of P and evapotranspiration are modified by the topographic and soil characteristics. Therefore, even in the same site, the soil moisture can be tremendously different due to variation in slope, texture, and structure of soil and substrate, etc. As a result, different plant community types can occur within a small area having uniform climate.

Unfortunately, the data from Ngari lack direct observations on soil moisture, which is inherently a variable factor. The data for topographic factors and soil texture are also incomplete and may be inaccurate. Consequently, the regression of AX2 on the independent variables (environmental factors) could not provide a clear interpretation of the gradient on AX2. However, it was found that the content of organic matter (*ORG*) and pH value (*PH*) of surface soil had quite high correlation coefficients with AX2 (−0.85 and 0.89, respectively). The regression equation for AX2 based on *ORG*, *PH*, and *PER* also gives an excellent result:

$$AX2 = -21.36 - 239.02 \log ORG - 22.23 PER + 6.68 PH \quad (r^2 = 0.896)$$

Although both *ORG* and *PH* are not independent or dominant factors that determine soil moisture, they are the conjugate and dependent factors of it. Therefore, they were used as the independent variables to predict AX2 in regression analysis in the absence of direct measurements of soil moisture. Generally speaking, *ORG* increased with increasing soil moisture, but pH was negatively correlated with it (Olson 1981).

This research has determined quantitative environmental indices for the plant community samples by means of correlation and regression analyses between environmental (climate and soil) and site factors. It also provided objective and quantitative environmental interpretations for various plant community types by way of correlation and regression analyses between vegetation ordination (DCA) scores and environmental factors. We hope in the future to collect more vegetational and environmental data in order to derive a more precise understanding of vegetation and environment of Ngari.

ACKNOWLEDGMENTS

The original data were collected with Wang Jin-ting during the expedition conducted by the Interdisciplinary Scientific Survey on the Tibetan Plateau, Academia Sinica, in 1976. The senior author is indebted to Drs. Brian F. Chabot, Peter L. Marks, and Arthur L. Bloom for their advice on this thesis research at Cornell University. The junior author acknowledges support from the U.S.D.A. Rhizobotany Project under Dr. Richard Zobel. We appreciate helpful suggestions on the manuscript from Drs. B. F. Chabot and P. L. Marks, and exceptionally insightful comments from the reviewers and editor.

LITERATURE CITED

Chang, D. H. S. 1985. The multivariate analysis of vegetation and environmental factors in Ngari, Tibet. Dissertation. Cornell University, Ithaca, New York, USA.

Christensen, N. L., and R. K. Peet. 1984. Convergence during secondary forest succession. Journal of Ecology **72**:25–36.

Gauch, H. G. 1977. ORDIFLEX—a flexible computer program for four ordination techniques: weighted averages, polar ordination, principal component analysis, and reciprocal averaging, Release B. Ecology and Systematics, Cornell University, Ithaca, New York, USA.

———. 1982. Multivariate analysis in community ecology. Cambridge University Press, Cambridge, England.

Grubov, V. I. 1963. Rasteniya Tsentralinoi Azii. Volume 1. IZD-VO Akademii Nauk USSR, Moscow, USSR.

Hill, M. O. 1979*a*. DECORANA—a FORTRAN program for detrended correspondence analysis and reciprocal averaging. Ecology and Systematics, Cornell University, Ithaca, New York, USA.

———. 1979*b*. TWINSPAN—a FORTRAN program for arranging multivariate data in an ordered two-way table by classification of the individuals and attributes. Ecology and Systematics, Cornell University, Ithaca, New York, USA.

Hill, M. O., and H. G. Gauch. 1980. Detrended correspondence analysis: an improved ordination technique. Vegetatio **42**:47–58.

Holdridge, L. R. 1967. Life zone ecology. Revised edition. Tropical Science Center, San Jose, Costa Rica.

Kira, T. 1976. Terrestrial ecosystems—a general survey. (In Japanese.) Handbook of Ecology 2, Kyoritsu Suppan, Tokyo, Japan.

Marks, P. L., and P. A. Harcombe. 1981. Forest vegetation of the Big Thicket, Southeast Texas. Ecological Monographs **51**:287–305.

Ogino, K., K. Honda, and G. Iwatsubo. 1964. Vegetation of the upper Swat and the East Hindukush. Pages 247-268 *in* S. Kitamura, editor. Plants of West Pakistan and Afghanistan. Committee of the Kyoto University Scientific Expedition to the Karakoram and Hindukush, Kyoto University, Kyoto, Japan.

Olson, G. W. 1981. Soils and the environment. Chapman and Hall, New York, New York, USA.

Olsvig-Whittaker, L., M. Shachak, and A. Yair. 1983. Vegetation pattern related to environmental factors in a Negev desert watershed. Vegetatio **54**:153–165.

Rao, Y. P. 1981. The climate of the Indian subcontinent. Pages 67-182 *in* K. Takahashi and H. Arakawa, editors. Climate of southern and western Asia. Volume 9. World Survey of Climatology. Elsevier Scientific, New York, New York, USA.

Strahler, A. N. 1968. Physical meteorology. Wiley, New York, New York, USA.

Thornthwaite, C. W., and J. R. Mather. 1955. The water balance. Pages 1-104 *in* Publications in Climatology 8, Laboratory of Climatology, Drexel Institute of Technology, Centerton, New Jersey, USA.

Troll, C. 1972. The three-dimensional zonation of the Himalaya system. Pages 264–275 *in* C. Troll, editor. Geoecology of the high mountain regions in Eurasia. 4. Erdwissenschaftliche Forschung. Franz Steiner Verlag, Wiesbaden, Germany.

Ye, Du-zheng, and Gao You-xi. 1979. Meteorology of the Qinghai-Xizang Plateau. (In Chinese.) Science Press, Beijing, China.