A STUDY ON RESPONSES OF DOMINANT SPECIES TO ENVIRONMENTAL GRADIENTS IN *GLYCYRRHIZA URALENSIS* COMMUNITIES IN CHINA USING GENERALIZED LINEAR MODEL

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Abstract. *Glycyrrhiza uralensis* is an important endangered medicinal plant species and requires special conservation in China. Its relationships with environmental gradients are significant for its conservation. The responses of dominant species to environmental gradients in *G. uralensis* communities were simulated by using the general linear model (GLM). The data were collected from 100 quadrats of 5 m × 5 m in five sites from east to west in northern China. The results showed that GLM was very useful in modelling species responses to environmental gradients. Precipitation and soil nutrients (soil N, P, K, organic matter and pH) were the variables that correlated most to *G. uralensis* populations, dominant species and communities. *G. uralensis* showed the greatest responses to all comprehensive and single gradients, and was absolutely dominant in communities. Its response pattern was unimodal, i.e. it increased and then decreased after reaching the highest value, to almost all environmental gradients. Other four dominant species showed different response patterns with slight variation. To protect *G. uralensis* populations and communities, the measures of soil and water conservation, improving soil nutrients, utilization management etc., should be considered.

Keywords: *species response; generalized linear model, medicinal plant, Glycyrrhiza uralensis, conservation*

Introduction

Responses of medicinal plant species to environmental gradients are very important and most common topic in scientific studies because it is significant to conservation and culture of medicinal plants (Ravindra et al., 2019; Koltz et al., 2022). Many models can be used in such studies, among which regression models are the most frequently used ones to relate plant population with environmental variables (Madsen and Thyregod, 2011). Linear regression is a linear method to simulate the relationship between the dependent variable, i.e. species richness and independent variable, e.g. one or more environmental factors. In the study of ecology, our goal is usually to predict the change of population, so simple linear regression can be used to fit a prediction model using the dependent and independent variable values of the observation data set. The linear regression model assumes response variables following normal distribution. This assumption is applicable to some ecological data such as measured data from control experiments, for example the growth rate of population and the control of nutrient concentration. However, this is not appropriate for some types of response variables, such as when the response variable is considered to be always positive and changes with a wide range of spatial and temporal scale. Such

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variables are for example, change of population abundance with geographical, climatic and soil gradients (Marra and Wood, 2011; Song and Zhang, 2018a). Nelder and Wedderburn (1972) developed the linear model to generalized linear model (GLM), which is a generalization of ordinary linear regression by allowing the linear model to relate to response variables through a link function and allowing the variance of each measurement to be magnified as a function of its predicted value. GLM allows response variables following other distribution models, not restricted to normal distribution, which is applicable to many field survey data, such as medicinal plant response to climatic and soil gradients (Hastie and Tibshirani, 1990). Some applications of GLM to relate plant populations with environmental variables can be found recently (Nicoletti et al., 2020; Bedane et al., 2023). In China GLM simulating response of medicinal plant species, *Glycyrrhiza uralensis* is used to environmental gradients.

Glycyrrhiza spp. refers to a group of medicinal plant species in *Glycyrrhiza* genus of Leguminosae family. The medicine, called Gancao (Licorice) in Chinese traditional medicine dictionary, is the dried roots and rhizomes of *Glycyrrhiza* plant species. Gancao contains many biological-active chemicals, e.g. flavonoids, glycyrrhizin, coumarins, alkaloids, polysaccharides, etc. Pharmacologically proofs, based on in vitro, in vivo or even clinical experiments (Zhang et al., 2023), showed that these chemicals are effective against cough, general pains, inflammatory, detoxification, allergy, particularly against human immunodeficiency virus (HIV) (Shen et al., 2003; Ji et al., 2004; Zhao et al., 2006; Zhang et al., 2019). Three *Glycyrrhiza* species can be used as medicinal resources, they are *G. uralensis*, *G. inflate* and *G. glaba* (Zhou, 2003). *G. uralensis* is the super one and most useful for Chinese medicines (Hussain and Hore, 2007; Nautiyal et al., 2009). Annual production of Gancao medicine from *G. uralensis* is 60000-100000 tons, with the proportion of wild origin nearly 80%, in mainland of China. In addition to being used in medicine, Gancao is also used in food, tobacco, chemical industries etc., and its productivity needs to be improved (Zhou, 2006; Zhang et al., 2019). *G. uralensis* is a widely distributed species from east to west in temperate area of northern China, and is a good species with high-growth rate for ecological conservation in arid and semi-arid lands, such as sandy land, desert grassland etc. However, in the past few decades, its survival communities have been severely disturbed and degraded, and its wild resources have been decreased rapidly (Zhang et al., 2011). *G. uralensis* became a national protection plant species. The conservation and restoration of *G. uralensis* and its communities become urgent in Northern China (Pan and Zhang, 2002).

Some studies on the taxonomy and spatial distribution, biochemistry, medical pharmacology and cultivating technology of *G. uralensis* have been done (Hu and Shen, 1995; Zhang et al., 2019). This study is a fundamental work to relate *G. uralensis* with environmental gradients in its survival communities in northern China, which is useful for conservation, restoration and reasonable utilization for this species and its communities (Ji et al., 2004; Wan et al., 2019; Vasconcelos, 2023).

Material and methods

Generalized linear model

Generalized linear model (GLM) assumes a probability distribution and transforms it into a family of exponential distribution, thus obtaining different models.

In the general linear regression we assume that the independent observations $\boldsymbol{y_i}$ (i = 1, 2, 3, …, N) is normal distribution with mean $\boldsymbol{\mu_i}$ and variance $\boldsymbol{\sigma^2}$:

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$$Y_i : N(\mu_i, \sigma^2)$$

For generalized linear regression, supposing that the dependent variables $\boldsymbol{y_1, y_2, y_3, \ldots, y_n}$ are $\boldsymbol{n}$ independent observations and obey exponential distribution, that is, they have probability density function:

$$f_i(y_i) = \exp\left\{\frac{y_i\theta_i - b(\theta_i)}{a_i(\phi)} + c(y_i, \phi)\right\} \quad \text{(Eq.1)}$$

where $\boldsymbol{\theta_i}$ and $\boldsymbol{\phi}$ refer to parameters and $\boldsymbol{a_i(\phi), b(\theta_i)}$ and $\boldsymbol{c(y_i, \phi)}$ refer to functions. Of all the possible models, the considered function $\boldsymbol{a_i(\phi)}$ has the same form:

$$a_i(\phi) = \frac{\phi}{p_i} \quad \text{(Eq.2)}$$

where $\boldsymbol{p_i}$ refer to a known prior weight, commonly using 1. The parameters $\boldsymbol{\theta_i}$ and $\boldsymbol{\phi}$ essentially present location and scale parameters.

Supposing $\boldsymbol{x_1, x_2, x_3, \ldots, x_n}$ are the observed values of the p-dimension independent variable $\boldsymbol{X}$ corresponding to $\boldsymbol{y_1, y_2, y_3, \ldots, y_n}$. Note as:

$$\eta_i = x_i^T \beta \quad \text{(Eq.3)}$$

where $\boldsymbol{\beta}$ is the $p \times 1$ unknown parameter vector. Supposing

$$E(Y_i) = \mu_i \quad \text{(Eq.4)}$$

And $\boldsymbol{\mu_i}$ and $\boldsymbol{\eta_i}$ have relation:

$$\eta_i = g(\mu_i) \qquad i = 1, 2, 3, \ldots, n \quad \text{(Eq.5)}$$

where $\boldsymbol{\mu_i}$ is the expectation of $\boldsymbol{Y_i}$. The model so defined is called generalized linear model, $\boldsymbol{\theta_i}$ called natural parameter, $\boldsymbol{\phi}$ called discrete parameter and $\boldsymbol{g(\mu_i)}$ called connection function. The connection function determines the mean structure of the generalized linear model. For different type data, different connection functions will produce different generalized linear models.

(1) Gaussian model

For the Gaussian (normal) distribution, it has a probability density function:

$$f_i(y_i) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left\{-\frac{1}{2}\frac{(y_i - \mu_i)^2}{\sigma^2}\right\} \quad \text{(Eq.6)}$$

Let us expand the square, we can get:

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$$(y_i-\mu_i)^2 = y_i{}^2+\mu_i{}^2-2y_i\mu_i \quad \text{(Eq.7)}$$

So, the coefficient of $\boldsymbol{y_i}$ is $\frac{\eta_i}{\sigma^2}$. This defines $\boldsymbol{\theta_i}$ as $\boldsymbol{\mu_i}$ and $\boldsymbol{\phi}$ as $\boldsymbol{\sigma^2}$, with $\boldsymbol{a_i(\phi)} = \boldsymbol{\phi}$, and:

$$f_i(y_i)=\exp\left\{\frac{y_i\mu_i-\frac{1}{2}\mu_i{}^2}{\sigma^2}-\frac{y_i{}^2}{2\sigma^2}-\frac{1}{2}\log(2\pi\sigma^2)\right\} \quad \text{(Eq.8)}$$

For standard Gaussian (normal) distribution, when connection function $\eta_i = x_i^T\beta$ and $\boldsymbol{p_i}$ have the relation $p_i=\phi(x_i^T\beta)$, the generalized linear model is called the probit model.

(2) Poisson model

For the Poisson (random) model, it has a probability density function as:

$$f_i(y_i)=\frac{e^{-\mu_i}\mu_i{}^{y_i}}{y_i\,!} \quad \text{(Eq.9)}$$

y_i = 0, 1, 2, 3,…, *n*.

Taking common logarithm:

$$\log f_i(y_i)=y_i\log(\mu_i)-\mu_i-\log(y_i\,!) \quad \text{(Eq.10)}$$

Here the mean equal to the variance.

For standard Poisson distribution, the connection function is $g(p)=\ln(\frac{p}{1-p})$, and if $g(p_i)=\ln(\frac{p_i}{1-p_i})=x_i^T\beta$, the generalized linear model is called logit model. When the connection function satisfies $\mu_i = x_i^T\beta$, the generalized linear model defined in this way is called linear Poisson model.

(3) Gamma model

For the Gamma model, it has probability density function:

$$f(y_i\mid \mu_i,\sigma^2)=\frac{1}{\Gamma(\sigma^2)}\left(\frac{\sigma^2}{\mu_i}\right)^{\sigma^2} y_i{}^{\sigma^2-1}\exp\left(-\frac{v\sigma^2}{\mu_i}\right) \quad \text{(Eq.11)}$$

$y_i \ge 0, \mu_i > 0, \sigma^2 > 0$.

For standard Gamma distribution, the connection function is usually logarithmic. When the connection function satisfies $\ln\mu_i = x_i^T\beta$, the generalized linear model so defined is called the logit linear model.

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Model effective test

Here we use the Akaike Information Criterion (AIC) to estimate the relative simulation quality of different models. AIC estimates the fitting quality for each model, relative to each of the other models. Thus, AIC can provide a way for model effect test and comparison.

$$AIC = 2k - 2\ln(L) \qquad \text{(Eq.12)}$$

where $\boldsymbol{k}$ is the number of estimated parameters in the used model, and $\boldsymbol{L}$ is the maximum value of the likelihood function for this model. The less the AIC value, the better the model performs (Hastie and Tibshirani, 1990).

Gancao community data

A general survey of the distribution of *G. uralensis* populations and their communities was conducted prior to sampling in northern China in 2015. According to the survey result, we choose five sampling sites, they were in Weichang Manchu Mongolian Autonomous County (Chifeng City, Inner Mongolia Autonomous Region), Hangjin Banner (Erdos City, Inner Mongolia Autonomous Region), Minqin County (Wuwei City, Ganshu Province), Fuhai County (Altay Region, Xinjing Autonomous Region) and Shule County (Kashgar Region, Xinjing Autonomous Region) respectively (the study area and location please see Song et al., 2022). Each site had an area at least 40 ha. Twenty sampling quadrats were set up randomly at each sampling site. Quadrat size was 5 m × 5 m because all communities were grassland with some scrubland. The species name, individual number, coverage and average height of all species in a quadrat were measured and recorded. Species coverage was directly estimated by eyes, and the height of five individuals for each species was measured by use of a tape ruler and average height was used. Totally, 191 species of grasses, herbs and scrubs were recorded in 100 quadrats. Geographical variables, such as elevation, slope and slope direction for each quadrat were also measured. A GPS was used to measure elevation, and a compass meter was used to measure slope and slope direction (Zhang et al., 2011; Song et al., 2022).

Soil samples were also collected in each quadrat by using a small spade. Five soil samples of 30 cm in depth in a quadrat were taken and completely mixed, and then one quarter was taken and put into a soil bag. Soil samples were air-dried, grinded, sieved and chemically analyzed in the laboratory. The concentration of available N, available P, available K and organic matter, and soil pH value was measured as soil variables for each quadrat. These were the most important nutrient factors in semi-arid and arid area in China. Soil distilled water suspension of 1:2.5 was used to determine the pH value using a pH sensor meter. The Kjeldahl extraction, $HClO_4$-H_2SO_4 colorimetric method, Atomic Absorption Spectrophotometer and $K_2Cr_2O_7$ – capacitance method were used to measure nitrogen, phosphorus, potassium and organic matter respectively. The climate data were collected from the nearest weather stations to each study site.

Species Importance Value (IV) in each quadrat was used as species response data in the analysis. IV was calculated by the following formulas (Zhang, 2018):

$$IV_{\text{Scrubs}} = (RA + RC + RH) / 3 \qquad \text{(Eq.13)}$$

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$$IV_{Herbs} = (RC + RH) / 2 \quad \text{(Eq.14)}$$

RA, RC and RH refer to relative abundance, relative coverage and relative height respectively. The relative abundance, relative coverage and relative height refer to the percentage of one species abundance, coverage and height over the sum of all species abundance, coverage and height in a quadrat respectively. Species data matrix (191×100) consisted 191 species IV values in 100 quadrats.

Among the environmental variables, geographical factors (elevation, slope and slope direction) were not very significant from a previous analysis, so here we mainly analyze climate and soil data. Environment data matrix (10×100) consisted of 10 variables in 100 quadrats.

Results

Canonical ordination was used to summarize ecological information and get comprehensive gradients. Firstly a Detrended Correspondence Analysis (DCA) was carried out, which showed that the length of the first DCA axis gradient was over five, and therefore, Canonical Correspondence Analysis (CCA) ordination was selected rather than Redundancy Analysis (RA) (ter Braak and Šmilauer, 2012; Zhang, 2018). The first and second CCA axes were used as comprehensive gradients here (Song and Zhang, 2018b).

For CCA analysis, the test of Monte Carlo permutation showed that the eigenvalues for the first and all canonical axes were statistically significant ($P < 0.001$) and CCA summarized ecological information very well. Correlations between species and environment for the first four axes were 0.995, 0.994, 0.983 and 0.974 respectively. The *G. uralensis* populations and communities were significantly correlated with environmental variables (*Table 1, Fig. 1*). The first CCA axis was a comprehensive ecological gradient of precipitation, soil P, pH, temperature etc. and dominated by precipitation. The second CCA axis was a comprehensive ecological gradient of soil K, pH, organic matter, N, the lowest temperature, soil P etc. (*Table 1, Fig. 1*).

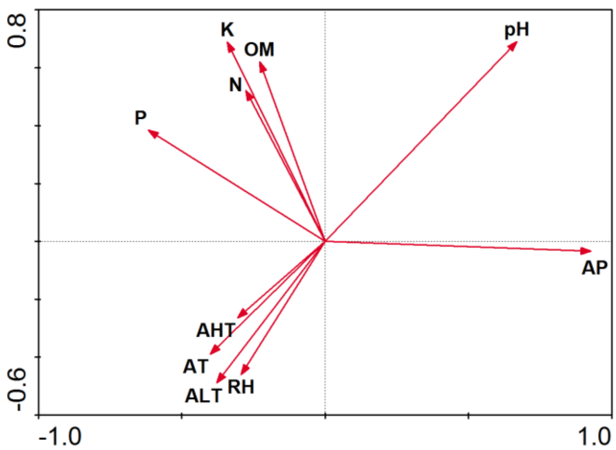

Figure 1. *CCA ordination diagram to show the effects of environmental variables on Glycyrrhiza uralensis communities in China. AT-annual mean temperature, AP-annual mean precipitation, AHT-annual mean highest temperature, ALT-annual mean lowest temperature and RH-relative humidity; N-soil available N, P-soil available P, K-soil available K, pH-Soil pH and OM-soil organic matter*

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Table 1. *Correlation coefficients between environmental variables and CCA axes in Glycyrrhiza uralensis communities in China*

Environmental variables	CCA axis 1	CCA axis 2	CCA axis 3	CCA axis 4
Annual mean precipitation	0.9076***	-0.0333	0.3345***	0.1442
Annual mean temperature	-0.3925***	-0.3833***	-0.2702**	-0.7450***
Annual highest temperature	-0.2992**	-0.2594**	-0.3238***	-0.8126***
Annual lowest temperature	-0.3705***	-0.4804***	-0.2233*	-0.7172***
Relative humidity	-0.2868**	-0.4526***	0.1577	0.7841***
Soil N	-0.2711**	0.5130***	-0.7600***	0.1899*
Soil P	-0.6045***	0.3778***	-0.6661***	0.0436
Soil K	-0.3341***	0.6773***	-0.5860***	0.2041**
Soil organic matter	-0.2230*	0.6100***	-0.7036***	0.1890
Soil pH	0.6549***	0.6788***	0.2686**	-0.0280

* $P < 0.05$, **$P < 0.01$, ***$P < 0.001$

Five dominant species, *G. uralensis, Stipa bungeana, Stipa sareptana, Artemisia frigida* and *Carex pediformis* were selected for modelling their responses. The responses of these five species abundance (importance values) to CCA axes, climate and soil variables were simulated by GLM using Gaussian, Poisson and Gamma distribution models. Results showed that these distributions were all significant in modelling species-environment relationships. Based on the AIC values and probabilities, Gaussian (normal) distribution model was the best in modelling population variation of *G. uralensis* along environmental gradients, though Poisson and Gamma distribution models were significant as well (*Table 2*). We mainly displayed fitting results of the Gaussian model.

Table 2. *Akaike Information Criterion (AIC) values of different distribution models in simulating response of Glycyrrhiza uralensis population using general linear model (GLM) in China*

Fitting variables	AIC values		
	Gaussian	Poisson	Gamma
CCA axis 1	1.299	3.804	8.470
CCA axis 2	1.007	2.826	8.925
Annual mean precipitation	1.104	3.103	9.403
Annual mean temperature	0.529	1.661	5.658
Annual highest temperature	0.518	1.640	5.578
Annual lowest temperature	0.512	1.642	5.522
Soil N	0.912	2.543	8.105
Soil P	1.003	2.833	8.511
Soil K	0.703	1.970	6.573
Soil organic matter	0.662	1.924	6.465
Soil pH	1.110	3.087	9.661

The response of *G. uralensis* abundance to comprehensive gradients (the first two CCA axes) showed significantly unimodal curves to environmental change. The

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abundance of *Stipa bungeana* and *Stipa sareptana* increased and decreased greatly along the first CCA axis respectively and both decreased gradually along the second CCA axis. *Artemisia frigida* and *Carex pediformis* showed gently variation along these axes (*Fig. 2*).

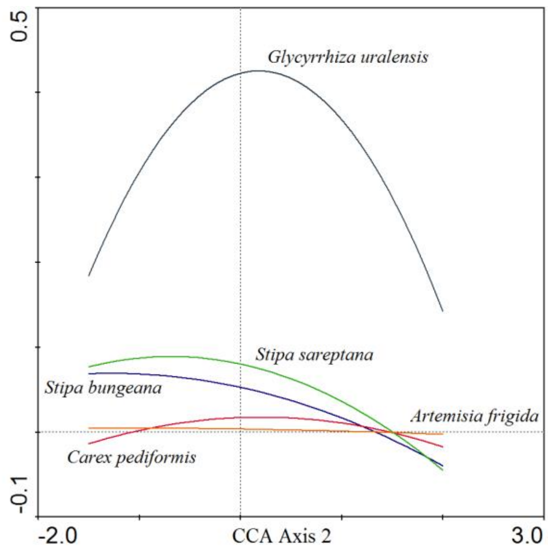

Figure 2. *Generalized linear modelling curves of five dominant species along comprehensive gradients (the first two CCA axes) in Glycyrrhiza uralensis communities in China*

The response of the five species to precipitation were the same as response to the first CCA axis, which further indicated that the first CCA axis was the gradient of precipitation and precipitation was a key factor affecting *G. uralensis* populations and communities. The response curves of the five species to the annual mean temperature showed a reverse unimodal for four species except for *Stipa bungeana* which was a unimodal (*Fig. 3*).

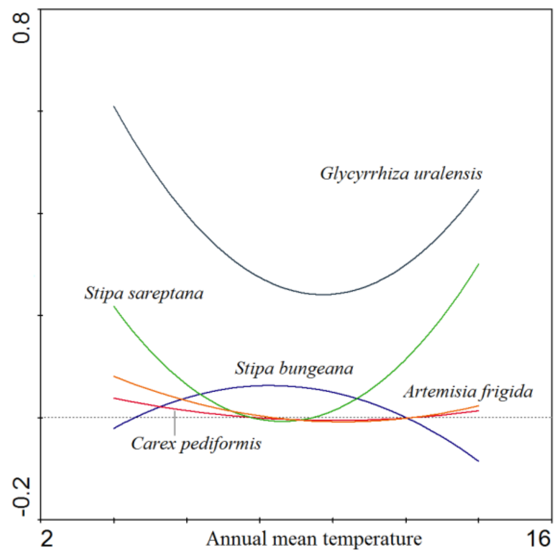

Figure 3. *Generalized linear modelling curves of five dominant species along precipitation and temperature gradients in Glycyrrhiza uralensis communities in China*

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For soil gradients, four of the five species, *G. uralensis*, *Stipa sareptana*, *Artemisia frigida* and *Carex pediformis* showed unimodal changes and their response intensity followed the order of *G. uralensis* > *Stipa sareptana* > *Artemisia frigida* > *Carex pediformis* along soil N, P, K, organic matter and pH gradients. Species *Stipa bungeana* showed decreased or reverse unimodal along soil N, P, K, organic matter gradients, but a unimodal along soil pH gradient (*Fig. 4*).

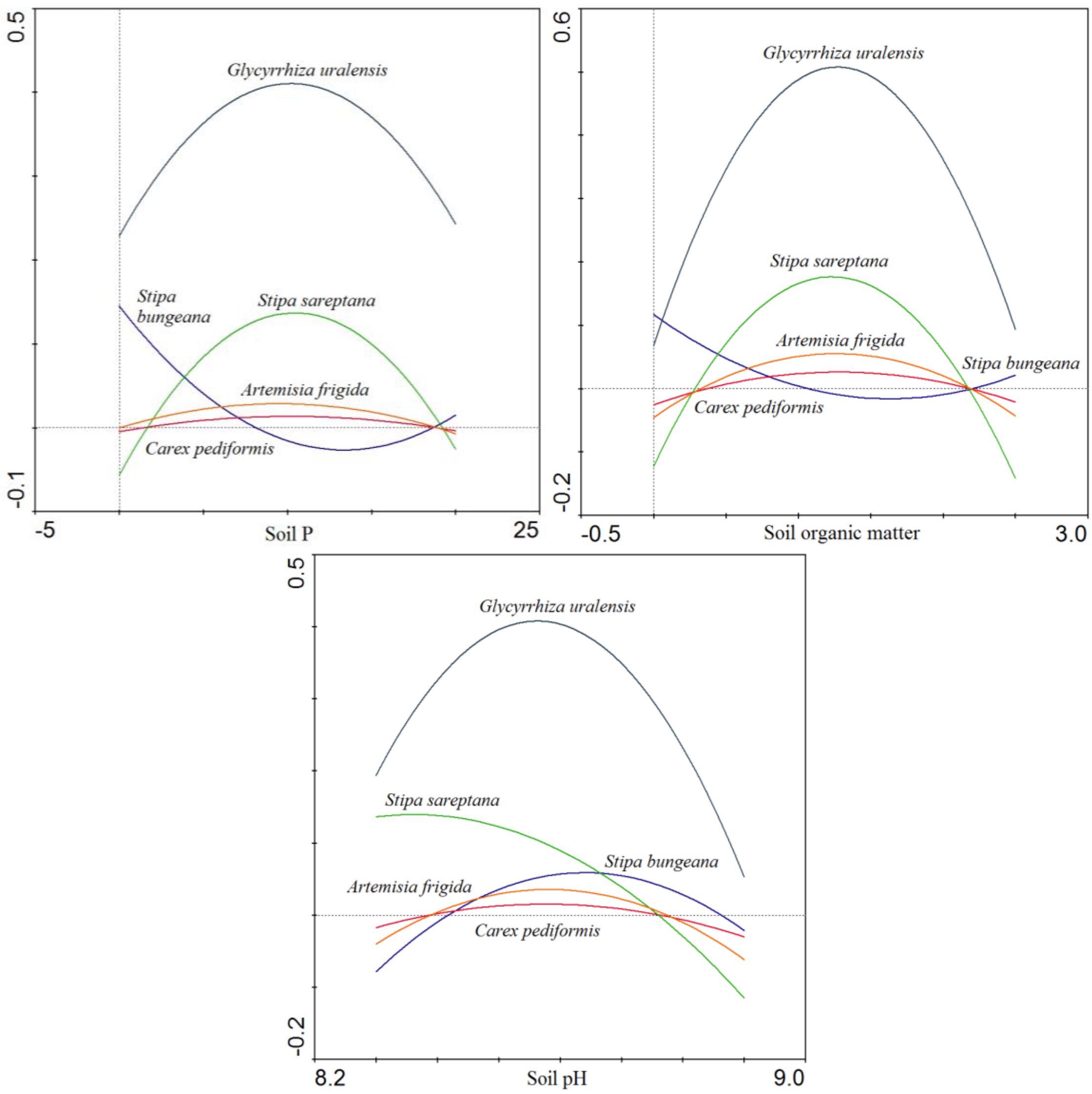

Figure 4. *Generalized linear modelling curves of five dominant species along soil gradients in Glycyrrhiza uralensis communities in China*

Discussion

Generalized linear model performed well in modelling responses of *G. uralensis* and other dominant species abundances (importance value) to comprehensive and single environmental gradients, which is also supported by other studies (e.g. Song and Zhang, 2018a; Zhang, 2018; Ravindra et al., 2019). GLM is an effective method for modelling species-environment relationships (Chen et al., 2010; Ravindra et al., 2019; Bedane et al., 2023). Gaussian (normal) distribution performed best among the three distribution models

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and was more suitable for modelling dominant species in *G. uralensis* communities, which is possibly because that the distribution of *G. uralensis* populations and communities was widely and showed a comparatively long and complete ecological gradient from east to west in northern China (Song and Zhang, 2017; Yang and Liu, 2019).

Modelling results showed that climate, soil variables and their groups were very significantly affecting species variation for the five dominant species in *G. uralensis* communities in China, which was consistent with the results of CCA ordination (Zhang, 2018). The responses of *G. uralensis* populations to comprehensive and single variables were most significant and had the greatest response values which showed that it was the most important species in the communities. This was true for *G. uralensis* was a constructive species and dominated absolutely in the studied communities (Zhang et al., 2011; Yang and Liu, 2019). Its distribution and response pattern will affect other species response to environmental gradients in the communities. The variation of *G. uralensis* along comprehensive and all single gradients except for annual mean temperature showed significantly unimodal curves, i.e. this species abundance increased along these gradients, reached a maximum and then decreased. This indicated that *G. uralensis* was greatly correlated with these environmental gradients (Madsen and Thyregod, 2011; Ravindra et al., 2019). Among single environmental variables, annual precipitation showed the greatest effects on *G. uralensis* abundance changes, which was further proved that precipitation was a key and limited factor to this species in the studied area, arid and semi-arid region in China (Pan and Zhang, 2002; Saeki, 2007). *G. uralensis* was also very significantly correlated to soil nutrients, for the soil was usually sandy and poor with great change in arid and semi-arid area in China (Ji et al., 2004; Zhang L et al., 2019; Wen et al., 2019). The response curve of *G. uralensis* to annual mean temperature was a reverse unimodal which illustrated that this species was not very sensitive to temperature in the studied communities and annual mean temperature was important but not limited factor for its distribution (Glaser et al., 2000; Hevia et al., 2019).

The response pattern of other four dominant species to environmental gradients was different. *Stipa bungeana* increased and *Stipa sareptana* decreased greatly along CCA 1 and precipitation gradients because they were significantly correlated with precipitation, and *S. bungeana* mainly distributed in the eastern area with comparatively higher precipitation, while *S. sareptana* occurred in the western area with lower precipitation (Zhou, 2003; Wen et al., 2019). *Artemisia frigida* and *Carex pediformis* showed gently unimodal changes along CCA 1 and precipitation gradients, which showed that their abundance was low with gentle variation along rainfall gradients (Zhou, 2006; Jin et al., 2019). The effects of annual mean temperature on these four species were weakly significant which was similar to that on *G. uralensis*. All the soil elements were significant influencing these four species, and their sensitivity to soil nutrients following the order of *G. uralensis* > *Stipa sareptana* > *Artemisia frigida* > *Carex pediformis* > *S. bungeana* (Hu and Shen, 1995). This was identical to the results of other studies in this area (e.g. Zhao et al., 2003; Zhou, 2006; Zhang et al., 2011; Wen et al., 2019).

Conclusions

Generalized linear model (GLM) was the perfect method for modelling species responses to environmental variables, particularly for long and complete gradients. *Glycyrrhiza uralensis* was absolutely dominant species in the studied communities and showed a greatest response to all gradients. Unimodal was its response pattern to almost

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all environmental gradients. Other four dominant species, *Stipa bungeana*, *S. sareptana*, *Artemisia frigida* and *Carex pediformis,* showed various response patterns. Precipitation and soil nutrients were most significant for distribution, growth and development of *G. uralensis* populations, dominant species and communities. Soil and water conservation and reasonable management must be considered for protection of *G. uralensis* populations and communities.

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