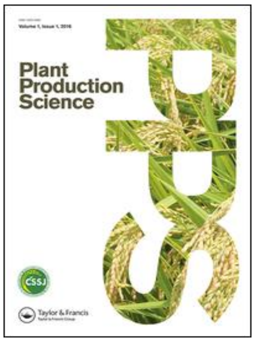

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Habitat Niche-Fitness and Radix Yield Prediction Models for *Angelica sinensis* Cultivated in the Alpine Area of the Southeastern Region of Gansu Province, China

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Abstract : Dried root of *Angelica sinensis* has been used for thousands of years in traditional Chinese medicinal prescriptions. Researches on better knowledge of appropriate habitats for cultivation of this species are required to encourage the potential ecological sustainable industry. From 2001 to 2004, transplanting trials on the regulation of fertilizers and planting density were conducted for collection of habitat factor data at four sites of four counties in the southeastern region of Gansu Province, China. Introducing the niche theory into the research, habitat niche-fitness (HNF) is defined as the degree of similarity of an actual habitat state to the optimum habitat. A new model of HNF is constructed to evaluate the adaptive extent of *A. sinensis*. The results showed that the model of HNF notably outperforms the proportional similarity index and the geometric parallelism formula both in mathematical justification and biological principle testing. With HNF as a surrogate for composite environmental factors, a radix yield model was constructed. Evaluation of the present model by the sampled subplots specified for data validation proved that the model could be well used for predicted of radix yield across a wide-spread area. The radix yield prediction model and its uses are recommended within the limitations of the data used in the study area. Beyond this range, validation of the radix yield prediction model will be necessary.

Key words : *Angelica sinensis,* Habitat niche-fitness (HNF), Radix yield.

The genus *Angelica* comprises of several dozen species and several hundred varieties distributed on all continents of the Northern Hemisphere. These plants are commercially important, which are used for a variety of purposes around the world (Konoshima et al., 1987; Callery, 1997). In Korea, Japan and China, dried roots of several different species and varieties of *Angelica* are used as natural medicines because of containing useful secondary metabolites such as coumarins, essential oils and sesquiterpenes (Heywood, 1971; Konoshima et al., 1987). In China, the dried root of *Angelica sinensis* (Oliv.) Diels, called Danggui as its Chinese name, has been used quite frequently in the prescriptions of Traditional Chinese Medicine for thousands of years. It has been reported that Danggui contains significant amounts of ferulic acid, ligustilide, butylphthalide, butylidenephthalide, allo-ocimene, and angelicide in its extracts (Zhang and Cheng, 1989; Zheng et al., 1998; Hamzah et al., 2004; Huang et al., 2004; Lu et al., 2004) and has been used to enrich the blood, promote blood circulation, regulate female irregular menstruation and amenorrhoea, regulate immunoreaction and relieve pain (Pharmacopoeia Committee of China, 2000; Guo et al., 2003). Recent studies indicated that its polysaccharide not only promoted normal hematopoiesis, but also inhibited the proliferation of leukemia cell and it can be a natural inducer for therapy of malignant tumor (Wang et al., 2003; Cao et al., 2004; Li and Liu, 2005). In recent decades, many people are paying more attention to Danggui due to its advantages of low toxicity, high pharmacological activity, and rarity of complications (Hassel et al., 2002).

Angelica sinensis (Oliv.) Diels is herbaceous perennial plant, which belongs to the genus *Angelica* L. in the family Umberlliferae (Heywood, 1971; Konoshima et al., 1987). It has a 3-year growth cycle: its seeds were sown for raising seedling in June-July of the first year, and seedlings were dug up and stored at the end of October. Transplanting seedlings was performed at mid of March in the second year, and most of fleshy roots were harvested at the end of October and dried to use as natural medicines. The residual were reserved for propagation until third year, and the seeds were collected for the next cycle. Danggui derived from Gansu Province is believed to be pharmacologically the most effective because of its good taste and fragrance. Almost 80% of the output in China was derived from Gansu Province (Ma et al., 2005). As a stenotopic species, it was mainly confined to the transition zone between the Loess Plateau and the eastern rim of the Qinghai-Tibetan Plateau (including

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Tanchang, Mingxian, Weiyuan, and Zhangxian Counties in Gansu Province). These certain habitats are characterized by chilliness, dankness and high altitudes. Because of its therapeutic effectiveness and a worldwide interest in oriental medicine, production of this plant has grown rapidly in recent years (Ma et al., 2005). In Gansu Province 16.7 thousand tons of Danggui were harvested from 11,860 ha in 1995, and 50.4 thousand tons from 62,847 ha in 2003. As a result of increasing requirement for Danggui recently, *A. sinensis* has been cultivated uncontrollably as a medicinal material on a large scale. The following trends for many cultivators were evident: 1) cultivated area were increasing blindly, resulting in lower yield in unsuitable habitats and leading to a dramatic reduction in its major components which determines the diversity of therapeutic effects and decreasing in inhabitants' income; 2) it was cultivated unfortunately in unsuccessful regimes due to pursue high yield, and large amounts of pesticides and chemical fertilizer are being consumed, even though some dangerous pesticides such as DDT had been banned in China, it was still used unofficially because of their wide spectrum of effectiveness and cheaper costs. Still, incidents of Danggui contamination with residue of heavy metals and pesticide had been reported in many places (Ma et al., 2005). Problems might arise due to lack of adequate production procedures without contamination and understanding the direct or indirect causal effects of habitat factors on radix yield. To standardize the production procedures of *A. sinensis* and ensure its quality, people should firstly find out the relationship between ecological environment factors and the growth of *A. sinensis*. Therefore, research on appropriate habitats for cultivation of this species and adequate production procedures are required. Such research could improve radix yield, encourage potential, ecological medicine industry, and predict where *A. sinensis* will produce well.

A species' habitat requirements can be used to predict its presence or absence from particular localities. From the perspective of plant production, radix yield is affected by habitat factors (mainly rainfall, temperature, geographic range, and soil nutrition) as well as cultivation practices (Ellenberg, 1988; Bazzaz, 1991; Li and Lin, 1997; Guisan and Zimmermann, 2000). Under the same standardized cultivation practices without contamination, it is obvious that local habitat factors will play a key role in the survival and productivity of plants and could be used to identify suitable and unsuitable sites for planting (Li and Lin, 1997). In general, the nonlinear multifactor relationships of a species with its habitat are complex, and often difficult to describe mathematically, imposing a challenge for predictions of radix yield using traditional methods (Li and Lin, 1997; Lin and Li, 1998; Guisan and Zimmermann, 2000; Scott et al., 2002; McCune, 2004). The empirical relationships between specific habitat factors and radix yield derived from regression-type models have been criticized (Li and Ren, 1997; Scian and Bouza, 2005) and have created difficulties in determining whether *A. sinensis* could be introduced or not to specific sites. In fact, habitat factors can be relatively independent or interrelated, and under certain circumstances they are complementary and cooperative in determining plant growth. These habitat factors and their ecological impacts may be counter-intuitive or at least not immediately apparent. An extensive literature has developed using different approaches to analyze species-environment relationships. Some approaches are reductionist and rely entirely on the choice of specific ecological factors for study. Each factor is individually experimentally manipulated to study its influence, but the relative importance and potential impacts of different factors on large-scale eco-geographical distribution are very difficult to investigate experimentally (Retuerto and Carballeira, 2004). In contrast, the theory of specific niche-fitness has recently been used to determine the relationships between fitness and grain yield for spring wheat (Li and Lin, 1997; Lin and Li, 1998). Based on the results of experiments on the regulation of water and fertilisers for spring wheat in given farmland of semi-arid regions, Lin and Li (1998) defined the niche-fitness of spring wheat mathematically as the closeness between the actual resource state and the optimum niche points. Their results demonstrated that moderate fertilising and watering had the effect of increasing fitness and grain yield of spring wheat. Up to now, researches on *A. sinensis*, as a cultivated crop have focused on anatomical traits (Ma et al., 2001a,b, 2005), chemical composition in the dried roots (Zhang and Cheng, 1989; Chen et al., 2002; Lu et al., 2003, 2004; Hamzah et al., 2004; Huang et al., 2004), medical value (Pharmacopoeia Committee of China, 2000; Wang et al., 2003; Cao et al., 2004; Li and Liu, 2005) and the breeding of cultivars (Gu, 1982; Zhang and Cheng, 1982,1986; Huang et al., 1996; Tsay and Huang, 1998; Luo et al., 2004). However, no report has been published on the potential adaptive extent and radix yield predictions following a large-scale eco-geographical study of *A. sinensis*.

The goal of the present study was to assess the adaptation of the species to a broad geographical region and to test the hypothesis that distribution can be accurately predicted by easily measured main habitat variables. Transplanting trials under standardized cultivating procedures without contamination were undertaken over wide-spread area from 2001 to 2004 and the species' responses to main habitat factors were analysed. As a part of this large-scale research, the objective of this paper is to 1) discuss the meaning of habitat niche-fitness (hereafter

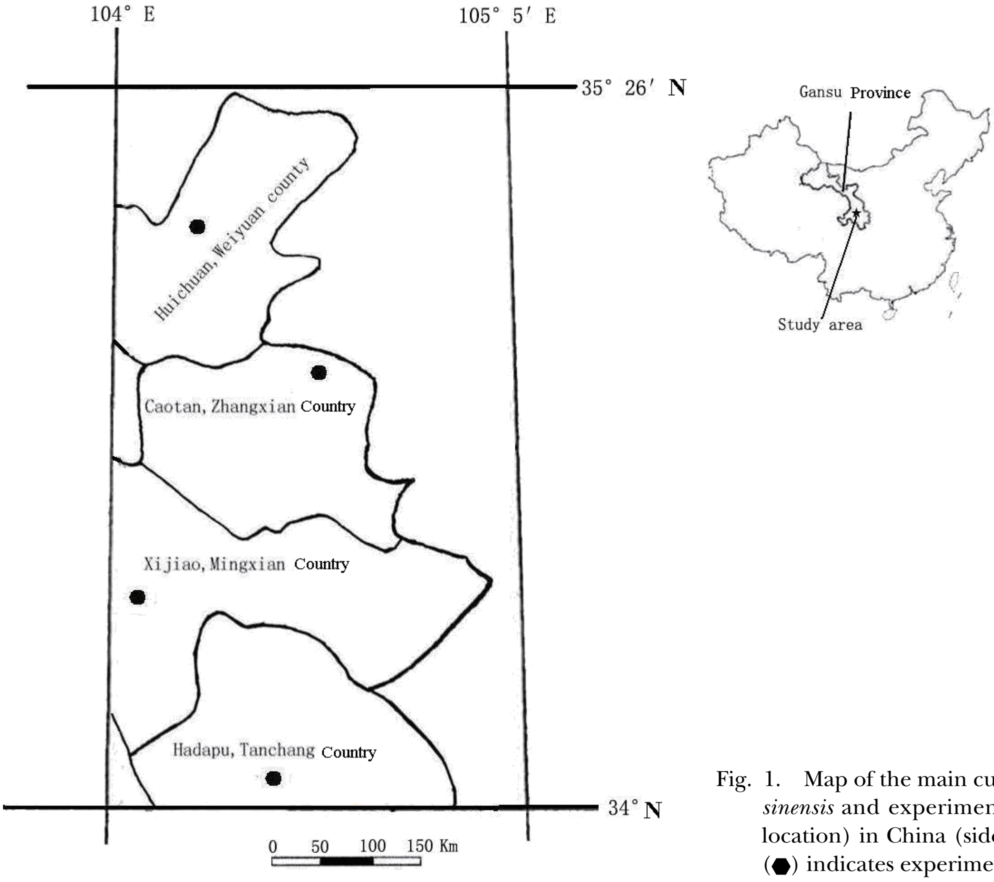

Fig. 1. Map of the main cultivation area of *A. sinensis* and experimental sites (showing location) in China (side right). Filled dot (●) indicates experimental site.

HNF), 2) construct a mathematical model for this plant with the main habitat factors as independent variables and factor weights as parameters, and 3) establish a prediction model for radix yield using HNF as the regressor. It is hoped the HNF and radix yield prediction models will provide farmers and advisors with a reliable tool for identifying likely areas for its production and indicate appropriate management (including fertilizer applications) of *A. sinensis* in regions similar to the southeastern region of Gansu Province, China.

Materials and Methods

1. The experimental sites description

The experiments were conducted on rain-fed farmland in raising plantations of Hadapu (34°4′ N, 104°23′E) in Tanchang County, Xijiao (34°26′ N, 104°5′E) in Mingxian County, Huichuan (35°8′ N, 104°5′E) in Weiyuan County, and Caotan (34°53′ N, 104°28′E) in Zhangxian County, Gansu Province, northwest China (Fig. 1). Sites were selected because (1) they were representative sites in the typical chill-dankness regions; (2) they were within the major cultivation areas for *A. sinensis*; and (3) there was wide variation in their habitat characteristics. The data were collected in different years at different sites over the period 2001 to 2004 and the meteorological and geographic features of each site were described in Table 1. The natural precipitation usually permeates into the farmland; there is no surface water flowing and also no other water supply in this area. The annual >0°C accumulated temperature, and the annual mean temperature in terms of growing-degree-days are also shown in Table 1. The soil types were cultivated black mature soil and black gunny-soil (70–120 cm deep) with an analysis of 15.4–30.8 g kg^{-1} organic matter, 1.35–1.69 g kg^{-1} total nitrogen, 0.62–1.02 mg kg^{-1} phosphorus, 20.5–33.5 mg kg^{-1} potassium and pH of 8.2–8.5. The field water-holding capacity is about 25–40%.

2. Experimental design and treatments

Among these habitat conditions, the limited quantities of heat and soil fertility are the restrictive factors in the prevailing rain-fed farming systems. The principal problem is how to achieve the heat and fertility balance of supply-demand relation as well as high yield. Considering the adequate natural precipitation in these farming systems, the aim of transplanting experiment is to achieve a high radix yield with high quality through manipulating planting density and fertilizer soundly.

The fields in each experimental site were divided into subplots of 4m×4 m with 1 m buffer strips and permutated randomly. Planting density is at three

Table 1. Meteorological and geographic features of the experimental sites*.

Site	Altitude (m)	Annual mean temperature (°C)	Annual>0°C accumulated temperature (°C)	Annual mean precipitation (mm)	The total lengths of frost-free time annually (d).	The total lengths of rainy day annually (d).	Duration of experiment (Month/Year)
Hadapu, Tanchang County	2060	5.7	2580	526	145	110	3-10/2001-2002
Xijiao, Mingxian County	2236	5.5	2341	570	133	118	3-10/2001-2002
Huichuan, Weiyuan County	2314	5.2	2354	578	134	134	3-10/2003-2004
Caotan, Zhangxian County	2360	5.1	2309	592	131	150	3-10/2003-2004

*The data in the table are mean values of collected data during the duration of experiment.

levels: 45 thousand plants ha^{-1} at the low density (LD), 75 thousand plants ha^{-1} at the moderate density (MD) and 105 thousand plants ha^{-1} at the high density (HD). A compound of nitrogen fertilizer, named 'High Efficiency Organic Fertilizer' (supplied by Gansu Agricultural University), made up of the decomposed compound of nitrogen and phosphorus with the percentage at 8% and organic matter at 60% (Qiu et al., 2005a,b), was used for controlling the amount of fertilizer on the fertility gradient without chemical fertilizer and pesticide applications ensuring residue of heavy metals and pesticide contained in Danggui in safe range. Using 13.5, 9, 4.5 t ha^{-1} for high (HF), moderate (MF) and low (LF) fertilizer application respectively, the High Efficiency Organic Fertilizer was regulated by when the crops were transplanting. No fertilizer application (CK) in the control field. Matching the two factors (planting density and soil nutrition) alternately (every treatment repeated three times), we got 36 subplots in each experimental site. The seedlings of *Angelica sinensis* (Oliv.) Diels supplied by Lanzhou Foci Pharmaceutical Group was transplanted by hand on 20 March each year. Weeding was performed thrice annually. The experimental field was not irrigated. Other field management practices were identical to those for other crops grown at this area.

The method of timing and positioning, commonly accepted in agricultural science, was used in observing the fields for field study of *A. sinensis* growth and radix yield indexes. At end of October, fleshy root was harvested. The fleshy roots were then oven-dried at 80°C to constant weights and the data were recorded as radix yield. Soil samples were taken at the 0-30cm layer in each subplot on 15 May, 15 July and 15 September, respectively. Available nitrogen (AVN, determined by the Kjeldahl method, Honda, 1962), phosphorus (AVP, determined by the Olsen method, Olsen and Sommers, 1982) and potassium (AVK, determined by flame photometry, Black, 1979) of soil samples were measured in laboratories of Lanzhou University.

3. Data analysis

(1) Constructing habitat niche-fitness model

The niche theory as a kernel of modern ecology provides a sound theoretical background for habitat niche-fitness (Grinnel, 1924; Hutchinson, 1957; Levins, 1968; MacArthur and Levins, 1967; McNaughton and Wolf, 1970; May, 1974; Odling-Smee et al., 1996; Li and Lin, 1997; Lin and Li, 1998; Buggeman and O' Nuallain, 2000). The characteristics of habitats are usually different from a plant species' optimum requirements in at least some aspects. In an actual or a modified habitat which suited the species, the population would increase, promoting an increase in radix yield; otherwise, it would decrease, resulting in a decrease in radix yield. This is consistent with the concept of habitat niche-fitness.

Taking *A. sinensis* as an example, the quantitative indexes of habitat factors can be marked as x_1, x_2, $\ldots x_n$. The observed values of each group under experiment No. t can be noted as $X_t=(x_{t1}, x_{t2},\ldots x_{tn})$. X_t stands for a realized habitat state or a modified habitat state. Biologically, a plant will show certain adaptation to variables of each habitat factor, so the optimum value of habitat factor i can be marked as x_{ai} (i = 1, 2, ..., n). Habitat niche-fitness makes the assumption that species responses to single habitat factors are a single-humped curve (May, 1981), and can be modeled by a bell-shaped curve (Levins, 1968). $X_a=(x_{a1}, x_{a2},\ldots x_{an})$ represents the optimum habitat niche point as described by Grubb (1977) and is a quantitative description of species attributes for the optimum habitat requirements. A species is at its best for the optimum habitat, and is decreasingly good at handling increasingly dissimilar habitats, or resource levels. The balance between requirements for the optimum habitat and supply of a realized habitat in the development of the species, is an important characteristic. This means that given a certain species, there is one optimal value for the optimum habitat, yielding maximal fitness and other values yielding less fitness, which can be measured by HNF. We suggest that HNF for *A. sinensis* be defined as the degree of similarity between the supply of an actual habitat factor and the requirement for the habitat to be optimum, in which the supply of the actual habitat factor and the requirement for the optimum habitat represent realistic habitat conditions and species attributes, respectively. This is a measurement of the '*n*-dimensional hypervolume' defined by Hutchinson (1957). The mathematical model for HNF can be expressed as follows:

$$HNF = f(X_t,\ X_a, K) \quad \cdots\cdots (1).$$

In this formula, the value of HNF, which is in the range of [0, 1], means the fitness degree of *A. sinensis* in an actual habitat condition. Because there is wide variation among the actual habitat states in the large-scale eco-geographical regions, the HNF value needs a wide distribution within the subset [0, 1]. $f(X_t,\ X_a, K)$ is the measurement of the distance or the degree of similarity between two vectors: $X_t=(x_{t1},\ x_{t2},\ldots x_{tn})$ and $X_a=(x_{a1},\ x_{a2},\ldots x_{an})$. However, in these rain-fed farmland systems, the relative importance of the different habitat factors to *A. sinensis* varies. Thus, we have to allow for unequal weights among the different habitat factors, and extend Eq.(1) where vector $K=(k_1,\ k_2,\ldots k_n)$ is a set of weights for the habitat factors and k_i the weight coefficient of the habitat factor *i*, Given $\sum_{i=1}^{n} k_i = 1$.

In this study, the weight coefficient of each habitat factor is estimated by grey relational grades derived from the grey relational analysis (Deng, 1984, 1985, 1987, 1989a,b; Che and He, 1993; Guo, 1994; Wu et al., 1999; Huang and Lee, 2004). Grey relational analysis gives whole relational orders (wholeness) over the entire relational space to determine the relationships among a referential sequence (radix yield) and compared sequence (habitat factors) by calculating the grey relational grade (GRG). Its size depicts each habitat factor's influence. The measurement method of grey relational grade (GRG) is given in the Appendix 1.

In order to establish a new HNF model, suppose there were *m* experimental treatments and *n* habitat factors. The related observation results are as follows:

No.	Index			
	x_1	x_2	$\cdots$	x_n
1	x_{11}	x_{12}	$\cdots$	x_{1n}
2	x_{21}	x_{22}	$\cdots$	x_{2n}
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
i	x_{i1}	x_{i2}	$\cdots$	x_{in}
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
m	x_{m1}	x_{m2}	$\cdots$	x_{mn}
m+1	x_{a1}	x_{a2}	$\cdots$	x_{an}

Where $a=m+1$; line i $(x_{i1},x_{i2},\ldots,x_{in})$ in the table stands for observed values from experiment No. *i*, which is an actual habitat state in the experiment No. *i*. The data are standardized by the sum of the values so that they vary in the range 0-1 according to the following formulas:

$$x'_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m+1} x_{ij}},\ i=1,2,\ldots,\ m,\ j=1,2,\ldots,\ n \quad \cdots\cdots (2)$$

$$x'_{aj} = \frac{x_{aj}}{\sum_{i=1}^{m+1} x_{ij}},\ j=1,2,\ldots,\ n \quad \cdots\cdots (3)$$

The six habitat factors used for the evaluation of HNF, according to previous research by Xu et al. (1998) are as follows: x_1 is the altitude (m) (AL); x_2 and x_3 the >0°C accumulated temperature (°C) (AT) and the annual precipitation (mm) (AP) during *A. sinensis* growth cycle from March to October, respectively; x_4, x_5 and x_6 the values for available nitrogen (AVN), phosphorus (AVP) and potassium (AVK) (mg kg^{-1}) in the soil layer of 0–30 cm, respectively.

In order to test the validity of the HNF model as a measure of the degree of similarity of an actual habitat to the optimum habitat, and to explain its mathematical justification, the proportional similarity index (PSI, Eq. (A:3), in the Appendix 3, Feinsinger et al., 1981) and the geometric parallelism formula proposed by Li and Lin (F, Eq. (A:10), in the Appendix 3, Li and Lin, 1997) were tested and verified.

(2) Constructing the radix yield prediction model

The data sets collected from the sites of Hadapu (experiment No. 1–12) and Huichuan (experiment No. 25–36) were used to construct a radix yield prediction model by regression analysis of ln-transformed dependent (radix yield per hectare) and independent (HNF) variables. Ln transformations functioned by converting values to a scale where the variance in the relationship was more homogeneous for effective use of least-squares regression (Steel and Torrie, 1980). The radix yield prediction model with HNF as a surrogate for composite environmental factors was validated based on the statistical and biological requirements. Statistical validation was done first through the coefficient of determination (R^2), the adjusted R^2 and the standard error of the estimate. The regression analyses were done using the statistics program SPSS 7.5 (SPSS Institute, 1997). To test the applicability of the regression equation over wide-spread area, independent data sets collected from Xijiao (experiment No. 13–24) and Caotan (experiment No. 37–48) that were not used for regression model construction were used for the model validation and confirmation with the help of root mean square error (RMSE, % value) and 45-degree line test. The RMSE against the observed

Table 2. The observed index values of habitat factors in Hadapu of Tanchang County, Gansu Province*.

No.	Planting density	Fertility	Index of main habitat factors			Radix yield (kg ha^{-1})
			AVN(mg kg^{-1})	AVP(mg kg^{-1})	AVK(mg kg^{-1})	
1	LD	CK**	112.00	28.00	116.00	582.8
2		LF	135.61	29.02	140.46	891.9
3		MF	172.77	33.58	178.94	1151.3
4		HF	194.53	40.18	201.48	1089.2
5	MD	CK**	117.04	27.49	121.22	696.9
6		LF	138.28	29.51	143.21	926.8
7		MF	170.13	35.11	176.20	1150.0
8		HF	188.69	39.16	195.43	1104.2
9	HD	CK**	117.31	25.45	121.50	721.5
10		LF	135.88	28.51	140.73	910.7
11		MF	162.15	31.55	167.94	1171.6
12		HF	175.17	33.07	181.43	1154.7

*The data in the table are mean values of collected data.
**Non-fertilizing condition.

Table 3. The observed index values of habitat factors in Xijiao of Mingxian County, Gansu Province*.

No.	Planting density	Fertility	Index of main habitat factors			Radix yield (kg ha^{-1})
			AVN(mg kg^{-1})	AVP(mg kg^{-1})	AVN(mg kg^{-1})	
13	LD	CK**	112.00	28.00	116.00	882.9
14		LF	135.61	29.02	140.46	1179.1
15		MF	172.77	33.58	178.94	1842.3
16		HF	194.53	40.18	201.48	1660.0
17	MD	CK**	117.04	27.49	121.22	967.3
18		LF	138.28	29.51	143.21	1480.5
19		MF	170.13	35.11	176.20	1831.0
20		HF	188.69	39.16	195.43	1797.2
21	HD	CK**	117.31	25.45	121.50	1003.4
22		LF	135.88	28.51	140.73	1286.4
23		MF	162.15	31.55	167.94	1765.6
24		HF	175.17	33.07	181.43	1824.2

*The data in the table are mean values of collected data.
**Non-fertilizing condition.

mean, was used to calculated the fitness between the predicted results and observed data (Rinaldi et al., 2003):

$$\mathrm{RMSE}=\sqrt{\frac{\sum_{i=1}^{n}(Y_{pre_i}-Y_{obs_i})^2}{n}}\times\frac{100}{\overline{Y}_{obs}} \quad \cdots\cdots\cdots\cdots(4)$$

Where: Y_{pre_i}=predicted radix yield per hectare by the radix yield prediction model; Y_{obs_i}= observed radix yield per hectare; $\overline{Y}_{obs}$= the observed mean value. RMSE (%) shows the relative difference between the simulated and observed data. The prediction is considered excellent with the RMSE<10%, good if 10–20%, fair if 20–30%, poor if >30% (Jamieson et al., 1991; Pan et al., 2006). The observed radix yield values were plotted against the estimated data to find the trend of the slope of the expected curves. If the expected curve approaches an angle of 45 degree with the axes, this means that there is no significant difference between the actual and predicted values. The null hypothesis was that there was no significant difference between outputs from the sampled subplots specified for data validation and the corresponding expected values from the model.

Table 4. The observed index values of habitat factors in Huichuan of Weiyuan County, Gansu Province*.

No.	Planting density	Fertility	Index of main habitat factors AVN(mg kg^{-1})	AVP(mg kg^{-1})	AVN(mg kg^{-1})	Radix yield (kg ha^{-1})
25	LD	CK**	107.00	6.00	91.00	979.7
26		LF	129.56	6.22	110.18	1351.3
27		MF	165.06	7.20	140.38	2329.6
28		HF	185.85	8.61	158.06	2941.7
29	MD	CK**	111.82	5.89	95.10	1066.7
30		LF	132.10	6.32	112.35	1529.4
31		MF	162.53	7.52	138.23	2378.7
32		HF	180.27	8.39	153.31	2880.9
33	HD	CK**	112.07	5.45	95.31	959.5
34		LF	129.81	6.11	110.40	1349.7
35		MF	154.91	6.76	131.75	2109.2
36		HF	167.35	7.09	142.32	2503.3

*The data in the table are mean values of collected data.
**Non-fertilizing condition.

Table 5. The observed index values of habitat factors in Caotan of Zhangxian County, Gansu Province*.

No.	Planting density	Fertility	Index of main habitat factors AVN(mg kg^{-1})	AVP(mg kg^{-1})	AVN(mg kg^{-1})	Radix yield (kg ha^{-1})
37	LD	CK**	140.00	4.70	69.00	736.7
38		LF	169.52	4.87	83.55	1127.5
39		MF	215.97	5.64	106.44	1522.1
40		HF	243.16	6.75	119.84	1694.9
41	MD	CK**	146.30	4.61	72.11	775.0
42		LF	172.85	4.95	85.19	1174.2
43		MF	212.66	5.89	104.81	1558.1
44		HF	235.87	6.57	116.25	1593.1
45	HD	CK**	146.64	4.27	72.27	784.5
46		LF	169.85	4.79	83.71	1127.5
47		MF	202.69	5.30	99.90	1511.7
48		HF	218.96	5.55	107.92	1379.8

*The data in the table are mean values of collected data.
**Non-fertilizing condition.

Results

1. Construction of a habitat niche-fitness model for *A. sinensis*

The results of AVN, AVP and AVK are shown in Tables 2-5. Overall, the main habitat factors included the following controllable factors namely available nitrogen (AVN), phosphorus (AVP) and potassium (AVK) (mg kg^{-1}), which could be improved through agricultural cultivation practices, and the uncontrollable factors, namely altitude (m) (AL), >0°C accumulated temperature (°C) (AT) and the annual precipitation (mm) (AP). *A. sinensis* have hump-shaped response functions to habitat gradients, the theoretical optimum values of main habitat factors were easily obtained by modeling the bell-shaped curves (Xu et al., 1998). In practical works, theoretical optimum values of main habitat factors substituted by their observation values when plants grow at the best conditions. After four years observation, the most suitable values of main habitat factors are: $x_{a1}=2200$ m; $x_{a2}=2350$°C; $x_{a3}=580$ mm; $x_{a4}=186$ mg kg^{-1}; $x_{a5}=8.6$ mg kg^{-1}; $x_{a6}=158$ mg kg^{-1}, respectively.

The three-base points with respect to the response of *A. sinensis* to each main habitat factor are the upper limit, the optimum value and the lower limit calculated

Table 6. The treatment comparisons of HNF, PSI and F in different experimental conditions.

No.	Treatment		HNF	F	PSI	No.	Treatment		HNF	F	PSI
	Planting density	Fertility					Planting density	Fertility			
1	LD	CK	0.592	0.229	0.819	25	LD	CK	0.675	0.473	0.871
2		LF	0.661	0.258	0.836	26		LF	0.733	0.486	0.909
3		MF	0.712	0.291	0.828	27		MF	0.863	0.555	0.964
4		HF	0.690	0.290	0.804	28		HF	0.981	0.899	0.993
5	MD	CK	0.606	0.233	0.827	29	MD	CK	0.683	0.473	0.878
6		LF	0.670	0.265	0.834	30		LF	0.742	0.489	0.913
7		MF	0.711	0.288	0.818	31		MF	0.865	0.558	0.963
8		HF	0.707	0.338	0.806	32		HF	0.954	0.729	0.989
9	HD	CK	0.609	0.234	0.837	33	HD	CK	0.673	0.469	0.875
10		LF	0.663	0.259	0.839	34		LF	0.731	0.485	0.909
11		MF	0.714	0.297	0.834	35		MF	0.818	0.521	0.948
12		HF	0.713	0.295	0.832	36		HF	0.867	0.560	0.966
13	LD	CK	0.658	0.450	0.832	37	LD	CK	0.645	0.374	0.865
14		LF	0.728	0.478	0.838	38		LF	0.708	0.406	0.893
15		MF	0.779	0.511	0.830	39		MF	0.740	0.399	0.916
16		HF	0.757	0.510	0.806	40		HF	0.763	0.406	0.927
17	MD	CK	0.673	0.454	0.838	41	MD	CK	0.655	0.376	0.873
18		LF	0.736	0.485	0.836	42		LF	0.717	0.415	0.895
19		MF	0.778	0.508	0.820	43		MF	0.747	0.404	0.917
20		HF	0.773	0.558	0.808	44		HF	0.758	0.403	0.926
21	HD	CK	0.676	0.455	0.852	45	HD	CK	0.649	0.375	0.871
22		LF	0.729	0.479	0.841	46		LF	0.707	0.406	0.893
23		MF	0.780	0.517	0.836	47		MF	0.739	0.412	0.909
24		HF	0.780	0.516	0.834	48		HF	0.736	0.396	0.916

from the results of the experimental observations. The nearer a site approaches the border of this response curve, the lower the fitness will be with respect to the particular habitat factor. Therefore, the value of HNF responds to variations in each of main habitat factors, presenting a bell-shaped curve along its gradients. The HNF model can be constructed by calculating the relative degree of similarity between an actual habitat state and the optimum habitat requirement, which is intuitively and mathematically meaningful, as follows:

$$HNF_i = \sum_{j=1}^{6} k_j \min\{(\frac{x'_{ij}}{x'_{aj}}), (\frac{x'_{aj}}{x'_{ij}})\}, j=1,\cdots,6 \cdots\cdots\cdots\cdots (5)$$

In Eq.(5), the value of HNF_i, represents the degree of similarity of an actual habitat to the optimum habitat under the experiment No.i, which reflects the demand-supply relation between plant growth and its habitat resources. The observation results of each main habitat factor index are shown in Tables 1–5. In order to emphasize the median trend, all collected data of x_4 (AVN), x_5 (AVP) and x_6 (AVK) at each experimental condition were transformed into the average over three sampling, each was sampled three times in the period between elongation stage and maturity stage (on 15 May, 15 July and 15 September)–crucial stages for *A. sinensis*–which reflect characteristics of fertility in the subplots on an average level. When all data in Tables 1-5 are standardized according to Eqs. (2) and (3), then k_i the weight coefficient of main habitat factor i, can be calculated using the formula:

$$k_i = \frac{GRG(Y, x_i)}{\sum_{i=1}^{6} GRG(Y, x_i)}, i=1,2,\ldots,6 \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (6)$$

Where $GRG(Y, x_i)$ is the grey relational grade (GRG) between habitat factor i and radix yield per hectare calculated by Eq. (A:2), and their values are given in the Appendix 2. The larger the contribution of a particular habitat factor, the higher the weight coefficient of that habitat factor will be. After calculating, the results of the weight coefficients were: $k_1=0.1681$, $k_2=0.1678$, $k_3=0.1682$, $k_4=0.1693$, $k_5=0.1592$, $k_6=0.1673$ and the values for HNF could be calculated (Table 6).

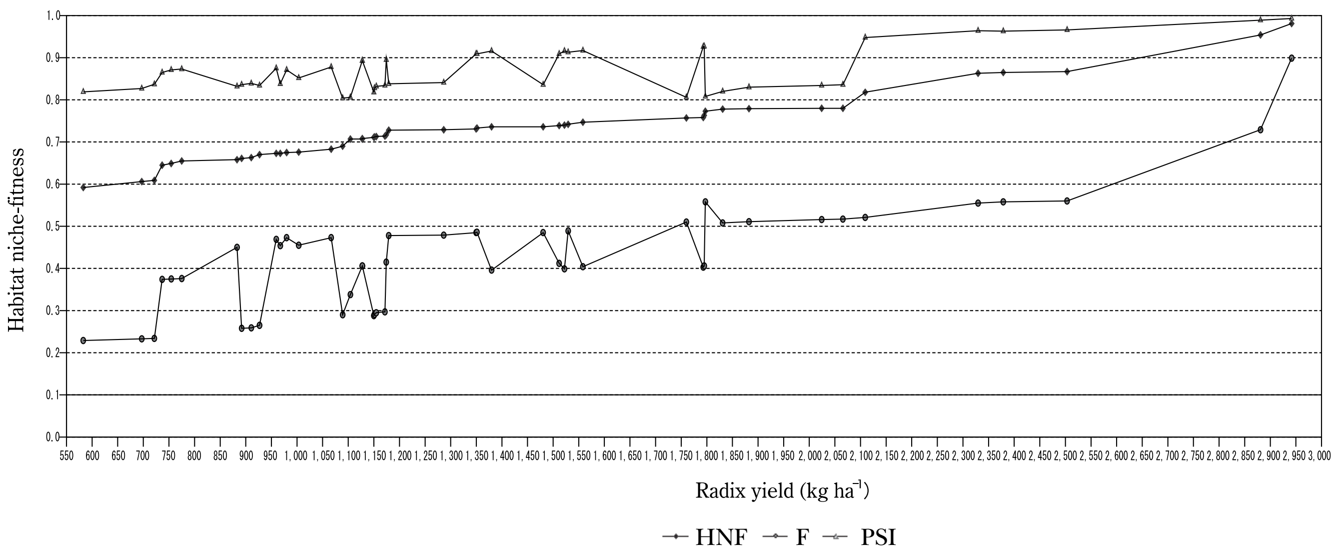

Fig. 2. Graphical comparison between HNF, F and PSI along radix yield (kg ha^{-1}) axis.

The ranges of HNF, F and PSI were $0.592 \leq$ HNF ≤ 0.981, $0.229 \leq$ F ≤ 0.899, and $0.804 \leq$ PSI ≤ 0.993, respectively (Table 6). Obviously, the varied ranges of HNF and F are more extensive than that of PSI, hence HNF and F better reflect the varied differences of fitness under different habitat conditions on a large-scale eco-geographical study. However, we found that using the geometric parallelism formula (F) yielded unrealistically low estimates in some experimental conditions. For example, radix yield averaged 582.8 kg ha^{-1} in experiment No.1 (Table 2), whereas the F value was only 0.229 which is not clearly interpretable in biological terms, whereas the value of 0.592 for HNF is more realistic. The yield curve shifted upward with increasing habitat quality and the yield monotonically increased with fitness. The results the experiment No.13 with HNF of 0.658, compared with experiment No.2 produced comparable radix yields of 882.9 kg ha^{-1} (Table 3) and 891.9 kg ha^{-1} (Table 2) respectively. The values of F at these sites were counter-intuitive whereas the values of HNF were reflected in the radix yields. When the three estimates of habitat niche-fitness were plotted against average radix yield (Fig.2), both HNF and PSI gave relatively smooth curves in contrast to that of F. Furthermore, the biological meaning of Eq. (A:10) is not obvious.

Compared to the value under no fertilizer, the average of HNF with high planting density increased 8.51%, 16.99 % and 18.71%, respectively, under low, moderate and high fertilizer. With low, moderate and high fertilizer, the average of HNF with moderate planting density increased 9.52%, 18.54% and 22.02% compared to that with no fertilizer. Under low planting density, it increased 10.03 %, 20.30 %, and 24.07 %, respectively (see Table 6). The average of HNF will increase with the increasing of fertilizer whatever under low, moderate and high planting density, which is reflected on Fig. 3. On the whole, the value of HNF is the highest with high fertilizer and is the lowest under no fertilizer application.

The analysis of the values of HNF (Table 6) indicate that the value of HNF is increasing from low planting density to moderate planting density and is decreasing from moderate planting density to high planting density. The value of HNF has the most significant responses under moderate planting density. The average of HNF with high fertilizer application is 0.797, 0.798 and 0.774 under low, moderate and high planting density, respectively. With moderate fertilizer, the three values are 0.774, 0.775 and 0.763. While under low fertilizer. They are 0.708, 0.716 and 0.708. The average of HNF with no fertilizer application is 0.643 0.654 and 0.652 under low, moderate and high planting density. From Fig. 3, we can also find that the value of HNF increase initially and then decrease with the increasing of planting density.

2. Radix yield—habitat niche-fitness relationship

The radix yield was highly correlated with HNF, but it is not a linear relationship. According to the results of radix yield observed from the sites of Hadapu (experiment No. 1-12) and Huichuan (experiment No. 25-36) Counties and the corresponding values of HNF as regressor, the relationship was fitted by least squares as ln-ln regressions of radix yield on HNF, as follows:

$$lnY = 8.208 + 3.338\ ln\ NHF \quad \cdots\cdots (7)$$

Where Y is the estimated radix yield per hectare at HNF level. R^2, adjusted R^2 and the standard error of the estimate reached 0.980, 0.979 and 0.066, respectively, i.e. the radix yield regression model satisfied the statistical criteria. Using independent data

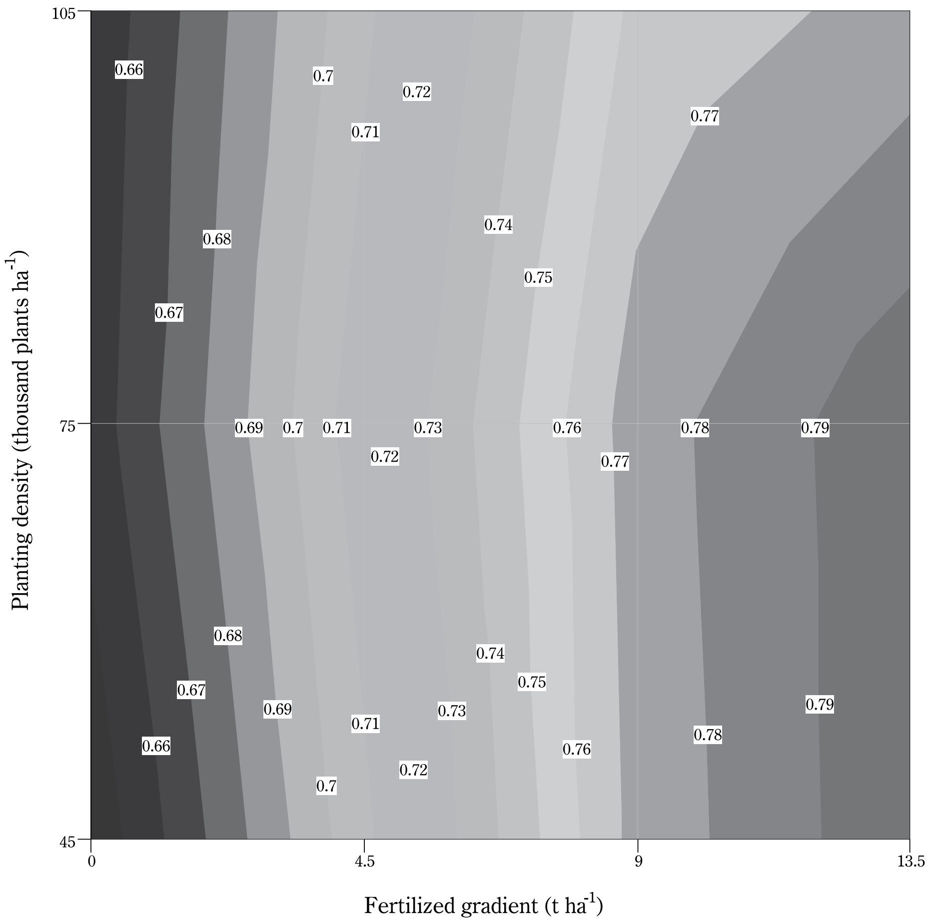

Fig. 3. Visual relationships between planting density, fertilizer application and the value of HNF as a contour plot.

Table 7. The predicted radix yield (kg ha^{-1}) and prediction error of radix yield (kg ha^{-1}) for validity check from independent data sets.

No.	Predicted radix yield (kg ha^{-1})	RMSE	No.	Predicted radix yield (kg ha^{-1})	RMSE
13	907.7	2.80	37	849.2	15.28
14	1272.0	7.88	38	1159.1	2.80
15	1594.6	15.29	39	1343.3	11.74
16	1449.1	17.66	40	1487.8	17.11
17	978.6	1.17	41	893.9	15.35
18	1319.3	10.89	42	1209.0	2.96
19	1587.7	13.28	43	1386.2	11.03
20	1553.9	13.54	44	1455.5	18.83
21	993.2	1.01	45	866.9	14.90
22	1277.8	0.67	46	1153.6	2.31
23	1601.4	22.47	47	1337.3	11.54
24	1601.4	20.89	48	1319.3	4.39

sets collected from Xijiao (experiment No. 13-24) and Caotan (experiment No. 37–48) Counties, Eq. (7) was tested. Comparison of the predicted with the observed radix yield indicated that the RMSE values were less than 22.5%, averaging 15.19% for independent data sets (Table 7). When the observed radix yield was plotted against the predicted data for independent data sets (Fig. 4), all points were close to the bisecting line with high coefficient of determination (R^2=0.685) and produced a slope of about 45°. This indicates that the model could well predict the radix yield across a wide range of situations. The predicted values of the radix yield per hectare derived from Eq. (7) were then plotted against HNF (Fig. 5).

Discussion

1. Construction of the habitat niche-fitness model for *A. sinensis*

An apparent supply-demand relationship exists between a realized habitat and the species' optimum habitat requirements during the *A. sinensis* growth cycle. This study extended Hutchinson's (1957) concept of a niche as *n*-dimensional upper-volume. Our model for HNF in Eq.(5) first calculated the relative degree of similarity between an actual habitat state and the optimum habitat requirement. Because there are unequal weights among the different habitat factors, the weights of these habitat factors as HNF model parameters play a crucial role in the usefulness of this model. These weight determinations of the different habitat factors were integrated with grey relational grades derived from a grey relational analysis (Deng, 1984, 1985, 1987, 1989a,b; Wu et al., 1999; Huang and Lee, 2004).

Our method of comparing the degree of similarity of an actual habitat to the optimum habitat is a recent improvement compared with the familiar proportional similarity index (Feinsinger et al., 1981) and geometric parallelism method (Li and Lin, 1997). The proportional similarity index, in which the weights were treated equally, has a narrow distribution on the subset [0, 1]. The geometric parallelism method (Li and Lin, 1997) accounted for a reasonable distribution of niche-fitness, but its index, F, has the unfortunate mathematical property of curvilinear distortion (Fig. 2). The curve of HNF shifted upward with increasing radix yield which was reasonably consistent with accepted biological principles. In our opinion the curve of HNF shows that our model notably outperforms the proportional similarity index (PSI) and the geometric parallelism formula (F) both in mathematical justification and consistence with accepted biological principles (Table 6 and Fig. 2). From the point view of agro-ecology, the HNF is a new concept which provides a description of the adaptability of a species to its habitat. Our results suggested that the HNF model can be used as a response surface as a function of environmental space and a powerful tool in assessment about the adaptive

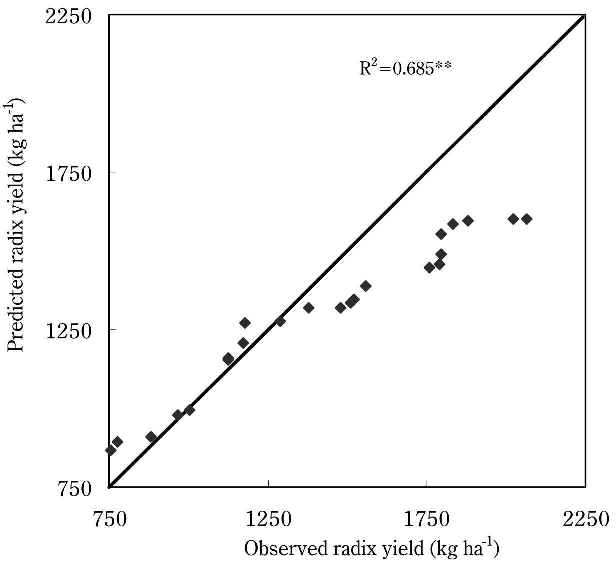

Fig. 4. The trend of the slope from the sampled subplots specified for data validation and the corresponding expected radix yield values from the radix yield prediction model.

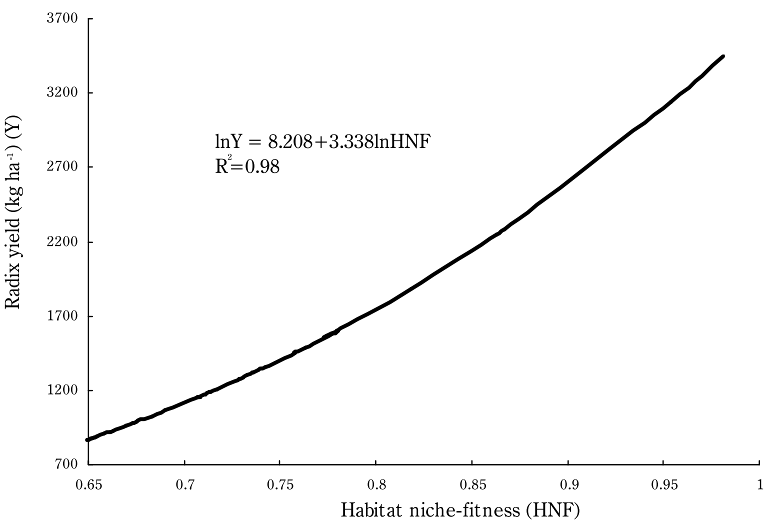

Fig. 5. Radix yield—habitat niche-fitness relationship for *Angelica sinensis*.

Table 8. Upper limit of HNF and radix yield (kg ha^{-1}) for *Angelica sinensis* at all study sites.

Site	Upper limit of HNF	Upper limit of radix yield (kg ha^{-1})	Prediction intervals of Upper limit of radix yield (kg ha^{-1}) with the 95% confidence interval	
			Lower bound	Upper bound
Hadapu, Tanchang County	0.959	3192.6	2746.1	3711.8
Xijiao, Mingxian County	0.994	3598.4	3085.7	4196.3
Huichuan, Weiyuan County	0.991	3562.3	3055.5	4153.1
Caotan, Zhangxian County	0.982	3455.4	2966.2	4025.3

Table 9. The grades of HNF for *A. sinensis* and potential distribution patterns in different HNF intervals.

Grades	HNF interval	Distribution zone	Suitability and biological performance	Predictive radix yield interval (kg ha^{-1}) with a 95% confidence interval.
1	0.9–1	The core area	Optimal. It thrives and has high reproduction.	2231.9–4283.8
2	0.75–0.9	Appropriate eco-environmental zone	Suitable. It grows and reproduces satisfactorily.	1222.8–2231.9
3	0.55–0.75	Restricted zone	Less suitable. Its growth is restrained and reproductive capacity is restricted.	429.2–1222.8
4	0.40–0.55	Marginal zone	Rarely suitable. Its growth and survival are abnormal, and reproduction is impossible.	143.0–429.2
5	<0.40	Survival forbidden zone	Unsuitable. Its growth is poor. Forbidden.	<143.0

extent of *A. sinensis* across a wide eco-geographical area. This is gaining ecological insight or guiding for better applications in agricultural practices.

Moderate planting density in the fields can reduce the consumption of soil nutrient level and raise the effective use of soil nutrient and compensate for the soil nutrient inadequacy to some extent. In order to obtain the highest HNF, it suggests that the optimum matching of planting density and fertilizer for effective habitat use of *A. sinensis* in the crop growth system is moderate density and high fertilizer. And this analysis offers a clear theoretical framework and corresponding quantitative method on how to improve the values of HNF and radix yield by the regulation of planting density and fertilizer application.

2. The radix yield prediction model

Many yield prediction models which have been developed since the 1960s (Dahl, 1963; Duncan and Hesketh, 1968; Rosensweig, 1968; Murphy, 1970; Duncan and Woodmansee, 1975; Seligman and Van, 1989; Wang, 1990), require numerical data for physiological processes, such as rates of photosynthesis, assimilation, and respiration, and their responses to climatic conditions, soil moisture, and fertilizer application. However, determining these values is quite difficult. The HNF not only reflects the relationship between the growth potential and habitat conditions, but can also be used as a predictor for radix yield. Using HNF as a surrogate for composite environment factors to establish the radix yield prediction model is a new approach and has proved to be effective. The predictions of the model are compared graphically with the independent data in Fig.4. The scatter diagram in Fig.4 plots actual against predicted radix yield. If the model's predictions were perfect all points on the graph would lie on a 1:1 line arising from the origin. In Fig.4 the model's predictions do not have large systematic errors, and although there was a slight tendency for underestimate in the higher yielding range (>1500 kg ha^{-1}), this trend was small indicating that the proposed radix yield model has the potential to forecast yield over the large-scale eco-geographical region of the southeastern Gansu Province.

3. Upper limit of HNF and radix yield, threshold value of HNF and radix yield limit

The study of the variation in HNF and particularly of the main habitat factors, whether controllable or uncontrollable, provided a good estimate for fitness variance. We included six main habitat factors simultaneously in the analysis. The effects of controllable habitat factors on the survival and growth of *A. sinensis* were examined with different planting density and fertilized gradient experiments from four sites among four counties in the southeastern region of Gansu Province. The results of experiments demonstrated that the values of HNF increased with the increasing of fertilizer, but the value of HNF increased initially and then decreased with the increasing of planting density, which implies that agricultural practices debugged controllable habitat factors to approach or bias their optimum values resulting in habitat modification. In general, the main habitat factors explaining variability in HNF is technological change, including moderate fertilization, improved management practices and disease control, as well as other human interventions aimed at increasing radix yield and quality. However, even if technological innovations in cultivation are optimized, the increase in HNF cannot be infinite and each site has its upper limit of HNF. Eq.(5) was used to forecast this limit when all controllable habitat factors reach their optimum values and the radix yield corresponding to the upper limit of HNF for each study site was forecast using Eq.(7). The maximum upper limit of radix yield was predicted as 3598.4 kg ha^{-1} at Xijiao of Mingxian County and the minimum upper limit of radix yield was 3192.6 kg ha^{-1} at Hadapu of Tanchang County, Gansu Province (Table 8). These results suggest that Xijiao of Mingxian County has the greatest habitat modification potential among the four study sites. The upper limit of radix yield should be obtainable under optimized agricultural technology when the effects of the relationship between HNF and radix yield are understood and managed accordingly.

When HNF=0.75, the prediction interval with a 95% confidence interval for radix yield by Eq.(7) ranges between 1222.8 to 1615.5 kg ha^{-1}. This is commercially acceptable as the dried root is currently priced as US$ 3.63 kg^{-1}. To determine whether a site was considered satisfactory for *A. sinensis* cultivation, a minimum 'HNF' threshold value of 0.75 was considered essential. Thus, the HNF model makes it possible to assess the adaptation of *A. sinensis* to a broad eco-geographical region. A habitat niche-fitness matrix, which included consideration of commercial aspects and the Good Agricultural Practice for Chinese Crude Drugs (GAP) (Food and Materia Medica Supervisory Bureau of PR China, 2002) of the plant, was constructed to depict the relationship between HNF and radix yield (Table 9). Therefore, HNF can be used as a decision making tool to tell the farmers whether *A. sinensis* can be planted commercially at a target site or not. An appropriate value of NHF predicts that the plants will thrive but an excessively low value would result in physiological malfunctions to the plants and perhaps followed by death. From a theoretical point of view, when all values of the habitat factors reach their optimum, then the value of HNF attains the maximum (i.e. HNF=1) and the radix yield reaches the limit predicted by Eq. (7) which is 3671.4 kg ha^{-1} with a 95% confidence interval 3146.6 to 4283.8 kg ha^{-1}. Models of HNF and radix yield prediction fulfill two roles by helping in the selection of suitable cultivation sites and by providing information on the relationship between habitat factors and the plant. They provide the answers to farmers' questions relating to utilization and development of *A. sinensis* with respect to the following main aspects: whether a site is suitable for introduction of *A. sinensis* or not, judged by calculating the HNF (>0.75), together with the potential radix yield after application of rational fertilizing procedures without contamination and planting density, and the radix yield potential after all controllable main habitat factors are optimized. The radix yield prediction model and its uses should be within the limitations of the data used in the study area. Beyond this range, validation of the radix yield prediction model will be necessary.

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* In Chinese with English abstract.
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*** In Japanese.

Appendixes

Appendix 1: The measurement method of grey relational grade (GRG)

The grey system theory was first presented in China (Deng, 1984). Thereafter it has been increasingly and widely applied in many research fields to deal efficiently with an uncertain system through grey methodologies, including grey generation, grey relational analysis, grey modeling, grey prediction, grey decision making, and grey control (Deng, 1984, 1985, 1987, 1989a,b). An increasing number of studies in the life sciences are beginning to apply grey theory to analyzing uncertain systems such as grain yields (Luo and Zhang, 1991), vegetable yields (Long et al., 1993; Ma et al., 1996), crop breeding (Guo, 1994; Zeng et al., 1993), population growth (Jin and Tang, 1994), and changes in the ecological environment (Che and He, 1993; Yang et al., 1999).

As a measurement method, grey relational analysis (GRA) (Deng, 1984, 1985, 1987, 1989a,b; Wu et al., 1999; Huang and Lee, 2004) is proposed to determine the relationships among a referential sequence and compared sequence by calculating the grey relational grade (GRG). Grey theory deals with solutions to problems that involve systems with incomplete information, or with uncertainty within the system, especially those systems with multiple variables or discrete data. The name comes from considering complete information as "white" and lack of information as "black", so that various shades of grey represent different degrees of incomplete (or undetermined) information. Grey relations quantitatively represent relationships among parts of the grey system, being derived from incomplete information. These relations are based on grey models, from which are developed grey predictions and grey decisions.

Grey relational analysis evaluates the differences between a reference part of the system and a comparison part, and explores the relationship between the two. The relationship is quantified from the influence of multiple factors and their relations, based on the level of similarity and variability among the factors. Grey relational analysis is a useful method because it has no specific probability assumptions or sample-size requirements, and it has simple calculations. Since it requires only a limited amount of data to estimate the behavior of an uncertain system, it has achieved widespread use in engineering and other fields requiring quantitative predictions.

Grey relational analysis involves quantification of data trends as they develop. This procedure thus has some conceptual similarity to the non-parametric comparison of two trend lines. The original data variables are transformed (normalized) as proportions, so that they are scale invariant, and then it is the sequences of transformed data that are compared. The grey relational grade quantifies the degree of grey relation between the reference and comparison sequences.

In practice, the reference sequence may be an "ideal" objective (such as the optimal habitat in this paper) and the comparison sequence or sequences may be alternatives (such as the potential habitats here). The best alternative is the one with the largest degree of grey relation (i.e. maximum grey relational grade).

One of the assumptions of grey relational analysis is that of nonlinearity among pairs of a referential sequence and compared sequence. Consider a set of observations $\{Y, x_1, x_2, ... x_n\}$, where $Y=\{y'_1, y'_2, ..., y'_m\}^T$ is the referential sequence and $x_1, x_2, ..., x_n$ are the compared sequences. Each compared sequence x_k has m observational value under m experimental treatments and is denoted as $x_k=\{x'_{1k}, x'_{2k}, ..., x'_{mk}\}^T$, $k=1,2,..., n$. The grey relational grade is expressed as follows:

$$GRG(Y, x_k)=\frac{1}{m}\sum_{i=1}^{m}\frac{\min\limits_{\forall j}\ \min\limits_{\forall i}|y'_i-x'_{ij}|+\xi\max\limits_{\forall j}\ \max\limits_{\forall i}|y'_i-x'_{ij}|}{|y'_i-x'_{ik}|+\xi\max\limits_{\forall j}\ \max\limits_{\forall i}|y'_i-x'_{ij}|} \quad \text{(A:1)}$$

Where x_k denotes a specific comparative sequence. ξ is the identification coefficient, $\xi\in[0,1]$ (and, normally, let $\xi=0.5$), $k=1,2,..., n$. Clearly, the GRG takes a value between zero and one.

Grey relational analysis gives a normalized measuring function (Normality)—a proper method for measuring the similarities or differences among observations—to analyze the relational structure. And grey relational analysis gives whole relational orders (wholeness (Wu et al., 1999)) over the entire relational space. In this paper, the relationships between radix yield and main habitat factors, used for determining weight coefficient of main habitat factor, are determined according to the relative magnitude of GRG.

In this study, $y'_i=\frac{y_i}{\sum_{j=1}^{m} y_j}$, $i=1,2,..., m$,y_i is the radix yield (kg ha^{-1}) in experimental No. i. $x_k=\{x'_{1k}, x'_{2k}, ..., x'_{mk}\}^T(k=1,2,..., n)$ denotes the observation of main habitat factor k, where, x'_{ik} is the actual state of main habitat factor k in experimental No. i normalized by Eq. (2).

Appendix 2: Calculation of grey relational grade (GRG)

Obviously, there are 48 experimental treatments and six main habitat factors, thus, $m=48$ and $n=6$.

First, the grey relational grade (GRG) between Y and x_k, for $k=1, 2,..., 6$, are calculated as follows:

$$\min_{\forall j}\ \min_{\forall i}\ |\ y'_i-x'_{ij}\ | = 7.02\times10^{-5}$$

and

$$\max_{\forall j}\ \max_{\forall i}\ |\ y'_i-x'_{ij}\ | = 0.035403$$

Where $j=1, 2,..., 6$; $i=1, 2,..., 48$ and let $\xi=0.5$.

Accordingly, the expression for the grey relational grade (GRG) is,

$$GRG(Y, x_k)=\frac{1}{48}\sum_{i=1}^{48}\frac{0.0000702+0.5\times0.035403}{|y'_i-x'_{ik}|+0.5\times0.035403} \quad \text{(A:2)}$$

Based on this formula, the grey relational grades have been calculated and are listed as follows:

$GRG(Y, x_1)=0.966$, $GRG(Y, x_2)=0.963$, $GRG(Y, x_3)=0.965$, $GRG(Y, x_4)=0.972$, $GRG(Y, x_5)=0.914$, $GRG(Y, x_6)=0.961$, respectively. The results showed that the order of main habitat factor to radix yield was:

$GRG(Y, x_4)>GRG(Y, x_1)>GRG(Y, x_3)>GRG(Y, x_2)>GRG(Y, x_6)>GRG(Y, x_5)$.

Appendix 3: The proportional similarity index and the geometric parallelism formula

There are two familiar measure functions for habitat niche-fitness: the one is the proportional similarity index proposed by Feinsinger et al. (1981); the other is the geometric parallelism formula proposed by Li and Lin (1997).

1. The familiar proportional similarity index (PSI, Feinsinger et al., 1981), which is common used in similarity measures to many ecological studies such as niche overlap, niche breadth and community similarity, is tested and verified as follows:

$$PSI_i=1-0.5\sum_{j=1}^{n}|p_{ij}-q_{ij}|=\sum_{j=1}^{n}\min\{p_{ij}, q_{ij}\} \quad \text{(A:3)}.$$

In which,

$$p_{ij}=\frac{x'_{ij}}{\sum_{j=1}^{n}x'_{ij}},\ q_{ij}=\frac{x'_{ai}}{\sum_{j=1}^{n}x'_{aj}} \quad \text{(A:4)}$$

x'_{ij} is the actual state of main habitat factor j in experimental No.i normalized by Eq. (2). x'_{aj} represents the optimum value of main habitat factor

j normalized by Eq. (3). In this study, n and m are the numbers of main habitat factors and experiments, i.e. n=6 and m=48, respectively. The values of PSI calculated by Eq. (A:3) are shown in Table 6.

2. Li and Lin (1997) proposed a model for measuring niche-fitness using the geometric parallelism, which has a wide range of fitness value and a regulated parameter in practical calculation. The details are as follows:

The absolute difference is repeatedly calculated between x'_{ij} and x'_{aj}

$$\delta_{ij}=|x'_{ij}-x'_{aj}|,\ i=1,2,\ldots,m,\ j=1,2,\ldots,n \quad \text{(A:5)}$$

$$\delta_{\min}=\min\{\delta_{ij}\}=\min\{|x'_{ij}-x'_{aj}|\} \quad \text{(A:6)}$$

$$\delta_{\max}=\max\{\delta_{ij}\}=\max\{|x'_{ij}-x'_{aj}|\} \quad \text{(A:7)}$$

The corresponding model of niche-fitness was established:

$$F_i=\frac{1}{n}\sum_{j=1}^{n}\frac{\delta_{\min}+\alpha\delta_{\max}}{\delta_j+\alpha\delta_{\max}},\ i=1,2,\ldots,m \quad \text{(A:8)}$$

In Eq. (A: 8), F_i stands for the value of niche-fitness under experiment No. i. $F_i \in [0, 1]$, α is the parameter of the model, $\alpha \in [0, 1]$. In order to have a reasonable distribution of F_i, suppose $\delta_{ij}=\overline{\delta}_j$, then $F_i=0.5$, i.e.

$$\overline{\delta}_{ij}=\frac{1}{mn}\sum_{i=1}^{m}\sum_{j=1}^{n}\delta_{ij},\quad \frac{\delta_{\min}+\alpha\delta_{\max}}{\delta_{ij}+\alpha\delta_{\max}}=0.5 \quad \text{(A:9)}$$

α can be estimated from formula (A:9).

Applying Eqs.(A: 5)–(A: 7) and (A:9) to the collected experimental data set, we can obtain $\delta_{\min}=9.34\times10^{-6}$, $\delta_{\max}=0.0345$, and $\alpha=0.0281$. The specific calculation formula is

$$F_i=\frac{1}{6}\sum_{j=1}^{6}\frac{0.00097879}{\delta_{ij}+0.00096945},\ i=1,2,\ldots,48 \quad \text{(A:10)}$$

The values of F calculated by Eq. (A:10) are shown in Table 6.