The occurrence of C_4 plants and their morphological functional types in the vegetation of Xinjiang, China

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Abstract

Floristic composition, morphological functional types and habitat distributions for C_4 species were studied in Xinjiang, North-western China. 89 species, in 9 families and 41 genera, were identified with C_4 photosynthesis. 48 % of these C_4 species were found in *Monocotyledoneae*, *e.g.* *Cyperaceae* (5 species), *Gramineae* (38 species), the other 52 % was in *Dicotyledoneae*, *e.g.* *Chenopodiaceae* (29 species), *Amaranthaceae* (7 species), and *Polygonaceae* (5 species). Compared with those in semi-arid grasslands in North China and tropical forests in South China, more plant families were found with the occurrence of C_4 plants in this arid region. Relatively higher annual species (63 %), shrubs (18 %), and *Chenopodiaceae* C_4 species (33 %) compositions were the primary characteristics for the C_4 species occurring in Xinjiang, and this was remarkably related with its arid environment. More *Chenopodiaceae* C_4 species occurring in the region suggested that this type of C_4 species may have higher capacity to fit the air and soil droughts. There was a strong relationship between C_4 occurrence and habitat distributions, more than half of the total 89 C_4 species were found in disturbed and cultivated lands and early stages of vegetation successions, indicating C_4 occurrence was not only related with climate changes, but also with land uses and vegetation dynamics.

Additional key words: annual C_4 species; arid region; habitats.

Introduction

On the global basis, it is estimated that one-half of the 10 000 grass species and fewer than a thousand of the 165 000 dicots can be characterized by C_4 photosynthetic pathway (Hattersley and Watson 1992, Ehleringer *et al.* 1997). But the identified C_4 species was only 1/3 of those estimated in the world. C_4 identification, geographic distribution of these plants, and relation to climatic patterns have been well documented for many ecosystems (Downton 1975, Teeri and Stowe 1976, Raghavendra and Das 1978, Teeri *et al.* 1980, Collins and Jones 1985, Mateu Andrès 1993, Redmann *et al.* 1995, Collatz *et al.* 1998, Pyankov *et al.* 2000, Wang 2002a). The occurrence of C_4 species is correlated with climatic variables, vegetation dynamics, land-use history, or disturbances. However, C_4 occurrence in many key ecological regions remains unclear.

Xinjiang autonomous region, located in the centre of Eurasian continent (34°22'–49°33'N; 73°21'–96°21'E), occupies a large area (1 660 000 km^2, about 1/6 of the total China) and is the biggest province in China. It is primarily a mountain-plateau-basin region, with an average altitude of about 2 000 m above sea level (a.s.l.). Large expanses of plateaus, plains, and basins are surrounded by mountains that rise as high as 8 000 m a.s.l., *e.g.* Altay shan in the north and northeast (4 374 m), Tian shan in the middle (7443 m), and Kunlun shan in the south (8 611 m). But the lowest elevation in the Turpan basin is 154 m below sea level. General topographic characteristic of the region is the elevation increasing from north (2 000 m) to south (4 800 m), with two big basins (Tarim and Jungger) in the middle. Geo-location and complex geo-relief of Xinjiang lead to an extreme continental climate and very low precipitation. Main climatic characteristics are long cold winter, dry and windy spring, short warm summer, and cool autumn with early frosts. Mean annual air temperature is about 10 °C, ranging from 5–9 °C in the north to 10–11 °C in the south. Moisture gradient varies with relief changes, with annual precipitation of 400–800 mm in the north to 100–250 mm in the south, in some regions even less than

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10 mm. Average annual precipitation of the whole region is 145 mm (Chinese Central Meteorological Office 1984).

Large area and complex geo-relief lead to poly-vegetation types in the region, including deserts, forests, rangelands, and farmlands. Mountains and hills make up about 43 % of the whole regional area, followed by deserts and Gobi deserts (about 33 %). Most of the region has sandy soils, chestnut, and chernozem. More than 2 500 vascular plant species in 654 genera and 107 families have been identified in the region, but the C_4 species and their morphological functional types in the region/or the center Asian deserts and mountains have not been studied in detail. The objective of this study was to investigate occurrence of C_4 plants and their morphological functional types in Xinjiang. This study brings new information for better understanding the responses of C_4 plants to global climatic changes and land use.

Materials and methods

Floristic species were obtained from references about Xinjiang flora published from 1977 to 1999 (*e.g.* Commissione redactorum florae Xinjiangensis 1996, Delectis Florae Reipubicae popularis Sinicae Agendae Academiae Sinicae Edita 1977–1999, Institute of Botany 1978) and some local flora. The data on photosynthetic pathway types were compiled from references published between 1968 and 2004 (Downton and Tregunna 1968, Black 1971, Downton 1975, Raghavendra and Das 1978, Stowe and Teeri 1978, Waller and Lewis 1979, Mateu Andrès 1993, Redmann *et al.* 1995, Pyankov *et al* 2000, Wang 2002a, 2004). C_4 photosynthetic types were determined from microscopic studies of Kranz anatomy (K), $\delta^{13}C$ fractionation (D), as well as low CO_2 compensation concentration (L) (0–10 μmol mol^{-1}) (Redmann *et al.* 1995, Wang 2002a, 2004).

Results

C_4 taxa: Xinjiang possesses more than 2 500 vascular plant species. 3.6 % (89 species) of these vascular species, 41 genera and 9 families, were characterized by C_4 photosynthetic pathway (Table 1). About 6 % genera and 8 % families in the region were C_4 species. Of the total 89 C_4 species, 52 % (46 of 89) was found in *Dicotyledoneae*, *e.g*. *Chenopodiaceae* (29 species), *Amaranthaceae* (7 species), and *Polygonaceae* (5 species). The other 48 % was found in *Monocotyledoneae*, *e.g.* *Gramineae* (38 species) and *Cyperaceae* (5 species). Of these C_4 species, *Gramineae* was the leading C_4 family with 38 C_4 species, about 43 % of the total C_4 species and 17 % of the total grasses identified in Xinjiang. *Chenopodiaceae* (29 species; 33 % of the total C_4 species and 19 % of the total *Chenopodiaceae* species), *Amaranthaceae* (8 % of the total C_4 species), *Polygonaceae* and *Cyperaceae* (7 % of the total C_4 species for each family) followed. The C_4 species occurring in the other families were only 2 % of the total C_4 species. *Amaranthus* and *Anabasis* were the leading C_4 genera with 7 C_4 species in each genus. *Eragrostis* (6 species), *Kochia* (5 species), *Salsola* (5 species), *Calligonum* (5 species), and *Cyperaceae* (5 species) followed. C_4 species in three *Chenopodiaceae* genera (*e.g*. *Anabasis, Kochia,* and *Salsola*) made up 20 % of the total C_4 species in Xinjiang. However, more than 100 species in the genera with C_4 plants have not been determined, including 67 species in *Chenopodiaceae*, 17 species in *Polygonaceae*, and 11 species in *Gramineae*. This indicates that more C_4 species may be identified in further studies. The abundance of *Chenopodiaceae* C_4 species was much higher in Xinjiang, compared with that in northeast China grasslands and tropical region. No endemic C_4 species has been found in the region.

Morphological functional types of C_4 species: Within the region, 89 C_4 species fell within 6 plant functional types (Table 1). 48 % of the total C_4 species was in grass and sedges category, including annual grasses and sedges, ANG (30 %), short perennial grasses and sedges, SPG (10 %), and high perennial grasses and sedges, HPG (8 %). 33 % was in annual forbs, ANF (29 species of 89), 18 % in shrubs, SHR (16 species of 89), and only 1 species (1 %) in trees, TRE. Relatively higher amount of annual C_4 species (63 %) (*e.g.* C_4 species in *Amaranthus*, *Salsola*, and *Digitaria*) and C_4 SHR (*e.g.* species in *Anabasis*, *Calligonum, Atriplex cana* C.A. Mey.) were the two primary morphological functional characteristics for the C_4 species identified in Xinjiang, mainly due to its arid environment. Relatively higher ANF, ANG, and SHR composition indicated that these C_4 species have higher tolerance to environmental stresses, *e.g*. drought, high temperature, and high irradiance.

The C_4 species in Xinjiang fall within 9 habitat distributions (Table 1). 50 % C_4 species was found in disturbed and cultivated lands (DB) (*e.g*. species in *Amaranthus*, *Portulaca*, *Digitaria*, *Setaria*), 30 % in WL (*e.g*. species in *Cyperaceae* and *Gramineae*), 24 % in GL (*e.g*. *Anabasis aphylla* L., *A. brevifolia* C.A. Mey., *Halogeton glomeratus* (Bieb.) C.A. Mey.), 20 % in each of sand lands, SL [*e.g. Mollugo cerviana* (L.) Ser., *Calligonum ebi-nuricum* Ivanova, *C. gobicum* (Bge.) A. Los.], 17 % in each of saline lands, SS and river valley, RV [*e.g. Atriplex cana* C.A. Mey., *Suaeda acuminata* (C.A. Mey.) Moq., *S. heterophylla* (Kar. *et* Kir.) Bge., *Fimbristylis dichotoma* (L.) Vahl., *Anabasis eriopoda* (Schrenk) Benth *ex* Volkens], 11 % in each of rangeland, RL and hill side, HS, and 9 % in cultivated aerea, CU. Relative high C_4 abundance in DB suggested that most of these species have higher tolerance to environmental stresses caused by land uses (*e.g.* desertification, cultivation, and grazing).

Table 1. The occurrence, morphological functional types and ecological distribution of C_4 species in Xinjiang, China. C_4 features: D = $^{13}C/^{12}C$, K = Kranz anatomy, L = low CO_2 compensation concentration. Plant function al types: SHR = shrubs, TRE = trees, HPG = high perennial grass and sedge, SPG = short perennial grass and sedge, ANG = annual grass and sedge, ANF = annual forb. Habitat types: RL = rangeland, DB = disturbed and cultivated land, WL = wet land, HS = hillside, RV = river valley, CU = cultivation, SS = saline lands, SL = sand lands.

Family	Species	C_4 feature	PFTs	Habitats	Elevation
Dicotyledoneae					
Amaranthaceae	*Amaranthus albus* L.	K	ANF	DB	
	A. caudatus L.	K	ANF	DB	
	A. hypochondriacus L.	K	ANF	DB CU	
	A. lividus L.	K	ANF	DB	
	A. paniculatus L.	K	ANF	DB CU	2 200
	A. retroflexus L.	D	ANF	DB	1 200
	A. tricolor L.	K	ANF	DB	
Chenopodiaceae	*Anabasis aphylla* L.	D	SHR	GL DB HS	500–1 200
	A. brevifolia C.A. Mey.	D	SHR	RV GL	500–1 700
	A. elatior (C.A. Mey.) Schischk.	D	SHR	HS GL	330–1 900
	A. eriopoda (Schrenk) Benth. *ex* Volkens	D	SHR	RV WL SS	500–1 200
	A. pelliotii Danguy	K	SHR	HS	
	A. salsa (C.A. Mey.) Benth.	D K	SHR	GL RL	500–1 300
	A. truncata (Schrenk) Bge.	K	SHR	GL HS	
	Atriplex cana C.A. Mey.	D	SHR	SS GL	400–1 000
	A. laevis C.A. Mey.	D	ANF	DB WL	
	A. sibirica L.	K	ANF	DB SS WL	
	A. tatarica L.	D	ANF	SS GL	400–1 750
	Bassia hyssopifolia (Pall.) O. Kuntze	D	ANF	WL DB	
	Halogeton glomeratus (Bieb.) C.A. Mey.	D	ANF	GL	700–1 000
	Haloxylon ammodendron (C.A. Mey.) Bge.	D	TRE	SL GL SS	450–1 500
	Iljinia regelii (Bge.) Korov	D	SHR	GL SS WL	500–1 600
	Kochia iranica Litv. *ex* Bornm.	D	ANF	SL WL	
	K. krylovii Litv.	K	ANF	DB RV	
	K. melanoptera Bge.	K	ANF	HAS RL	2 700
	K. prostrata (L.) Schrad.	D K	SHR	RL HS GL	430–1 680
	K. scoparia (L.) Schrad.	D K	ANF	DB HS	500–1 800
	Londesia eriantha Fisch. *et* Mey.	K	ANF	SL GL	
	Petrosimonia sibirica (Pall.) Bge.	K	ANF	GL DB SS	480–1 030
	Salsola arbuscula Pall.	D	SHR	GL SL SS	450–1 000
	S. collina Pall.	D	ANF	DB HS SL	400–2 100
	S. ikonnikovii Iljin	K	ANF	SL	
	S. paulsenii Litv.	D	ANF	SL SS GL	
	S. rosacea L.	K	ANF	GL HS	700–1 100
	Suaeda acuminata (C.A. Mey.) Moq.	D	ANF	SS RL SL	
	S. hetrophylla (Kar. *et* Kir.) Bge.	K	ANF	SS RV WL	400–1 200
Euphorbiaceae	*Euphorbia mongolicum* Prokh.	D	ANF	DB RL	
Molluginaceae	*Mollugo cerviana* (L.) Ser.	K	ANF	SL GL	
	Calligonum ebi-nuricum Ivanova	K	SHR	SL GL	
Polygonaceae	*C. gobicum* (Bge.) A. Los.	K	SHR	SL	
	C. junceum (Fisch. *et* Mey) Litv.	D	SHR	SL GL	500–800
	C. mongolicum Turcz.	K	SHR	SL	
	C. pumilum A. Los.	K	SHR	GL SL	

Table 1 (continued)

Family	Species	C_4 feature	PFTs	Habitats	Elevation
Portulacaceae	*Portulaca grandiflora* Hook.	D K	ANF	DB	
	P. oleracea L.	K	ANF	DB CU	
Zygophyllaceae	*Tribulus terrestris* L.	D	ANF	DB	
Monocotyledoneae					
Cyperaceae	*Cyperus esculentus* L. var. *sativus* Boeck.	D L	SPG	CU	
	C. glomeratus L.	K	ANG	RV WL	140–580
	C. iria L.	D K	ANG	WL	
	C. michelianus (L.) Link	D K	ANG	RV WL	
	Fimbristylis dichotoma (L.) Vahl.	D K	ANG	RV WL DB	
Gramineae	*Achnatherum splendens* (Trin.) Nevski	K	HPG	SS WL	450–4 200
	Aeluropus micrantherus Tzvel.	D	SPG	SS WL	450–1 449
	A. pungens (M. Bieb.) C. Koch	D	SPG	SS WL	
	Aristida heymannii Regel	D K	ANG	SL RL	400–2 600
	Arthraxon hispidus (Thunb.) Makino	D	ANG	RV WL	170–1 220
	A. viridis ssp. *centrasiaticus* Tzvel.	D	ANG	RV WL	
	Bothriochloa ischaemum (L.) Keng	K D	HPG	RL	1 000–1 700
	Buchloe dactylon (L.) Pers.	D	SPG	DB CU	
	Chloris virgata Sw.	D	ANG	DB RV WL	
	Cleistogenes songorica (Rashev.) Ohwi.	D	SPG	RL	440–2 000
	C. squarrosa (Trin.) Keng	D	SPG	RL	640–2 000
	Coix lachryma-jobi L.	K	ANG	CU	
	Crypsis aculeata (L.) Engelm.	K	ANG	WL RV	
	C. schoenoides (L.) Lam.	K	ANG	RV WL	
	Cynodon dactylon (L.) Pers.	D K	SPG	RV WL	
	Digitaria ciliaris (Rotz.) Koel	K	ANG	DB WL	
	D. ischaemum (Schreb.) Schreb. *ex* Mnchl.	L	ANG	DB	1 400
	D. sanguinalis (L.) Scop.	D K	ANG	DB WL	
	Echinochloa colonum (L.) Link	L	ANG	DB WL	
	E. crusgalii (L.) Beauv.	D	ANG	DB WL	
	E. crusgalii var. *mitis* (Pursh) Peterm	D	ANG	DB	
	Enneapogon borealis (Griseb.) Honda	D	SPG	SS WL	500–1 500
	Eragrostis cilianensis Link. *ex* Vignolo	D	ANG	DB SL	
	E. collina Trin.	K	HPG	GL RV	500–720
	E. curvula Nees	K	HPG	DB CU	
	E. minor Host	D	ANG	DB SL	510–1 700
	E. pilosa (L.) Beauv.	K	ANG	DB	
	E. suaveolens A. Beck.	K	ANG	DB RV	
	Erianthus ravennae (L.) Beauv.	K	HPG	SL	
	Imperata cylindrica Tzvel.	D	HPG	DB CU	
	Panicum miliaceum L.	D K	ANG	DB CU	
	Pennisetum centrasiaticum Tzvel.	D K	HPG	DB WL	900–3 200
	Setaria glauca (L.) Beauv.	L	ANG	DB WL	
	S. italica (L.) Beauv.	D K	ANG	DB	
	S. viridis (L.) Beauv.	D	ANG	DB	
	S. viridis ssp. *pycnocoma* Tzvel.	D	ANG	DB	
	Sorghum sudanense Stapf	K	ANG	CU	
	Tripogon purourascens Duthie	D	SPG	RL	1 380–2 000

Discussion

The common occurrence of C_4 species and the relations with geographical distributions, climate changes, and land uses have been well documented in the grasslands in China (Redmann *et al*. 1995, Wang 2002a, 2004) and Mongolia (Pyankov *et al*. 2000). But no has looked at the C_4 species occurrence and their morphological functional types in arid regions in China. In Xinjiang, 9 of 107 vascular plant families (8 %) were identified with C_4 species occurrence, which was much more than those found in grassland regions and agro-forestry ecotones (Wang 2002b, 2003b, 2004), but similar to that in Mongolia (Pyankov *et al*. 2000). 3.6 % of the total vascular species and 6 % genera found with the plants characterized by C_4 photosynthetic pathway (Table 1) suggest that C_4 species were more common in the arid region, especially in *Gramineae* (17 %), *Chenopodiaceae* (19 %), and *Amaranthaceae* (80 %). Of the total 107 vascular plant families, *Gramineae* ranks the second leading in abundance, and *Chenopodiaceae* ranks the third in Xinjiang, while these two families rank the first and second leading in C_4 abundance with 38 and 29 C_4 species in each families. Xinjiang autonomous region makes up about 1/6 of the total area in China, but its total plant species represent only 8 % of China flora (Institute of Botany 1978). The amount of vascular plant families and genera, however, are 32 % and 22 % of the China flora, mainly due to greater occurrence of monogeneric families and monotypic genera, and occurrence of some C_4 species (*e.g*. *Amaranthaceae*, *Molluginaceae,* and *Portulacaceae*). Compared with that in northeast China grasslands (7–8 species) and tropical region (2–3 species), relatively more *Chenopodiaceae* C_4 species were identified in Xinjiang, indicating that *Chenopodiaceae* C_4 species may have larger tolerance than the other plant types to drought, high temperature, and high irradiance. Pyankov *et al*. (2000) also proved that *Chenopodiaceae* C_4 species were strongly related with aridity in Mongolia (Pyankov *et al*. 2000). This may be also related with C_4 plant origin, for many *Chenopodiaceae* C_4 species have been found in tertiary period (*e.g*. *Anabasis brevifolia* C.A. Mey. and *A. salsa* (C.A. Mey.) Benth.), miocene period [*Halogeton glomeratus* (Bieb.) C.A. Mey., *Haloxylon ammodendron* (C.A. Mey.) Bge., *Calligonum junceum* (Fisch. *et* Mey) Litv., *Salsola arbuscula* Pall.] and tethys [*Calligonum junceum* (Fisch. *et* Mey) Litv.] (Institute of Botany 1978). This may provide some evidence for studying the C_3 and C_4 plant origin and evolution. The occurrence of C_4 species in *Calligonum* of *Polygonaceae* and *Halogeton* and *Haloxylon* of *Chenopodiaceae* in Xinjiang also proved this plant types tolerate arid conditions, for these C_4 species have not been found in semi-arid grasslands, agro-pastoral and agro-forestry ecotones.

Morphological functional type compositions in Xinjiang represent the regional climate and land use patterns (Table 1). Like that in the semi-arid grasslands and steppes in China, more than 63 % of the identified C_4 species was annual species, *e.g*. ANG (30 %) and ANF (33 %). Relative abundance of annual C_4 species is mainly due to their higher tolerance to seasonal drought stress, for these species can withstand the severe dry seasons as form of seeds (Wang 2004). Annual species can use seasonal precipitation efficiently in arid regions where the precipitation mainly falls between June and August (70–90 % of total rain fall). Therefore most of annual C_4 species can be found in disturbed and cultivated lands, (DB), with relatively less soil moisture and high irradiance (Wang 2002c, 2004). More C_4 shrub species (18 %) in Xinjiang is another typical trait of arid regions. In general, the short leaf life span associated with small leaf area is the main characteristics of these C_4 shrubs, for both short leaf life span and small leaf area can reduce water consumed by transpiration. Relative abundance of annual and shrub C_4 species in Xinjiang consists with the arid environments in the region (Wang 2003b, 2004). Because of the confounding factors, *e.g*. climate, geographic distribution, soil fertility, physiological difference between plants with different photosynthetic pathways, further studies, *e.g*. C_3 and C_4 plant identification, climatic patterns of C_3 and C_4 species, and physiological difference between C_3 and C_4 plants, are needed to explore the relationships between occurrence of C_4 and C_3 plants and climatic variations, as well as vegetation dynamics and land-use in Xinjiang.

References

Black, C.C.: Ecological implications of dividing plants into groups with distinct photosynthetic production capacities. – In: Cragg, J.B. (ed.): Advances in Ecological Research. Vol. 7. Pp. 87-114. Academic Press, New York – London 1971.

Chinese Central Meteorological Office (ed.): Climatological data of China, Beijing. – Meteorology Press of China, Beijing 1984.

Collatz, G.J., Berry, J.A., Clark, J.S.: Effects of climate and atmospheric CO_2 partial pressure on the global distribution of C_4 grasses: present, past, and further. – Oecologia **114**: 441-454, 1998.

Collins, R.P., Jones, M.B.: The influence of climatic factors on the distribution of C_4 species in Europe. – Vegetatio **64**: 121-129, 1985.

Commissione Redactorum Florae Xinjiangensis: Flora Xinjiangensis. – Xinjiang Science & Technology & Hygiene Publishing House, Urmqi 1996.

Delectis Florae Reipublicae Popularis Sinicae Agendae Academiae Sinicae Edita: Flora Reipublicae Popularis Sinicae. Vol. 9, 10, 11, 12, 25, 26, 44, and 63. – Science Press, Beijing 1977-1999.

Downton, W.J.S.: The occurrence of C_4 photosynthesis among

plants. – Photosynthetica **9**: 96-105, 1975.
Downton, W.J.S., Tregunna, E.B.: Carbon dioxide compensation – its relation to photosynthetic carboxylation reactions, systematics of the *Gramineae* and leaf anatomy. – Can. J. Bot. **46**: 207-215, 1968.
Ehleringer, J.R, Cerling, T.E., Helliker, B.R.: C_4 photosynthesis, atmospheric CO_2, and climate. – Oecologia **112**: 285-299, 1997.
Hattersley, P.W., Watson, L.: Diversification of photosynthesis. – In: Chapman, G.P. (ed.).: Grass Evolution and Domestication. Pp. 38-116. Cambridge University Press, Cambridge 1992.
Institute of Botany, Chinese Academy of Sciences (ed.): Vegetation in Xinjiang and its Use. Science Press, Beijing 1978.
Mateu Andrès, I.: A revised list of European C_4 plants. – Photosynthetica **26**: 323-331, 1993.
Pyankov, V.I., Gunin, P.D., Tsoog, S., Black, C.C.: C_4 plants in the vegetation of Mongolia: their natural occurrence and geographical distribution in relation to climate. – Oecologia **123**: 15-31, 2000.
Raghavendra, A.S., Das, V.S.: The occurrence of C_4-photosynthesis: A supplementary list of C_4 plants reported during late 1974 – mid 1977. – Photosynthetica **12**: 200-208, 1978.
Redmann, R.E., Yin, L., Wang, P.: Photosynthetic pathway types in grassland plant species from Northeast China. – Photosynthetica **31**: 251-255, 1995.
Stowe, L.G., Teeri, J.A.: The geographic distribution of C_4 species of the dicotyledonae in relation to climate. – Amer. Naturalist **112**: 609-623, 1978.
Teeri, J.A., Stowe, L.G.: Climatic patterns and the distribution of C_4 grasses in North America. – Oecologia **23**: 1-12, 1976.
Teeri, J.A., Stowe, L.G., Livingstone, D.A.: The distribution of C_4 species of the *Cyperaceae* in North America in relation to climate. – Oecologia **47**: 307-310, 1980.
Waller, S.S., Lewis, J.K.: Occurrence of C_3 and C_4 photosynthetic pathways in North American grasses. – J. Range Manage **32**: 12-28, 1979.
Wang, R.Z.: The C_4 photosynthetic pathway and life forms in grassland species from North China. – Photosynthetica **40**: 97-102, 2002a.
Wang, R.Z.: Photosynthetic pathways and life forms in different grassland types from North China. – Photosynthetica **40**: 243-250, 2002b.
Wang, R.Z.: Photosynthetic pathways, life forms and reproductive types for forage species along desertification gradient on Hunshandake desert, North China. – Photosynthetica **40**: 321-329, 2002c.
Wang, R.Z.: C_4 plants in the vegetation of Tibet, China: Their natural occurrence and altitude distribution pattern. – Photosynthetica **41**: 21-26, 2003a.
Wang, R.Z.: Photosynthetic pathway and morphological functional types in the steppe vegetation from Inner Mongolia, North China. – Photosynthetica **41**: 143-150, 2003b.
Wang, R.Z.: C_4 species and their response to large-scale longitudinal climate variables along the Northeast China Transect (NECT). – Photosynthetica **42**: 71-79, 2004.