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NOTES ON NEGLECTED AND UNDERUTILIZED CROPS

A psammophyte *Agriophyllum squarrosum* (L.) Moq.: a potential food crop

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Abstract *Agriophyllum squarrosum* is an annual psammophyte adapted to mobile sand dunes in arid and semi-arid regions of Central Asia. The species has evolved a range of physiological, morphological, and ecological adaptations to allow it to be a pioneer species of unstable, nutrient-poor, drought-prone and hot sand dunes. Local populations in the sandy desert regions of China consume the seed of the species during periods of food shortage, and refer to the plant as "shami" in Chinese, which translates as "sand rice". The sand rice seeds have high nutritional value, containing around 23 % protein, 9 % lipid, 45 % carbohydrates, 8 % crude fiber and 5 % ash. The protein fraction includes the full range of essential amino acids required in the human diet. The lipid fraction comprises mostly polyunsaturated fatty acid. The ash fraction is rich in iron. Sand rice is a good candidate species for domestication to provide a food crop resilient to future climate change.

Keywords *Agriophyllum squarrosum* · Chenopodiaceae · Heat tolerance · Quinoa · Sandy desert · Wild plant domestication

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Introduction

Continuing global population growth, rising expectations of the standard of living, potential climate change and ongoing degradation of soil and water resources are conspiring to put pressure on crop production. The global future climate is likely to be warmer than the present one; while overall the amount of rainfall should increase, the expectation is that its distribution, both temporally and spatially, will become more unpredictable, and some regions which are already short of rainfall may well become even drier. The negative consequences of climate change on global food security (Wheeler and von Braun 2013) have encouraged interest in accessing crop wild relatives as a genetic resource for crop adaptation (Tester and Langridge 2010; McCouch et al. 2013), but at the same time there is also a need to identify potential new crop species which are known already to be able to survive levels of abiotic stress too high for current crops to retain a viable level of productivity. Here we propose an edible psammophyte species as a potential candidate for domestication.

Agriophyllum squarrosum belongs to the tribe Corispermeae including *Corispermum*, *Anthochlamys* and *Agriophyllum*, and to the subfamily Chenopodioideae of Chenopodiaceae (Kühn et al. 1993; Kadereit et al. 2003). It is an annual psammophyte found mostly on mobile sand dunes in arid and semi-arid regions of Central Asia (Liu 1985a; Wu et al. 2003). The species has evolved a number of physiological and morphological adaptations to allow it to survive on the unstable, nutrient-poor, drought-prone and hot sand dune. Its local name in Western China is shami, which translates as "sand rice". Archaeological records dating to 688 CE show that soldiers collected sand rice seed to supplement their rations (Gao 2002). The local population in the Dunhuang Caves region still retain the tradition of eating sand rice seed during periods of food shortage. The nutritional value of sand rice is as high, if not higher than the Chenopodiaceae species quinoa (Bioversity International and FAO 2012). However, unlike quinoa, *A. squarrosum* has not as yet been domesticated. Here we review the ecology and physiology of *A. squarrosum*, and discuss the potential of its domestication.

Botanical description

The species is an annual psammophyte (Fig. 1a), which grows to a height of 20–100 cm, forming erect, obscurely ribbed stems, which branch from the base. The leaves are sessile, lanceolate to linear, of length 1–8 cm and thickness 1–10 mm, with an attenuate base and an acute apex. The leaves feature 3–9 prominent longitudinal veins. The flower has ovate bracts with an abruptly acute mucronate apex (Fig. 1b). The membranous perianth segments number from one to three. The flower develops two or three stamens bearing ovoid anthers. The utricle is ovoid or ellipsoid. The beak is separated into two slightly recurved compressed beaks, each usually bearing a sub-apical, small, flattened tooth. The spikes are axillary, sessile and dense (Fig. 1c). The flattened seed is almost round (Fig. 1d) and has a starchy endosperm (Liu 1985a; Wu et al. 2003).

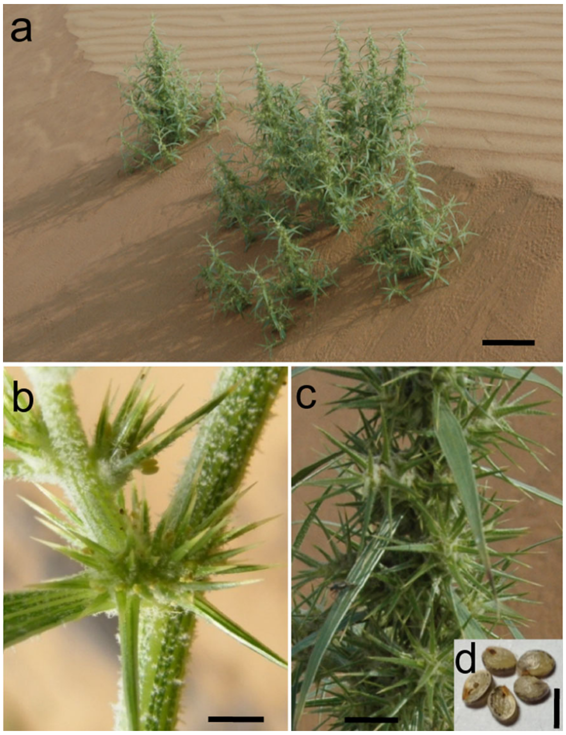

Fig. 1 The appearance of the *A. squarrosum* plant. **a** Two plants growing on the top of a sand dune, with the lower section of the main stem buried by sand. *Bar* 20 cm. The appearance of **b** the flower (*bar* 0.5 cm), **c** the spike (*bar* 2 cm) and **d** the seed (*bar* 2 mm)

The species can survive on infertile, sandy soils, can withstand periods of burial in sand and loss of soil through wind action, and is the dominant species on mobile and semi-fixed sand dunes in arid and semi-arid regions of Western China (Li 1980; Li et al. 1992; Wu et al. 2003; Zhang et al. 2005; Zuo et al. 2008). It is also endemic to desert regions in the Caucasus, Siberia, Central Asia, Mongolia and Eastern Europe (www.ars-grin.gov/cgi-bin/npgs/html/taxon.pl?310926). It has a pronounced ability to survive drought (Bai et al. 2004; Nemoto and Lu 1992; Wang et al. 1998; Zheng et al. 2004). Its mean seed weight is about 1.5 mg (Liu et al. 2003, 2004), and each plant produces about 2,000 seeds (Yan et al. 2005). Seeds remain viable in the sand for at least a year (Liu et al. 2006). It can complete its life cycle in under three months (Liu 1985b), but in the Horqin Sandy Land in China, it typically germinates in May following a significant rainfall episode, emerges in June, flowers in mid-August, sets seed in late August and matures by late September (Li et al. 1992). The species is an important stabilizer of mobile sand dunes, an environment where survival requires a rapid germination and emergence when water is available and a special growth adaptation.

Seed germination

Freshly harvested mature seed is capable of rapid germination given the right combination of moisture and temperature (Cui et al. 2007; Tobe et al. 2005). The germination of seed in nature is affected by both moisture and light. In the growing season (May–September) a sufficient rainfall triggers germination; a few seeds germinate within 1–2 days, but a week is usually required for full germination (Li et al. 1992). Germination is strongly inhibited by light (Tobe et al. 2005), preventing the germination of seed lying on the soil surface. The germination rate of seed present in the top 10 cm of the soil profile is significantly higher than for those buried below this depth, so plant density tends to be highest at the top of the dunes and on their windward slope (Bai et al. 2004). Seedling survival is low in the native environment (Li 1980). Thus, an important adaptation is to disperse germination over a prolonged period (Li et al. 1992; Wang et al. 1998; Zheng et al. 2004, 2005), achieved by the wind-induced burial of surface seed and mixing of the sand which brings closer to the surface seed which was previously deeply buried.

Growth adaptation

The sand dune surface environment is hot during the main growing season, drought-prone, nutrient-poor and liable to soil loss and plant burial through wind action. Rapid root growth upon germination is the first adaptation strategy adopted by *A. squarrosum.* A taproot develops soon after germination (Nemoto and Lu 1992; Wang et al. 1998), which is able to penetrate deep into the soil profile to access stored moisture. Roots growth is fast: the tap root reaches a length of 3.5 cm at emergence, more than doubling in length over the next 7 days (Chen 1986; Liu et al. 2003). Horizontal lateral roots form once the tap root reaches a supply of moisture. The length of the taproot is high compared to the height of the plant above ground (Nemoto and Lu 1992, Wang et al. 2004). Some lateral roots can reach a length of 5 m by the time the main stem has grown to just 67 cm (unpublished data). This rapid root growth also provides physical support against wind damage.

A special shoot growth pattern at seedling stage is the second adaptation strategy adopted by *A. squarrosum.* The first pair of lateral branches develops shortly after emergence and the main stem growth is inhibited at this stage (Fig. 2a). A second pair and the main stem then grows, protected from the wind by the first pair (Fig. 2b). Thus the young plant comprises a main stem surrounded by four branches, a structure which is effective for locally reducing the wind speed and inhibiting the flow of sand around the base of the plant (Fig. 2c). The main stem grows faster than the four branches do later, establishing a highly branched plant structure (Fig. 2d).

The other adaptation strategies adopted by *A. squarrosum* include transpiration response, cation accumulation, and root distribution pattern. The rate of transpiration responds rapidly to changes of moisture availability, especially during the vegetative stage (Liu et al. 2003). The plants accumulate K^+ in the stem when stressed by drought, a physiological adaptation which serves to increase the osmotic gradient between

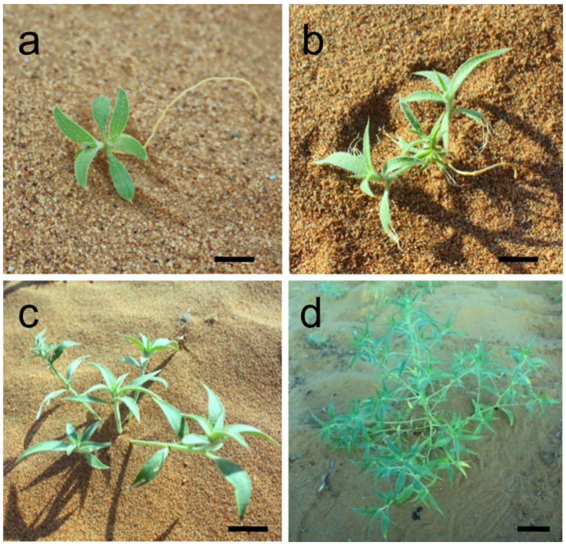

Fig. 2 The shoot growth pattern of *A. squarrosum.* **a** The first pair of branches develop shortly after the appearance of the first pair of true leaves. The cotyledons are obscured by the two branches. *Bar* 1 cm. **b** The second pair of branches and the main stem are protected from wind damage by the first branches. *Bar* 2 cm. **c** The main stem and the four branches of a mature plant. *Bar* 4 cm. **d** The main stem grows faster than the four branches, establishing a highly branched structure. *Bar* 10 cm

the plant and the soil and so to support the process of water uptake (Wang et al. 2004). Part of the root system is shallow, and the other deeply buried (Chen 1986). Shallow roots enable the rapid uptake of water during and immediately after a rainfall episode, while the deeper roots access stored water further down the soil profile, especially during drought periods (Liu et al. 2003).

The above-mentioned adaptation strategies ensure the survival of *A. squarrosum* on mobile sand dunes. *A. squarrosum* plants have leaves and bracts with hard and acute apexes (Liu 1985a; Wu et al. 2003), which play a major role in defenses against herbivores. Thus, *A. squarrosum* can successfully establish communities on mobile sand dunes in arid and semi-arid regions of Central Asia.

Nutritional value of sand rice seed

The earliest record of sand rice seed consumption dating to the 7th century CE (Gao 2002). A supplement to the *Compendium of Materia Medica* (Zhao 1765) mentions that consuming the seed is healthy for the spleen, stomach and large intestine. In Mongolian medicine, the seed was used for alleviating fever, diuresis and diabetes (Gong et al. 2012). The local population consumes sand rice seed in a variety of dishes, of which the most popular is "shami liangfen", a cold starchy jelly usually served during the summer months, seasoned with vinegar, sesame paste, crushed garlic, shallot, chili and salt. In addition, the seed is consumed in similar ways as quinoa, a pseudocereal which has a rather higher nutritional value than the true cereals (Abugoch 2009; Stikic et al. 2012; Hager et al. 2012). Sand rice seed contains about 23.2 % protein, 9.7 % lipid, 45.0 % carbohydrates, 8.6 % crude fiber and 5.0 % ash, and is nutritionally superior to quinoa seed (Table 1). The amino acid composition of *A. squarrosum* seed protein is similar to that of quinoa (Table 2), and provides a good balance for growing children, particularly with respect to phenylalanine, histidine, isoleucine, threonine and valine (FAO 1990). From the point of view of essential amino acids, the sand rice seed protein needs no supplementation with other sources of protein to meet the requirements of a healthy human diet. With respect to the lipid content of the seed, the content of linoleic acid is greater, that of linolenic acid comparable and that of oleic acid less in sand rice than in quinoa (Table 3). Polyunsaturated fatty acids such as linoleic acid reduce the risk of cardiovascular disease (Abeywardena et al. 1991) and improve insulin sensitivity (Lovejoy 1999), and have been recommended as a healthy substitute for saturated animal fats (Dietary Guidelines for Americans 2010). With respect to the mineral content of sand rice and quinoa seed, the former is richer in iron, the two are comparable for phosphorus, magnesium and zinc, and the latter is richer in calcium and potassium (Table 4). Diets limited in iron can lead to the development of anemia (Muñoz et al. 2009), perinatal mortality, and the loss of both cognitive and physical ability (Ortiz-Monasterio et al. 2007). The iron-rich sand rice might be a functional food that aims at lowering the risk of these diseases.

Yield potential of *A. squarrosum*

Like most non-domesticated species, the seed yield of natural stands of sand rice is very low. Based on a

Table 1 Proximate analysis of the seed (g per 100 g dry weight) of four ecotypes of sand rice and eight of quinoa

Component	Sand rice			Quinoa		
	Range	Mean	References	Range	Mean	References
Protein	21.59–25.5	23.21	Wang et al. (2009), Sun et al. (1995), Ren et al. (2005), Gao et al. (1991)	11.32–16.1	13.80	Miranda et al. (2012), Wright et al. (2002):
Fat	7.7–11.8	9.70		5.30–7.15	6.16	
Total carbohydrates	32.5–51.2	44.97		56.73–69.10	64.18	
Crude fiber	4.9–14.9	8.62		1.33–2.81	1.82	
Ash	3.2–6.6	4.97		2.60–3.65	3.31	
Moisture	8–9.42	8.36		7.74–15.18	11.25	

Table 2 Essential amino acid profile of the seed (g per 100 g protein) of five ecotypes of sand rice and 12 of quinoa

Amino acid	Sand rice			Quinoa		
	Range	Mean	References	Range	Mean	References
Histidine	1.4–2.1	1.8	Wang et al. (2009), Sun et al. (1995), Ren et al. (2005), Gao et al. (1991), Brad (2011a)	1.4–3.6	2.4	Repo-Carrasco et al. (2003), Gonzalez et al. (2012), Palombini et al. (2013)
Isoleucine	3.3–4.1	3.8		1.7–3.4	2.5	
Leucine	6.2–9.3	7.5		3.8–7.5	5.3	
Lysine	4.4–6.3	5.1		2.4–6.2	4.3	
Methionine	1.5–4.7	3.3		0.7–3.1	1.4	
Phenylalanine	3.8–5.1	4.8		2.3–4.5	3.2	
Threonine	2.9–3.8	3.4		2.1–4.3	3.0	
Tryptophan	0.9–1.4	1.1		0.6–1.1	0.8	
Valine	4.1–9.6	5.7		2.2–4.2	3.1	

Table 3 Unsaturated fatty acid content of the seed (mg per g fatty acid) of two ecotypes of sand rice and three of quinoa

Fatty acid	Sand rice			Quinoa		
	Range	Mean	References	Range	Mean	References
Oleic	154–167	160	Brad (2011a, b)	241–248	245	Palombini et al. (2013), Peiretti et al. (2013), Ruales and Nair (1993)
Linoleic	674–713	693		488–523	509	
Linolenic	37–42	40		33–49	40	

Table 4 Mineral composition of the seed (mg per kg dry weight) of 2 ecotypes of sand rice and eight of quinoa

Mineral	Sand rice			Quinoa		
	Range	Mean	References	Range	Mean	References
Ca	130–782	456	Sun et al. (1995), Zhang et al. (2006)	771–2,113	1,201	Miranda et al. (2012), Ando et al. (2002), Konishi et al. (2004)
P	4,467	4,467		2,851–5,264	4,076	
Mg	887–2,856	1,872		1,509–5,020	2,377	
Fe	91–189	140		48–150	77	
Zn	34–39	37		8–50	35	
K	5,560–5,830	5,695		7,320–22,440	17,252	

thousand grain weight of 1.52 g and a canopy seed density of 1,400 seed per m^2 (Ma and Liu 2008), the yield of a natural stand can be estimated at about 21 kg/ha. Chang et al. (2003) have tried to cultivate *A. squarrosum* as a crop in Lanzhou. The dry matter above-ground yield was around 1.75 t/ha and the seed yield around 39 kg/ha. The domestication of quinoa shows that it is feasible to domesticate Chenopodiaceae species. A collection of quinoa accessions, when trialled by Fuentes and Bhargava (2011), produced between 25 and 1,193 kg/ha of seed. The best performing accessions recorded a harvest index (proportion of seed to total dry above-ground biomass) of 0.6 (compared to the unimproved *A. squarrosum* harvest index of 0.02). This suggests that a concerted improvement effort could raise the performance of sand rice to the level achieved by quinoa.

Future prospects for *A. squarrosum*

A. squarrosum is already effective as a desert reclamation species, but its domestication offers the prospect of a novel crop adapted to the warming of the global climate. At present, it is a little known species, both with respect to its ecological worth and its nutritional value. Lifting its yield potential via domestication would be required before it could be considered as a viable crop for arid and semi-arid environments. However, the effort to domesticate the species could pay large dividends in the context of food security.

Sandy desert regions are typically economically under-developed and have poor food security. The domestication of *A. squarrosum*, which has at least as good a nutritional value as quinoa, could make a significant economic and health contribution to rural populations based in the arid and semi-arid regions of Central Asia and beyond. In the future, consumers might incorporate sand rice in their daily diet as a healthy, nutritious, good tasting, and versatile food. Thanks to its remarkable high temperature tolerance, it should be considered as a potential crop adapted to a future climate warmer than to-day's. It may serve as a useful source of abiotic-tolerance genes for crop improvement. Plant domestication in the past has been a slow process of conscious and unintentional farmer-based selection (Olsen and Wendel 2013). The conscious and directed domestication of a species such as *A. squarrosum* should be achievable in a far shorter time frame since firstly, genetic mutations can be induced; and secondly, the traits which need to be selected for are already well defined. The most important traits for the domestication of sand rice will be the uniculm habit, the non-shattering of the seed, a much higher harvest index and large seeds. Our intention is to initiate a large-scale breeding programme based on mutagenesis and crossing to convert sand rice from a wild species into a manageable crop. At the same time, we will continue our efforts to optimize the agronomy of *A. squarrosum*. Our long term goal is to create a novel crop which is resilient to climate change.

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References

Abeywardena M, McLeannan P, Charnock J (1991) Differential effects of dietary fish oil on myocardial prostaglandin I2 and thromboxane A2 production. Am J Physiol 260: 379–385

Abugoch LE (2009) Quinoa (*Chenopodium quinoa* Willd.): composition, chemistry, nutritional, and functional properties. Adv Food Nutr Res 58:1–31

Ando H, Chen YC, Tang H, Shimizu M, Watanabe K, Mitsunaga T (2002) Food components in fractions of quinoa seed. Food Sci Technol Res 8:80–84

Bai W, Bao X, Li L (2004) Effect of *Agriophyllum squarrosum* seed banks on its colonization in a moving sand dune in Hunshandake Sand Land of China. J Arid Environ 59: 151–157

Bioversity International and FAO (2012) Concept note: celebrating the international year of quinoa. http://www.fao.org/quinoa-2013/publications/fao/concept-note-celebrating-the-%20international-year-of-quinoa/ar/?no_mobile=1. (Accessed 6 Sep 2013)

Brad K (2011a) Research on fatty acid and amino acid components of *Agriophyllum squarrosum* seeds from Xinjiang. Agric Sci Technol 12:789–791

Brad K (2011b) SPE extraction of *Agriophyllum squarrosum* seeds oil and analysis of its ingredients. J Anhui Agric Sci 39:10839–10841 (in Chinese)

Chang GZ, Wang CY, Wang JG (2003) Studies on experiments of cultivation of introduced *Calligonum mongolicum*, *Artemisia sphaerocephala* and *Agriophyllum squarrosum* in Lanzhou. J Tradit Chin Vet Med S1:47–49 (in Chinese)

Chen SH (1986) Root types of plants in inner Mongolia grassland. Inner Mongolia People's Press, Hohhot (In Chinese)

Cui JY, Li YL, Zhao HL, Su YZ, Drake S (2007) Comparison of seed germination of *Agriophyllum squarrosum* (L.) Moq. and *Artemisia halodendron* Turcz. Ex Bess, two dominant species of Horqin desert, China. Arid Land Res Manag 21:165–179

Dietary Guidelines for Americans (2010). 7th ed. Washington, DC: US Government Printing Office

FAO, WHO (1990) Protein Quality Evaluation. Report of a Joint FAO/WHO Expert Consultation. Food and Agriculture Organization/World Health Organization of United Nations, Rome

Fuentes FF, Bhargava A (2011) Morphological analysis of quinoa germplasm grown under lowland desert conditions. J Agron Crop Sci 197:124–134

Gao Q (2002) The "grass seed" is *Agriophyllum squarrosum* in Dunhuang manuscripts. J Dunhuang Stud 42:43–44 (in Chinese)

Gao B, Sun H, Liu H (1991) The investigation and utilization of nutritional value of *Agriophyllum squarrosum* seeds. Food Sci 12:50–53 (in Chinese)

Gonzalez JA, Konishi Y, Bruno M, Valoy M, Prado FE (2012) Interrelationships among seed yield, total protein and amino acid composition of ten quinoa (*Chenopodium quinoa*) cultivars from two different agroecological regions. J Sci Food Agric 92:1222–1229

Hager AS, Wolter A, Jacob F, Zannini E, Arendt EK (2012) Nutritional properties and ultra-structure of commercial gluten free flours from different botanical sources compared to wheat flours. J Cereal Sci 56:239–247

Gong B, Zhan KX, Zhou YH, Zhang L, Hui YQ, LI YS (2012) Separation and identification of chemical constituents from *Agriophyllum squarrosum* (L.) Moq. Chin Med Mat 10:7–11

Kadereit G, Borsch T, Weising K, Freitag H (2003) Phylogeny of Amaranthaceae and Chenopodiaceae and the evolution of C4 photosynthesis. Int J Plant Sci 164:959–986

Konishi Y, Hirano S, Tsuboi H, Wada M (2004) Distribution of minerals in quinoa (*Chenopodium quinoa* Willd.) seeds. Biosci Biotechnol Biochem 68:231–234

Kühn U, Bittrich V, Carolin R, Freitag H, Hedge IC, Uotila P, Wilson PG (1993) Chenopodiaceae. In: Kubitzki K, Rohwer JG, Bittrich V (eds) The families and genera of vascular plants, Springer, Berlin, vol 2, pp 253–281

Li M (1980) Shifting sand control at Shapotou area in the Tengger desert. Ningxia People's Press, Yinchuan (in Chinese)

Li S, Chang X, Zhao X (1992) Study of *Agriophyllum squarrosum*—pioneering plant on shifting sand. J Arid Land Resour Environ 6(4):63–70 (in Chinese)

Liu Y (1985a) Flora in Desertis Republicae Populorum Sinarum. Tomus I. Science Press, Beijing (in Chinese)

Liu SE (1985b) Natural forest and afforestation on sand dunes at Zhanggutai. Selected Publication of Liu Shen'e. Science Press, Beijing, pp 136–144 (in Chinese)

Liu Z, Li X, Li R, Luo Y, Wang H, Jiang D, Nan Y (2003) A comparative study on diaspore shape of 70 species in the sandy land of Horqin. Acta Pratacult Sin 12(5):55–61 (in Chinese)

Liu Z, Li R, Li X, Luo Y, Wang H, Jiang D, Nan Y (2004) A comparative study of seed weight of 69 plant species in Horqin Sandyland, China. Acta Phytoecol Sin 28:225–230 (in Chinese)

Liu Z, Yan Q, Baskin CC, Ma J (2006) Burial of canopy-stored seeds in the annual psammophyte *Agriophyllum squarrosum* Moq. (Chenopodiaceae) and its ecological significance. Plant Soil 288:71–80

Lovejoy J (1999) Dietary fatty acids and insulin resistance. Curr Atheroscler Rep 1:215–220

Ma J, Liu Z (2008) Spatiotemporal pattern of seed bank in the annual psammophyte *Agriophyllum squarrosum* Moq. (Chenopodiaceae) on the active sand dunes of northeastern Inner Mongolia, China. Plant Soil 311:97–107

McCouch S, Baute GJ, Bradeen J et al (2013) Agriculture: feeding the future. Nature 499:23–24

Miranda M, Vega-Gálvez A, Quispe-Fuentes I, Rodríguez MJ, Maureira H, Martínez EA (2012) Nutritional aspects of six quinoa (*Chenopodium quinoa* Willd.) ecotypes from three geographical areas of Chile. Chilean J Agric Res 72:175–181

Muñoz M, Villar I, García-Erce JA (2009) An update on iron physiology. World J Gastroenterol 37:17–26

Nemoto M, Lu X (1992) Ecological characteristics of *Agriophyllum squarrosum* a pioneer annual on sand dunes in eastern Inner Mongolia, China. Ecol Res 7:183–186

Olsen KM, Wendel JF (2013) A bountiful harvest: genomic insights into crop domestication phenotypes. Annu Rev Plant Biol 64:47–70

Ortiz-Monasterio JI, Palacios-Rojas N, Meng E, Pixley K, Trethowan R, Peña RJ (2007) Enhancing the mineral and vitamin content of wheat and maize through plant breeding. J Cereal Sci 46:293–307

Palombini SV, Claus T, Maruyama SA et al (2013) Evaluation of nutritional compounds in new amaranth and quinoa cultivars. Food Sci Technol 33:339–344

Peiretti PG, Gai F, Tassone S (2013) Fatty acid profile and nutritive value of quinoa (*Chenopodium quinoa* Willd.) seeds and plants at different growth stages. Anim Feed Sci Technol 183:56–61

Ren W, Liu X, Ni C (2005) An analysis on nutritional composition of natural *Agriophyllum squarrosum* of Maowusu desert. J Inn Mong Agric Univ 26:88–90 (in Chinese)

Repo-Carrasco R, Espinoza C, Jacobsen SE (2003) Nutritional value and use of the Andean crops quinoa (*Chenopodium quinoa*) and kañiwa (*Chenopodium pallidicaule*). Food Rev Int 19:179–189

Ruales J, Nair BM (1993) Content of fat, vitamins and minerals in quinoa (*Chenopodium quinoa* Willd.) seeds. Food Chem 48:131–136

Stikic R, Glamoclija D, Demin M, Vucelic-Radovic B, Jovanovic Z, Milojkovic-Opsenica D, Jacobsen SE, Milovanovic M (2012) Agronomical and nutritional evaluation of quinosa seeds (*Chenopodium quinoa* Willd.) as an ingredient in bread formulations. J Cereal Sci 55:132–138

Sun H, Liu H, Gong X, Gao K, Xiao M (1995) A study of the nutritional value of *Agriophyllum squarrosum*. J Baotou Med Coll 11:12–14 (in Chinese)

Tester M, Langridge P (2010) Breeding technologies to increase crop production in a changing world. Science 327:818–822

Tobe K, Zhang L, Omasa K (2005) Seed germination and seedling emergence of three annuals growing on desert sand dunes in China. Ann Bot (Lond) 95:649–659

Wang Z, Wang G, Liu X (1998) Germination strategy of the temperate sandy desert annual chenopod *Agriophyllum squarrosum*. J Arid Environ 40:69–76

Wang S, Wan C, Wang Y, Chen H, Zhou Z, Fu H, Sosebee RE (2004) The characteristics of Na^{+}, K^{+} and free proline distribution in several drought-resistant plants of the Alza Desert, China. J Arid Environ 56:525–539

Wang Y, Zhao P, Li J, Lin Y, Qi X (2009) Evaluation on nutritional composition of *Agriophyllum squarrosum* of Tengger desert. Sci Technol Food Ind 30:286–288 (in Chinese)

Wheeler T, von Braun J (2013) Climate change impacts on global food security. Science 341:508–513

Wright KH, Pike OA, Fairbanks DJ, Huber CS (2002) Composition of *Atriplex hortensis*, sweet and bitter *Chenopodium quinoa* seeds. J Food Sci 67:1383–1385

Wu ZY, Raven PH, Hong DY (2003) Flora of China. vol 5 (Ulmaceae through Basellaceae). Science Press, Beijing, and Missouri Botanical Garden Press, St. Louis, p 367

Yan Q, Liu Z, Zhu J, Luo Y, Wang H, Jiang D (2005) Structure, pattern and mechanisms of formation of seed banks in sand dune systems in northeastern Inner Mongolia, China. Plant Soil 277:175–184

Zhang JY, Zhao HL, Zhang TH, Zhao XY, Drake S (2005) Community succession along a chronosequence of vegetation restoration on sand dunes in Horqin Sandy Land. J Arid Environ 62:555–566

Zhang J, Zhao J, Li H (2006) Determination and analysis of seed nutrients of *Agriophyllum squarrosum*. Pratacult Sci 23:77–79 (in Chinese)

Zhao XM (1765) The supplement to compendium of materia medica. People's medical Publishing House, Beijing (in Chinese)
Zheng Y, Gao Y, An P, Shimizu H, Rimmington G (2004) Germination characteristics of *Agriophyllum squarrosum*. Can J Bot 82:1662–1670
Zheng Y, Xie Z, Yu Y, Jiang L, Shimizu H, Rimmington GM (2005) Effects of burial in sand and water supply regime on seedling emergence of six species. Ann Bot 95:1237–1245
Zuo XA, Zhao HL, Zhao XY, Zhang TH, Guo YR, Wang SK, Drake S (2008) Spatial pattern and heterogeneity of soil properties in sand dunes under grazing and restoration in Horqin Sandy Land, Northern China. Soil Tillage Res 99:202–212