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ORIGINAL ARTICLE

Liangju Zhao
Honglang Xiao
Xiaohong Liu
Ren Juan
Lu Mingfeng
Zhou Maoxian

# Correlations of foliar Δ with K concentration and ash content in sand-fixing plants in the Tengger Desert of China: patterns and implications

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L. Zhao · H. Xiao · R. Juan · L. Mingfeng
Z. Maoxian
Division of Hydrology and Water-land Resources in Cold and Arid regions, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou 730000, China

X. Liu
Key Laboratory of Cryosphere and Environment, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou 730000, China

L. Zhao (✉)
Shapotou Desert Research and Experiment Station, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou 730000, China
E-mail: zhlj@lzb.ac.cn
Tel.: +86-931-4967045
Fax: +86-931-8271124

**Abstract** In different-aged sand-fixing zones and shifting sand dunes, the seasonal variations of foliar carbon isotope discrimination (Δ), potassium (K) concentration and ash content were investigated in three dominated deserted plants (*Artemisia ordosica*, *Hedysarum scoparium* and *Caragana korshinskii*) during growth season in Shapotou, which is in the southeast margin of the Tengger Desert. The correlations of foliar Δ with foliar K concentration and ash content were examined to evaluate the foliar K and ash content as surrogates of Δ in those deserted plants. Results showed that there were significant effects of plant species, micro-habitation and growth season on foliar Δ, K concentration and ash content. Foliar Δ of *C. korshinskii* was significantly lower than those of *A. ordosica* and *H. scoparium*, and K concentrations in *A. ordosica* were 2.14 and 2.36 times those of *C. korshinskii* and *H. scoparium*. At the same time, micro-habitation and the conditions in growth seasons had significant effects on foliar Δ, K concentration and ash content. Ash content and K concentration were positively correlated to Δ in *A. ordosica* and *H. scoparium*, while there was significantly negative relationship between foliar K concentration and Δ in *C. korshinskii*. Thus, those findings suggest that foliar ash content and K concentration can serve as surrogates of carbon isotope discrimination (Δ) in *A. ordosica* and *H. scoparium*, while they do not in *C. korshinskii*. This result implied that the correlations of foliar Δ with ash content and K concentration were various due to the physiological features of plant species, and species differences should be fully considered when evaluating the surrogates of carbon isotope discrimination in plants.

**Keywords** Carbon isotope discrimination · Potassium concentration · Ash content · The Tengger Desert

## Introduction

High water-use efficiency (dry matter produced per kilogram of water consumed in its production) is considered to be a trait contributing to the successful growth and production of species in arid and semiarid environments where plant productivity is mainly constrained by soil water availability (Ehleringer 1993; Thumma et al. 1998). Water-use efficiency may be estimated from measurements of dry weight accumulation over time relative to amount of water transpired (transpiration efficiency, TE). However, there was not a simple, efficient method for estimating water-use efficiency, especially in the field (Thumma et al. 1998; Tsialtas et al. 2002). Farquhar et al. (1989) found that carbon isotope discrimination (Δ), which depends on the ratio of intercellular and ambient partial pressures of $CO_2$ ($C_i/C_a$), is related to transpiration efficiency; a useful method has been proposed to rank $C_3$ species according to their water-use efficiencies. In addition, theoretical and empirical studies have demonstrated that carbon isotope discrimination is highly correlated with plant water-use efficiency (Farquhar et al. 1989; Tsialtas et al. 2002). Furthermore, several recent studies have demonstrated that carbon isotope discrimination (Δ) may be used as a surrogate to select for improved water-use efficiency in crops and trees (Farquhar et al. 1989). Δ was found to be negatively associated with water-use efficiency for many cultivated and wild $C_3$ species (Condon et al. 1990; Wright et al. 1994; Ismail et al. 1994; Turner 1997). These studies suggested that genetic variation in Δ may be sufficient to be useful as a selection criterion for improved water-use efficiency (Farquhar et al. 1989; Hall et al. 1994). However, severe restrictions in the use of Δ in breeding programs, especially when a large number of genotypes have to be screened, are the persistent high cost of carbon isotope determinations (Hall et al. 1994; Voltas et al. 1998) and the technical skills required for carbon isotope analysis (Araus et al. 1998; Tsialtas et al. 2002). Therefore, many studies were conducted to select the surrogates of Δ, and have obtained many valuable results (Masle et al. 1992; Frank et al. 1997; Araus et al. 1998; Voltas et al. 1998; Merah et al. 2001; Rascio et al. 2001; Tsialtas et al. 2002).

Most minerals are mainly passively transported in plant organs via the xylem flux and accumulated in transpiring plant tissues. Then, a plant that needs more water for the same biomass accumulation would be proportionally richer in minerals. Flag leaf and kernel ash and mineral content, both of which are positively related to grain yield, have been used as surrogates of grain Δ for many cereals (Araus et al. 1998; Voltas et al. 1998; Merah et al. 2001). The mineral or ash content of vegetative tissues was found to be positively related to the transpiration ratio (1/TE) or Δ in $C_3$ species (Masle et al. 1992; Frank et al. 1997). The positive relationship between Δ and mineral or ash content is not yet well understood, but could be attributed to the fact that accumulation of minerals in the vegetative parts of the plants occurs, at least in part, passively through the transpiration stream (Masle et al. 1992). However, the positive relationship between Δ and ash or mineral content is not consistent. There are also reports of either negative or no correlations between these traits (Ray et al. 1998, 1999). Among the minerals concerned of absorption by plants, potassium (K) was found to be the most contributing element to the relationship between mineral content and transpiration ratio (Masle et al. 1992), and potassium was selected to be evaluated as a surrogate of Δ because of its role in plant water economy via regulation of stomatal function (Rascio et al. 2001). The positive correlations between Δ and K concentration were found in grassland species (Masle et al. 1992; Tsialtas et al. 2002). However, K showed lower correlations with Δ or 1/TE compared to total mineral or ash content in grasses (Masle et al. 1992). Because of these inconsistent relationships between foliar Δ and ash content or K concentration, it is imperative that a relationship between Δ and its surrogates be established for different species and under wild conditions before any technique can be reliably applied. Until now, most research has been carried out using a limited number of genotypes, or under controlled growing conditions, or both (Araus et al. 1998).

Desertification is a severe environmental problem in north-central China, where deserts are expanding at an estimated rate of 2,100 $km^2$ $year^{-1}$ (Mitchell et al. 1998), and threatens about 3.3 million $km^2$ of land where the lives of 400 million people are involved (Chen et al. 1996; Zha and Gao 1997). It was well known that revegetation is one of the most effective methods to reduce the hazards of desertification (Shapotou Desert Research and Experiment Station, Chinese Academy of Sciences 1986). Thus, since the 1950s large areas of arid desert regions of China were reclaimed by artificial vegetation. To protect the Baotou-Lanzhou railway, the Chinese Academy of Sciences and related institutions began establishing measures to provide sand fixation (Zhao 1998), and artificial sand-fixing zones were established in 1956, 1964, 1976, 1981 and 1987 (Shapotou Desert Research and Experiment Station, Chinese Academy of Sciences 1986). As a result of applying straw barriers and artificial shrub forests in the transition zone between desert and arid grassland, the mobile dunes have been stabilized (Xiao et al. 2003a). After about a 50-year succession of artificial vegetation, among the non-native sand-fixing plant species used to fix the sand, *Artemisia ordosica*, *Hedysarum scoparium* and *Caragana korshinskii*, especially *A. ordosica*, become dominant shrubs and play an important role in the experiment plot of shifting sand fixation (Ma et al. 2002). *A. ordosica*, which is a semi-shrub and succulent xerophyte, and belongs to desert and semi-desert biome (Walter and Breckle 1985), and *C. korshinskii* and *H. scoparium* are leguminous shrubs and belong to xerophytes (Shapotou Desert Research and Experiment Station, Chinese Academy of Sciences 1986). After the long-term succession, artificial vegetation system in Shapotou is going to develop towards a semi-natural and natural vegetation system (Xiao et al. 2003b). Many other cultivated sand-fixing plants such as *Caragana intermedia*, *Calligonum arboreses* and *Tamarix ramosissima* disappeared in artificial vegetation, while *A. ordosica*, *H. scoparium* and *C. korshinskii* survived during the succession of artificial ecosystem. Thus, it is very significant to study the physiological properties, especially in water-use efficiency by foliar Δ, K concentration and ash content, and evaluating the feasibility of leaf ash content and K concentration as surrogates of the Δ of those species.

The study was directed at: (1) studying the variations of foliar Δ, K concentration and ash content in *A. ordosica*, *H. scoparium* and *C. korshinskii* among species, in different growth seasons and under different growing conditions (1956, 1964, 1981, 1987 and shifting sand dune zones); (2) evaluating the feasibility of leaf ash content and K concentration as surrogates of the foliar Δ of *A. ordosica*, *H. scoparium* and *C. korshinskii* in the Tengger Desert. These results have implications for the study of restoration ecology, especially as relates to investigate the health of artificial ecosystems during the long-term succession.

## Materials and methods

### The study area

The Shapotou area (37°27.55′N, 105°00.64′E) borders on the southeast margin of the Tengger Desert, China (Fig. 1). It has abundant sunshine and low relative humidity. Average annual precipitation is 180.2 mm year$^{-1}$, with 80% of the rainfall occurring between May and September. Annual mean temperature is 10.0°C, with a mean January temperature of −6.9°C and a mean July temperature of 24.3°C. The maximum temperature at the surface of the sand may reach 74°C (Chen et al. 1991). The depth to the water table is more than 80 m, thus rainfall is usually the only source of water for plant growth. The frost-free period spans 150–180 days year$^{-1}$. The soil is an aeolian sandy soil (Xun and Li 1987).

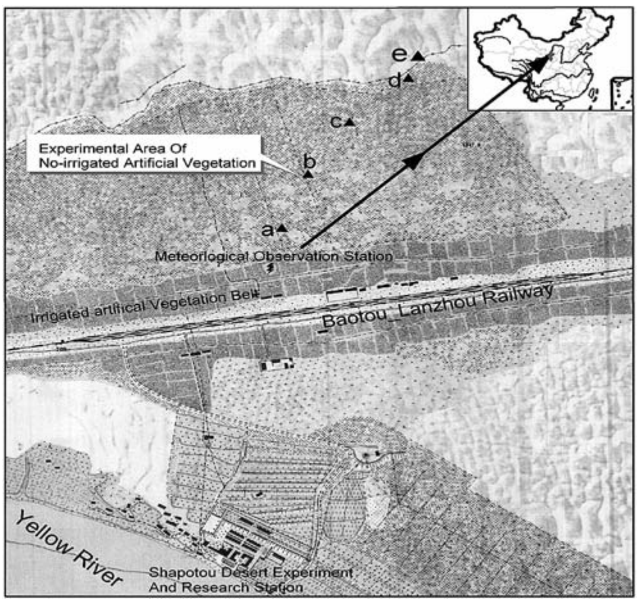


**Fig. 1** The study region and sampling sites of the artificial sand-fixing zones in Shapotou of the southeast margin of the Tengger Desert, China. The ‘a’, ‘b’, ‘c’, ‘d’ and ‘e’ represent the sampled sites, which indicate the no-irrigated artificial vegetation zones planted in 1956, 1964, 1981, 1987 and shifting sand dune, respectively

### Plant sampling

The field experiments and monitoring were in a windward slope of the artificial sand-accumulating zones, which were revegetated without irrigation in 1956, 1964, 1981 and 1987, and described 1956 zone, 1964 zone, 1981 zone and 1987 zone thereinafter, respectively. The shifting sand dune was conducted as a control treatment (SSD). In every zone, two plots of 5 m × 5 m region, which included 5∼6 shrubs of *A. ordosica* and 2∼3 shrubs of *C. korshinskii* and *H. scoparium* (with the similar height and canopy within species), were selected to sample leaves. For shifting sand dunes, only one plot of 6 m × 6 m region, which included four shrubs of *A. ordosica* and three shrubs of *H. scoparium*, were selected due to its lower coverage. In the selected sites, sampled leaves of *A. ordosica*, *C. korshinskii* and *H. scoparium* were collected on 15 and 27 May, 29 June, 27 July, 27 August, and 24 September in 2004. Climatic conditions of the experimental site during growth season in 2004 are presented in Table 1. At each sampling time, the leaves were taken between 8 and 10 AM, and about 20 leaves or assimilating shoots from each of selected shrubs were taken as a sample from each species growing in each of the selected zones. At the same zone, two samples were pooled as a sample. In a shifting sand dune, every sample was repeated two times and pooled as a sample.

**Table 1** Climatic conditions of the experimental site in Shapotou during growth season in 2004

| Month | Rainfall (mm) | RH (%) | DMT (°C) | SMT (°C) | WV (m s$^{-1}$) |
|---|---|---|---|---|---|
| March | 0.0 | 28.7 | 8.2 | 8.0 | 3.0 |
| April | 0.0 | 24.5 | 15.0 | 17.2 | 3.9 |
| May | 12.8 | 29.3 | 17.5 | 22.0 | 4.2 |
| June | 20.2 | 40.4 | 21.7 | 26.7 | 3.9 |
| July | 28.5 | 47.6 | 23.6 | 24.3 | 3.4 |
| August | 45.7 | 61.8 | 22.0 | 26.6 | 2.7 |
| September | 2.1 | 46.9 | 18.8 | 22.6 | 2.6 |
| Mean | | 39.9 | 18.1 | 21.1 | 3.4 |
| Total (RF) | 109.3 | | | | |

*Note*: RF, DMT and SMT represent the rainfall, daily mean temperature and soil surface temperature, respectively. RH and WV indicate mean relative humidity and mean wind velocity, respectively

## Foliar sample preparation and analysis

The samples were dried at 70°C for 24 h. Dried leaf samples were grinded in a stainless steel mill. K content of leaves was determined by means of flame spectrophotometry (Allen 1989). Approximately 1.5 g of dry matter was burned in a furnace at 500°C for 10 h. The analysis of ash content and K concentration was performed in pooled samples and the measurement was replicated two times. The K concentration and ash content were expressed as milligram per gram and grams per 100 g of sample dry weight, respectively.

The carbon isotope ratio ($^{13}C/^{12}C$) was determined by mass spectrometry (MAT 252 spectrometer) (Zhao et al. 2006). The precision of the analysis was better than 0.10‰. The $\delta^{13}C$ ($\delta p$, relative to Vienna Pee Dee Belemnite (V-PDB), the international standard) was expressed as:

$$\delta^{13}\mathrm{C}(‰) = \left[\left(R_{\mathrm{sample}}/R_{\mathrm{standard}}\right) - 1\right] \times 1000, \tag{1}$$

where $R$ is the $^{13}C/^{12}C$ ratio. The analysis of leaf $\delta^{13}C$ (leaf carbon isotope ratio) was performed in pooled samples and the measurement was replicated two times.

Foliar $\Delta$ (‰) is the carbon isotope discrimination by the plant and it was calculated by Eq. 2 (Farquhar et al. 1982):

$$\Delta = \frac{\delta^{13}\mathrm{C}_{\mathrm{air}} - \delta^{13}\mathrm{C}_{\mathrm{plant}}}{1 - \frac{\delta^{13}\mathrm{C}_{\mathrm{plant}}}{1000}}, \tag{2}$$

where $\Delta$ is the carbon isotope discrimination by the plant. $\delta^{13}C_{air}$ (−8‰) and $\delta^{13}C_{plant}$ are carbon isotope composition of air and plant tissue, respectively.

## Statistical analysis

Analyses of variance (ANOVA) for variables from measurements were used for testing the species and treatment differences. All statistical analysis was performed with SPSS 11.0 for Windows statistical software package.

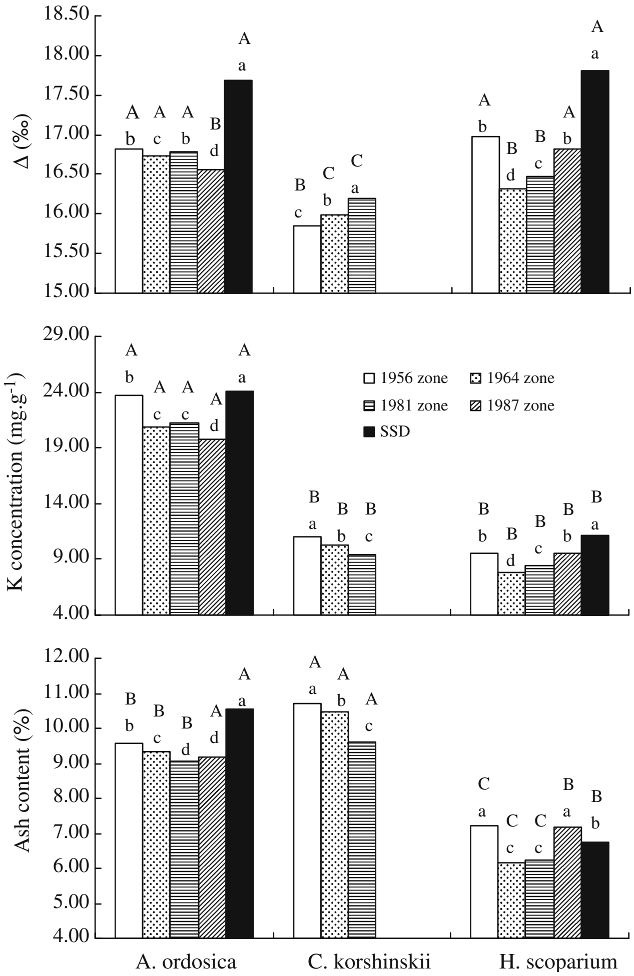


**Fig. 2** Seasonal means of carbon isotope discrimination ($\Delta$), K concentration and ash content for the shifting sand dunes and the different-aged sand-fixing zones (Planted in 1956, 1964, 1981 and 1987) for the *A. ordosica*, *C. korshinskii* and *H. scoparium* in 2004. *Capital letters* indicate a comparison of means for the same treatment among the different species. *Lowercase letters* indicate a comparison of treatment means within the same species. *Bars with the same letter* do not differ at $P < 0.05$ by Duncan's multiple range tests

# Results

## Effects of sand-fixing ages on foliar Δ, K concentration and ash content

The three traits measured, including $\Delta$, K concentration and ash content, were affected by species and microhabitation (Fig. 2). Among these species, means of foliar $\Delta$ in *A. ordosica* (16.92 ± 0.57‰) and *H. scoparium* (16.88 ± 0.62‰) were similar and, were significantly higher than that of *C. korshinskii* (16.01 ± 0.34‰). With the exception of the foliar $\Delta$ means in *A. ordosica* in 1964 and 1981 zones which were higher than those of *H. scoparium*, and in the 1987 zone that showed contrary trend, the two species had similar foliar $\Delta$ for the other treatments. The K concentration of *A. ordosica* was significantly higher than those of *C. korshinskii* and *H. scoparium*, and was 2.14 and 2.36 times than those of *C. korshinskii* (10.24 ± 3.46 mg $g^{-1}$) and *H. scoparium* (9.29 ± 2.67 mg $g^{-1}$). The significant differences of foliar ash content were found among three species, and the ash content in *C. korshinskii* was the highest, and in *H. scoparium* was the lowest.

In all species, except ash content in *H. scoparium*, the highest means of foliar $\Delta$, K concentration and ash content were found in shifting sand dune in *H*. *scoparium* and *A*. *ordosica*. Except in 1956 zone which foliar Δ and K concentration were similar to those of 1981 zone, foliar Δ and K concentration in *H*. *scoparium* increased significantly with the increase of sand-fixing time, while foliar ash content was the highest in 1956 and 1987 zones and the lowest in 1964 and 1981 zones. In *C*. *korshinskii*, foliar K concentration and ash content decreased with the increase of sand-fixing time, and foliar Δ showed a contrary trend. The highest means of foliar Δ, K concentration and ash content were found in shifting sand dune, while the lowest means of above data were in 1987 zone in *A*. *ordosica*. In artificial vegetation zones, foliar K concentration and ash content in *A*. *ordosica* showed the same changing trends as those of *C*. *korshinskii*, while foliar Δ in 1956 and 1981 zones were significantly higher than those of 1964 zone.

## Seasonal variations of foliar Δ with foliar K concentration and ash content

Seasonal variations of foliar Δ, K concentration and ash content varied significantly due to species (Table 2). With the exception of *H*. *scoparium*, with no significant effect of growth season on foliar Δ, foliar Δ, K concentration and ash content were significantly affected by species and growth season in *A*. *ordosica*, *C*. *korshinskii* and *H*. *scoparium*. Foliar Δ values in *A*. *ordosica* were the highest at the end of May, and the lowest at the end of September, while this parameter showed reverse trends in *C*. *korshinskii*. There were similar variational trends of foliar K and ash in *A*. *ordosica*. With the growth of *C*. *korshinskii* and *H*. *scoparium*, foliar K decreased excluding that of *H*. *scoparium* before 15 May, while foliar ash content increased gradually in *H*. *scoparium* with the exception of the end of June.

## Correlations of foliar Δ with foliar K concentration and ash content

As Figs. 3, 4 and 5 show, correlations of foliar Δ with K concentration and ash content varied significantly among species. Foliar Δ values were significantly positively related to K concentrations in *A*. *ordosica* ($P < 0.001$) and *H*. *scoparium* ($P = 0.002$), while the significantly negative relationship between above data was found in *C*. *korshinskii* ($P < 0.001$). The correlations of foliar Δ with ash contents were significantly positive in ($P < 0.001$) and *H*. *scoparium* ($P = 0.029$). However, a weak positive relationship between foliar Δ and ash content was found in *C*. *korshinskii* ($P = 0.236$).

**Table 2** One-way ANOVA table showing the seasonal variations of foliar carbon isotope discrimination (Δ), K concentration and ash content in *Artemisia ordosica*, *Caragana korshinskii* and *Hedysarum scoparium*

| | *Artemisia ordosica* | | | *Caragana korshinskii* | | | *Hedysarum scoparium* | | |
|---|---|---|---|---|---|---|---|---|---|
| | Δ (SD) (‰) | K (SD) ($mg\ g^{-1}$) | Ash (SD) (%) | Δ (SD) (‰) | K (SD) ($mg\ g^{-1}$) | Ash (SD) (%) | Δ (SD) (‰) | K (SD) ($mg\ g^{-1}$) | Ash (SD) (%) |
| 15 May | 16.90 (0.45)b | 24.62 (2.73)a | 9.20 (0.90)bc | 15.66 (0.14)c | 13.99 (1.75)a | 8.49 (0.94) d | 16.82 (0.34)a | 7.56 (1.08)b | 5.47 (0.52)d |
| 29 May | 17.55 (0.33)a | 22.80 (2.37)b | 9.95 (1.03)ab | 15.70 (0.28)c | 14.35 (0.69)a | 10.02 (1.16) bc | 16.75 (0.58)a | 10.90 (1.35)a | 6.13 (0.38)c |
| 29 June | 16.80 (0.55)bc | 19.08 (0.81)c | 8.86 (0.51)c | 16.14 (0.12)ab | 11.34 (1.55)b | 11.10 (1.41) ab | 16.84 (0.77)a | 12.14 (1.99)a | 7.01 (0.44)b |
| 27 July | 16.85 (0.32)b | 19.03 (1.77)c | 9.09 (0.60)c | 16.00 (0.09)b | 8.07 (2.05)c | 10.57 (0.87) abc | 16.95 (0.77)a | 11.14 (1.58)a | 6.20 (0.57)c |
| 27 August | 17.01 (0.52)b | 24.07 (2.96)a | 10.54 (0.64)a | 16.30 (0.36)a | 6.92 (1.18)c | 9.62 (0.42) cd | 16.98 (0.58)a | 7.24 (1.48)b | 7.06 (0.28)b |
| 24 September | 16.39 (0.58)c | 22.07 (1.78)b | 9.60 (1.01)bc | 16.25 (0.29)ab | 6.78 (0.50)c | 11.74 (0.70) a | 16.90 (0.65)a | 6.75 (1.70)b | 7.80 (1.10)a |
| Mean | 16.92**A** | 21.94*A* | 9.54B | 16.01**B** | 10.24*B* | 10.26A | 16.88**A** | 9.29*B* | 6.67C |
| Significance of season | ** | ** | ** | ** | ** | ** | ns | ** | ** |

Data were means of different zones and $n = 12$. Lowercase letters indicate a comparison of growth season means within the same species. Bold capital letters, italic capital letters and capital letters indicate a comparison of means for foliar Δ, potassium (K) concentration and ash content among the different species. Bars with the same letter do not differ at $P < 0.05$ by Duncan's multiple range tests

## Discussion

Variations of foliar Δ, K concentration and ash content

The significant differences of foliar Δ, K concentration and ash content among species, growth season and micro-habitation are shown in Fig. 2 and Table 2. In the study, means of foliar Δ in *A. ordosica* and *H. scoparium* were significantly higher than that of *C. korshinskii*, suggesting that water-use efficiency (WUE) of *C. korshinskii* was significantly higher than those of *A. ordosica* and *H. scoparium* inferred from the negative correlations between Δ and WUE for many $C_3$ species (Condon et al. 1990; Wright et al. 1994; Ismail et al. 1994; Turner 1997). This result agreed with the previous report of Zhao et al. (2006). Foliar K concentration of *A.* ordos*ica*, which was significantly higher than those of *C. korshinskii* and *H. scoparium*, and suggested that *A. ordosica* has more strong stomatal behavior, osmoregulation, and cell expansion than those of *C. korshinskii* and *H. scoparium* due to high K concentration in plant tissue (Elumalai et al. 2002). The significant differences of foliar ash contents among *A. ordosica*, *H. scoparium* and *C. korshinskii* showed that the capabilities of absorbing minerals were different in those species.

Except for foliar ash content in *H. scoparium*, which was lower than those of 1956 and 1987 zones, foliar Δ and K concentrations of *A. ordosica* and *H. scoparium* were the highest in shifting sand dunes, and were the second in 1956 zone, suggesting that the physiological activities such as carbon isotope discrimination, mineral and K absorbing capacities of *A. ordosica* and *H. scoparium* in 1956 zone were stronger than those of other artificial zones. This result confirmed the report of Xiao et al (2003a, b) who reported that an artificial vegetation system showed temporary stable status after 40 years of sand-fixation.

Seasonal variations of foliar Δ, K concentration and ash content were significant, and the seasonal patterns were different in *A. ordosica*, *H. scoparium* and *C. korshinskii*. Those results may be related with the different response to variations of climatic and environmental conditions during their growth season.

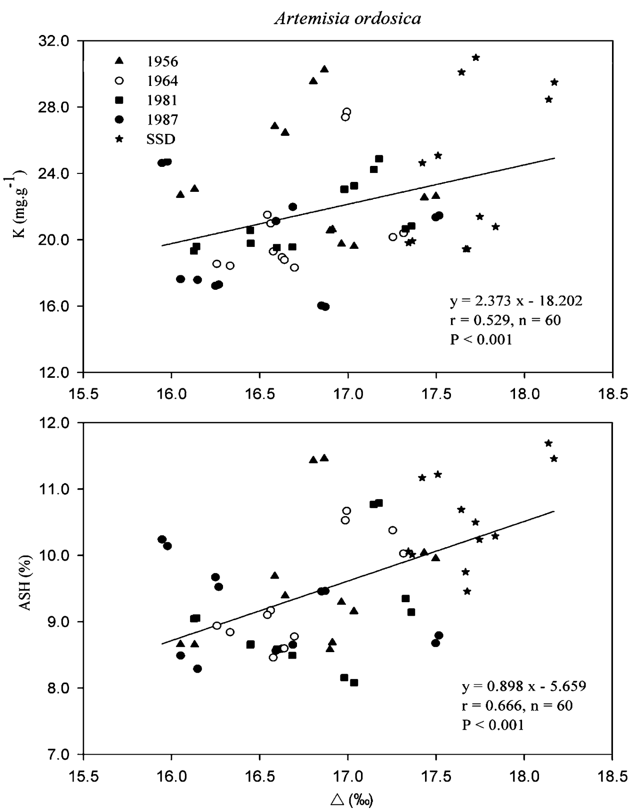


**Fig. 3** Correlations of foliar Δ with K concentration (g $kg^{-1}$) and ash content (%) in *A. ordosica*. The corresponding linear regression equations were showed in the figures. The '*a*' represents the slope of the linear regression, and thus represents the change in K concentrations and ash content increase in per unit foliar Δ (‰). The *r* represents the correlation coefficient

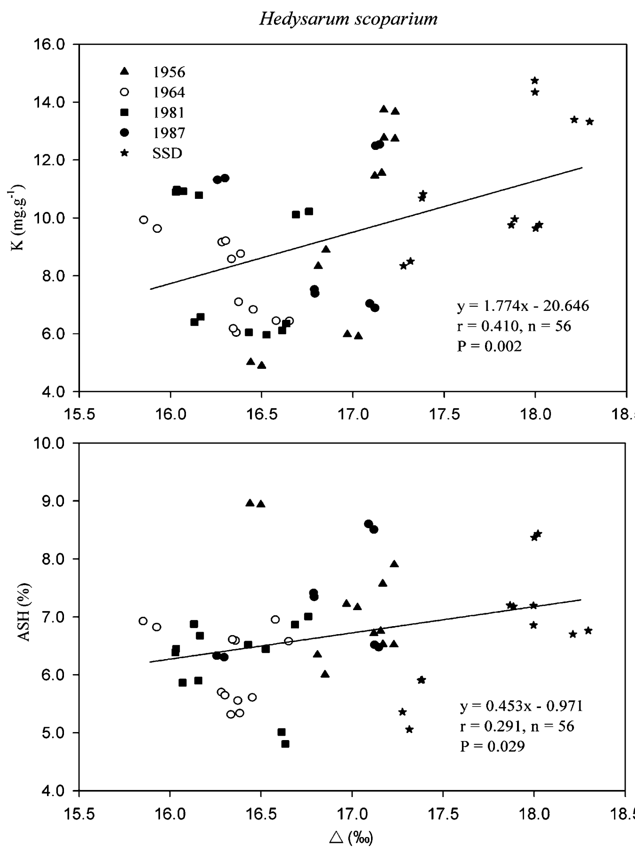


**Fig. 4** Correlations of foliar Δ with K concentration (g $kg^{-1}$) and ash content (%) in *H. scoparium*. The corresponding linear regression equations were showed in the figures. The '*a*' represents the slope of the linear regression, and thus represents the change in K concentrations and ash content increase in per unit foliar Δ (‰). The *r* represents the correlation coefficient

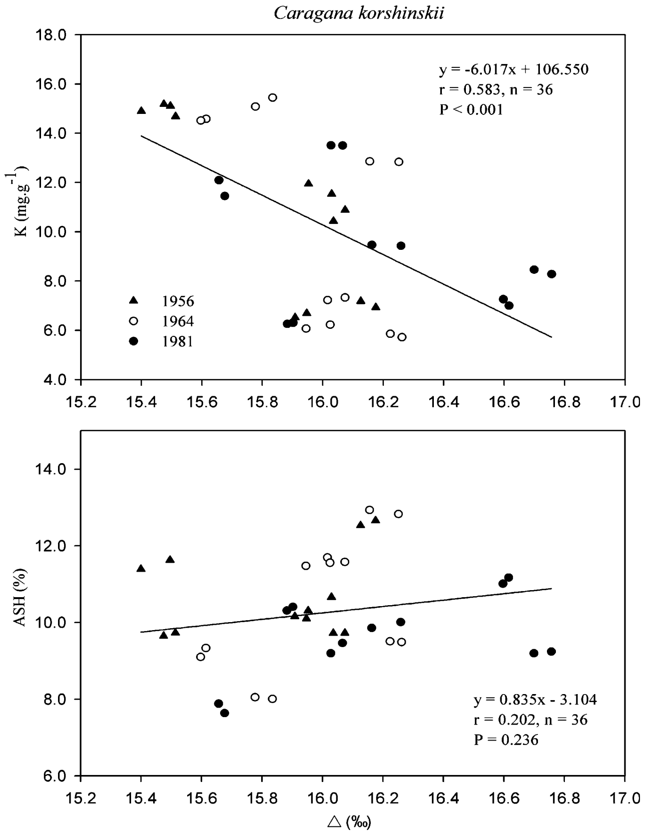


**Fig. 5** Correlations of foliar Δ with K concentration (g $kg^{-1}$) and ash content (%) in *C. korshinskii*. The corresponding linear regression equations were showed in the figures. The '*a*' represents the slope of the linear regression, and thus represents the change in K concentrations and ash content increase in per unit foliar Δ (‰). The *r* represents the correlation coefficient

The correlations of foliar Δ with foliar K concentration and ash content

A positive correlation between Δ and K concentration was found by Tsialtas et al. (2002) in grassland species. Masle et al. (1992) also reported a positive correlation in leaves of grasses. In this study, significantly positive correlations of foliar Δ with foliar K concentration were found in *A. ordosica* and *H. scoparium* (Figs. 3, 4), which was in agreement with previous studies that potassium content and Δ were related positively in wheat awns (Masle et al. 1992; Febrero et al. 1994; Merah et al. 2001). Especially, the relationship between foliar Δ and K concentration was significantly positive in *A. ordosica*. This could be due to the importance of potassium which is presents in the leaf of *A. ordosica* more than 23.0% of ash content. From the tightly positive correlations of foliar Δ with K concentration and ash content, it can be concluded that foliar K concentration and ash content can serve as selection criterion of foliar Δ in *A. ordosica* and *H. scoparium*. By contrast, foliar Δ and K concentration in *C. korshinskii* was significantly and negatively correlated within environments (Fig. 5). Similar results were also found in grain in durum wheat (Merah et al. 2001) and in bread wheat and barley (Masle et al. 1992; Febrero et al. 1994). Those results suggest that a passive transport of nutrients through the transpirative stream was not the only factor that determines mineral content in *C. korshinskii*. In addition, the relationships between foliar Δ and K concentration in *C. korshinskii* differed with its micro-habitation, showing weak positive and negative relationships under different planting regimes (Zhao et al. 2006) and different micro-habitation and planting regimes. The detailed reason may need further study.

The significantly positive relationship between Δ traits and ash content in vegetative tissues, which has been reported in the literature (Masle et al. 1992), has been observed in this study for *H. scoparium* and *A. ordosica* (Figs. 3, 4). Those results suggested that the existence of positive correlations between ash content and Δ traits indicate that their minerals are passively accumulated by the transpirational stream (Jones and Handreck 1965) of *H. scoparium* and *A. ordosica*. Similar results have been reported in bread wheat (Masle et al. 1992), barley (Voltas et al. 1998) and wheatgrass (Frank et al. 1997). By contrast, weak positive relationship between foliar Δ and ash content in *C. korshinskii* was found (Fig. 5), which suggests that mineral accumulation in *C. korshinskii* is not associated with the transpiration efficiency. This result is in agreement with work on barley (Voltas et al. 1998), and suggested that mineral accumulation is primarily regulated by processes other than transpiration, and consequently not directly related to transpirational efficiency in *C. korshinskii*.

## Conclusions

There were extremely close relationships between foliar Δ values and ash content and K concentration in *A. ordosica*. The positive correlations of foliar Δ values with ash content and K concentration in *H. scoparium* were also found. Those results verify that foliar ash content and K concentration can be suitable surrogates of foliar Δ values in *H. scoparium* and *A. ordosica*. However, ash content and K concentration do not seem to be suitable surrogates of foliar Δ values in *C. korshinskii* due to lack of positive relationships between foliar Δ values with ash content and K concentration.

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