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Metal-accumulating plants from serpentine habitats of Kızıldağ, Konya Province, Turkey

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Abstract. Serpentine (ultramafic) soils are generally deficient in essential plant nutrients such as phosphorus (P), potassium (K) and calcium (Ca) and often also have elevated concentrations of toxic trace elements such as, for example, nickel (Ni), chromium (Cr) and manganese (Mn). However, some serpentine areas have a species-rich plant cover, often with a few endemics. Thus, serpentine areas host valuable bioresources for understanding plant–metal interactions. In the present study, metal-accumulating plants from serpentine habitats in Kızıldağ, Konya Province, Turkey, viz., *Aethionema spicatum*, *Alyssum murale* ssp. *murale* var. *murale*, *Arenaria acerosa*, *Bornmuellera kiyakii*, *Cerastium macranthum*, *Dianthus crinitus*. var. *crinitus*, *Dianthus zonatus* var. *hypochlorus*, *Iberis sempervirens*, *Minuartia anatolica* var. *anatolica*, *Noccaea camlikensis*, *Saponoria kotschyi* and *Silene ozyurtii*, belonging to the families Brassicaceae and Caryophyllaceae, were investigated. All plant specimens collected were deposited in the Herbarium of the Biology Department of Akdeniz University. Samples of different plant parts, namely roots, stems, leaves and flowers, were analysed for Ni, Cr, cobalt (Co), Mn, copper (Cu), zinc (Zn), and iron (Fe) by inductively coupled plasma–optical emission spectroscopy. *Noccaea camlikensis*, *Alyssum murale* and *Bornmuellera kiyakii* accumulated 16 650 $\mu g\ g^{-1}$, 12 570 $\mu g\ g^{-1}$ and 8780 $\mu g\ g^{-1}$ Ni, respectively. *Noccaea camlikensis* is a new addition to the list of Ni hyperaccumulators. The majority of the floristic elements investigated were found to be tolerant to serpentine soil chemistry. A small proportion of the plant assemblages were endemics. Nickel hyperaccumulators were the least abundant in terms of number of species. The study assumes importance in understanding bioconcentration in different plants and, eventually, for gaining a knowledge of plant–metal interactions and applications in biogeochemistry and bioprospecting for metals, including phytoremediation.

Additional keywords: Brassicaceae, Caryophyllaceae, heavy-metal concentration, nickel, serpentinophytes.

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Introduction

Serpentine soil derived from ultramafic rocks exhibits unique biogeochemistry and contains significant elevations of some trace elements. Serpentine soils are widely distributed in different parts of the world. They are generally deficient in essential plant nutrients such as P, K and Ca. However, some serpentine areas host a rich diversity of plant species that are beneficial for making breakthrough progress in the fields of ecological restoration and possible phytoremediation of heavy metals (Brooks 1987; Reeves and Adıgüzel 2008). Serpentinophytes have been used as novel tools in the phytoremediation (or bioremediation) of heavy metals because these plants have developed specialised processes assisted by unique microflora, to flourish in some metal-contaminated environment (Rajkumar *et al*. 2009). They are potentially useful plant resources to solve environmental problems because of their ability to absorb toxic doses of heavy metals (Morel *et al*. 2006). A unique group of plants called 'hyperaccumulators' grows on serpentine soils and can accumulate remarkable concentrations of Ni in their tissues, exceeding 1000 $mg\ kg^{-1}$ Ni in the dry matter (Brooks *et al*. 1977). Some 390 plant species globally have been reported with this property (van der Ent *et al*. 2013*b*).

Complex and numerous explanations are put forward for accumulation of high metal concentrations in the shoots of hyperaccumulators. The fact that the actual mechanisms differ from family to family, among genera or even within species of the same genus is the subject of considerable research interest. The possible reasons for the evolution of such complex mechanisms have been explicitly discussed by Boyd and Martens (1992). Since then, investigations have been conducted by several other workers (e.g. Brown *et al*. 1995; Lasat *et al*. 1996).

Approximately 500 plant species are known to hyperaccumulate heavy metals and metalloids (Pollard *et al*.

2014). The family Brassicaceae has the highest number of taxa (11 genera and 87 species) that have been established as hyperaccumulators of any metal. In the Brassicaceae, Ni hyperaccumulation has been reported in seven genera and 72 species and Zn hyperaccumulation in three genera and 20 species (Reeves *et al*. 1999; Prasad and Freitas 2003). Until 2012, ~400 Ni hyperaccumulators had been reported in different parts of the world (van der Ent *et al*. 2013*a*, 2013*b*). Of these, ~25% (~100) are known from the Mediterranean region. The Brassicaceae and Asteraceae are particularly rich in Ni hyperaccumulators (Brooks *et al*. 1979; Reeves and Baker 2000; Reeves and Adıgüzel 2004). Mediterranean Ni hyperaccumulators in the Brassicaceae comprise the monospecific *Leptoplax emarginata* (= *Peltaria emarginata*) in Greece (Reeves *et al*. 1980), and the Turkish *Pseudosempervivum aucheri* and *P. sempervivum* (Reeves 1988).

Adıgüzel and Reeves (2012) explored 55 serpentine sites and 60 Ni-accumulating and more than 40 serpentine-endemic species have been reported from these Turkish serpentines.

In the present study, concentration of heavy metals in different organs (roots, stems, leaves and flowers) and in soil of 12 taxa growing in ultramafic soils were investigated. An attempt was made to understand the heavy-metal (Ni, Cr, Mn, Cu, Co, Zn, Fe) uptake behaviour in these plant taxa. Investigations conducted by the present authors (Aksoy *et al.* 2012) and other workers at Kızıldağ, Derebucak (Konya), during the past two decades resulted in notifying this site as a serpentine location of considerable significance. The special flora established at this location makes it one of the prime locations for serpentine flora in Turkey, ranking it on a par with such other better-known areas as Belen–Güzelyayla in the Amanus Mountains, the Pülümür Pass, the Altınyayla–Dirmil Pass area, and the Köyceğiz–Sandrasdağ-Marmaris.

The Kızıldağ flora is of interest with reference to serpentinophytes, as a model system for ecology and diversity of metallophytes for the following reasons (Harrison and Rajakaruna 2011):

(1) Discovery and publication relating to the new species *Bornmuellera kiyakii* (Aytaç and Aksoy 2000). This is the highlight of the present study.

(2) Plants and soils have been collected from this area by different researchers (Reeves *et al*. 2001, 2009; Reeves and Adıgüzel 2004, 2008). Reeves *et al*. (2009) established the Ni-hyperaccumulation status of *B. kiyakii*, and also provided further analytical data for the known Ni-hyperaccumulators *Alyssum murale*, *A. peltarioides*, *Pseudosempervivum sempervivum* and *Thlaspi elegans*, as well as data for a set of associated soil samples. It is noteworthy that, in Turkey, all genera of the Brassicaceae that exhibit Ni hyperaccumulation occur in a very small area.

(3) *Thlaspi elegans*, a related plant, was described as a new species (*Noccaea camlikensis*) from this area by Aytaç *et al.* (2006). *Noccaea camlikensis* appears to be very closely related to *Thlaspi cariense* (now *Noccaea cariense*), which was established as a Ni hyperaccumulator in 2001 (Reeves *et al*. 2001).

(4) Reeves and Adıgüzel (2008) suggested that *N. camlikensis* is likely to be a Ni hyperaccumulator. This prediction is confirmed by the results of the present study.

(5) The extensive collections made by Aksoy *et al*. (2008) suggest that Kızıldağ (Çamlık Village, Derebucak-Konya) could be a paradise for endemic serpentinophytes and these plant resources need to be conserved for possible utilisation for genomic diversity in the future.

Materials and methods

Materials

The study site is quite extensive and not uniform in its topography and vegetation. This is an area of ultramafic soils, with pine forest, steep slopes and grassy meadow-like areas; soils are very variable in both their depth and texture. Different species clearly favour different environments within the overall site. The ultramafic area of Kızıldağ ('red mountain'), lying in the Province of Konya in Turkey, is prominent from several points at a distance because of its colour set in a largely limestone landscape. Kızıldağ is located between 37°20N and 37°22N and 31°39E and 31°42 E, and between 1300 and 2000 amsl (Fig. 1).

Soils and the individuals of the following plant taxa were collected from this serpentine habitat in early July 2010: *Dianthus zonatus* Fenzi var. *hypochlorus* (Boiss. & Heldr) Reeves (*Aksoy 2377*), *Alyssum murale* Waldst. & Kit. subsp. *murale* var. *murale* (*Aksoy 2376*), *Dianthus crinitus* Sm. var. *crinitus* (*Aksoy 2378*), *Iberis sempervirens* L. (*Aksoy 2366*), *Aethionema spicatum* Post. (*Aksoy 2368*), *Saponoria kotschyi* Boiss. (*Aksoy 2369*), *Cerastium macranthum* Boiss. (*Aksoy 2370*), *Minuartia anatolica* (Boiss) Woron. var. *anatolica* (*Aksoy 2371*), *Bornmuellera kiyakii* Aytaç & Aksoy (*Aksoy 2372*), *Noccaea camlikensis* Aytaç, Nordt & Parolly (*Aksoy 2373*), *Arenaria acerosa* Boiss. (*Aksoy 2374*) and *Silene ozyurtii* Aksoy & Hamzaoğlu (*Aksoy 2375*) (Table 1). The specimens collected were deposited in the Herbarium of the Biology Department of Akdeniz University.

Sampling

Soils were taken from the 0–5-cm zone, returned to the laboratory, sieved with a standard 4-mm sieve and air-dried. At least 15 adult plants were randomly selected and collected from each site. Five plants were retained as herbarium specimens. Ten plants from each site were divided into above- and below-ground parts. These were transferred to the laboratory in plastic bags. Plant samples were carefully separated into roots, stems, leaves and flowers, and washed with tap water, followed by deionised water. They were dried in an oven (80°C) until constant weight and brittleness. The samples were subsequently ground with a pestle and mortar. Homogenised plant materials and soil samples were then stored in clean paper bags before heavy-metal analysis.

Chemical and statistical analyses

Soil samples (0.5-g dry weight) were digested with 10 mL of pure HNO_3 (65%), using a CEM–MARS 5 (CEM Corporation, Matthews, NC, USA) microwave digestion system (digestion conditions were the following: maximum power 1200 W; power 100%; ramp time 20 min, pressure 180 psi; temperature 180°C; and hold time 10 min). After digestion, the volume of each sample

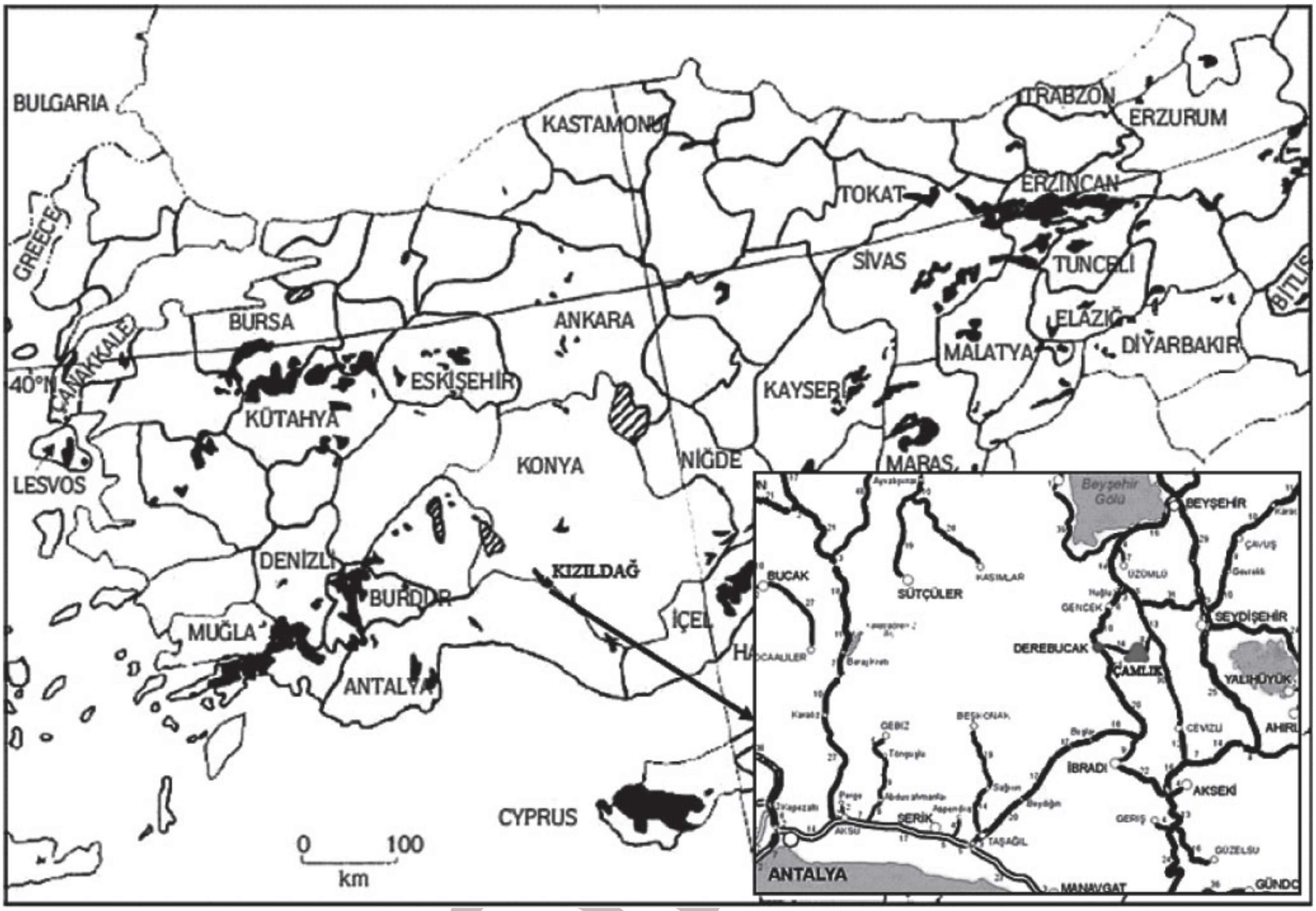

Fig. 1. Map of Turkey, showing areas of ultramafic geology (in black) and the study area. The map is adopted from Reeves and Adıgüzel (2004).

Table 1. Study area and plant collection localities

Species	Locality	GPS coordinates	Altitude (m)
Iberis sempervirens L.	Konya Derebucak, Çamlık village, around summit	37°21′00″N, 31°40′46″E	1882
Aethionema spicatum Post.	Konya Derebucak, Çamlık village, around summit	37°20′86″N, 31°40′45″E	1915
Saponoria kotschyi Boiss.	Konya Derebucak, Çamlık village, Üçoluk	37°21′09″N, 31°39′58″E	1580
Cerastium macranthum Boiss.	Konya Derebucak, Çamlık village, around summit	37°21′00″N, 31°40′46″E	1882
Minuartia anatolica (Boiss) Woron. var. *anatolica*	Konya Derebucak, Çamlık village, around summit	37°20′68″N, 31°40′97″E	1950
Bornmuelleria kiyakii Aytaç & Aksoy	Konya Derebucak, Çamlık Village, transmitter climbing from Kızılbel to summit	37°21′36″N, 31°40′92″E	1635
Noccaea camlikensis Aytaç, Nordt & Parolly	Konya Derebucak, Çamlık Village, transmitter climbing from Kızılbel to summit	37°21′36″N, 31°40′92″E	1635
Arenaria acerosa Boiss.	Konya Derebucak, Çamlık village, around summit	37°20′68″N, 31°40′97″E	1950
Silene ozyurtii Aksoy & Hamzaoğlu	Konya Derebucak, Çamlık village, Üçoluk	37°21′29″N, 31°39′50‴E	1410
Dianthus zonatus Fenzi var. *hypochlorus* (Boiss.and Heldr) Reeve	Konya Derebucak, Çamlık village, around summit	37°20′86″N, 31°40′45″E	1915
Alysum murale Waldst. and Kit. subsp. *murale* var. *murale*	Konya Derebucak, Çamlık village, around summit	37°20′86″N, 31°40′45″E	1915
Dianthus crinitus Sm. var. *crinitus*	Konya Derebucak, Çamlık village, Üçoluk	37°21′09″N, 31°39′58″E	1580

was adjusted to 25 mL by using double-deionised water. Homogenised plant samples (0.5-g dry weight) were also prepared using the same procedure as for heavy-metal analysis. The soil and plant samples were analysed for Ni, Cr, Mn, Cu, Co, Zn and Fe by inductively coupled plasma–optical emission spectroscopy (ICP–OES; Varian-Liberty II Varian Australia Pty Ltd, Mulgrave, Vic., Australia). All chemicals were of analytical reagent grade. Standard peach leaves (NIST, SRM-1547) were used as a reference material. All analytical procedures were also performed using this reference material.

Soil and plant samples were digested repeatedly three times and analysed. The means and standard deviation (s.d.) of the data were calculated by using the SPSS 15.00 version package (SPSS Inc., Chicago, IL, USA).

Results and discussion

Mean heavy-metal (Ni, Cr, Mn, Cu, Co, Zn and Fe) concentrations in soils and different organs of the species sampled are given in Tables 2 and 3. The soils are of typical ultramafic composition, with high concentrations of Fe, Mn, Ni, Cr and Co, but the concentrations of Cu and Zn were in the range similar to 'normal' soils.

Reeves *et al.* (2009) reported the metal concentration in soil of Kızıldağ (Table 4). Their data for the concentrations of Cr, Co, Cu, Zn and Mn in soil are similarly high, except their Fe value is higher than in our results. This difference may be due to different collection sites for the soils analysed. The concentrations of Ni in

Table 2. Mean ± s.d. concentration of nickel (Ni), chromium (Cr), cobalt (Co), manganese (Mn), copper (Cu), zinc (Zn) and iron (Fe) in the parts of plants collected from serpentine soils in Kızıldağ (mg kg^{-1} dry weight)

R = root, S = stem, L = laf, F = flower

Species	Plant part	Ni	Cr	Co	Mn	Cu	Zn	Fe
I. sempervirens	R	182 ± 1.2	3.53 ± 0.2	10.49 ± 2.1	121 ± 8.1	9.20 ± 1.4	57.70 ± 3.4	655 ± 12
	S	19 ± 1.3	2.65 ± 0.5	7.75 ± 2.4	38 ± 4.5	5.64 ± 0.4	10.87 ± 2.1	325 ± 5.4
	L	18 ± 1.7	4.18 ± 1.0	8.37 ± 1.4	64 ± 3.4	9.10 ± 2.1	12.93 ± 1.4	680 ± 7.4
	F	18 ± 2.4	3.82 ± 1.5	10.05 ± 2.4	47 ± 2.4	7.70 ± 0.4	22.60 ± 3.1	385 ± 5.4
A. spicatum	R	425 ± 4.1	9.73 ± 0.3	13.18 ± 1.4	205 ± 14	9.62 ± 1.2	46.19 ± 2.5	6050 ± 45
	S	200 ± 4.5	2.53 ± 1.4	32.45 ± 6.4	146 ± 7.4	5.76 ± 0.5	43.60 ± 4.2	675 ± 7.1
	L	472 ± 6.9	3.83 ± 1.4	54.05 ± 9.1	6261 ± 16	18.57 ± 4.1	54.11 ± 5.7	864 ± 6.4
	F	222 ± 8.4	10.19 ± 2.1	6.30 ± 1.8	420 ± 9.8	6.48 ± 0.5	39.32 ± 5.7	1632 ± 10
S. kotschyi	R	123 ± 2.5	29.19 ± 3.1	8.11 ± 0.4	105 ± 10	16.52 ± 2.4	18.19 ± 1.8	3220 ± 17
	S	235 ± 6.4	23.65 ± 7.5	20.54 ± 4.1	104 ± 3.1	14.65 ± 2.4	13.70 ± 1.6	2655 ± 10
	L	257 ± 10	35.91 ± 12.3	29.35 ± 5.4	144 ± 8.7	19.50 ± 6.1	16.67 ± 2.4	5546 ± 14
	F	716 ± 7.5	59.05 ± 10.1	30.27 ± 8.4	400 ± 7.4	23.17 ± 5.4	36.75 ± 4.1	16 380 ± 47
C. macranthum	R	165 ± 3.5	21.43 ± 5.4	8.57 ± 0.5	253 ± 14	10.40 ± 1.5	45.64 ± 2.4	3270 ± 21
	S	91 ± 5.2	6.48 ± 1.4	5.47 ± 0.4	42 ± 2.5	7.40 ± 2.1	17.23 ± 1.2	294 ± 0.8
	L	231 ± 14	26.79 ± 11.4	10.25 ± 1.4	558 ± 17	8.54 ± 2.1	53.16 ± 9.1	2475 ± 5.4
	F	62 ± 1.5	0.99 ± 0.1	5.26 ± 1.4	130 ± 5.2	7.60 ± 1.4	30.71 ± 2.5	1147 ± 5.8
M. anatolica	R	537 ± 8.5	42.96 ± 2.4	4.00 ± 0.5	374 ± 15	12.52 ± 2.4	26.82 ± 1.9	12 205 ± 56
	S	38 ± 3.2	2.11 ± 0.2	4.88 ± 0.2	49 ± 2.8	8.70 ± 1.8	15.48 ± 1.4	565 ± 2.4
	L	45 ± 2.4	3.41 ± 2.1	2.19 ± 0.1	142 ± 15	8.20 ± 1.7	22.01 ± 4.1	660 ± 2.4
	F	78 ± 4.5	0.16 ± 0.2	11.36 ± 2.3	189 ± 6.4	14.20 ± 3.1	33.44 ± 3.5	3363 ± 6.4
B. kiyakii	R	2679 ± 18	8.42 ± 0.9	6.36 ± 2.1	88 ± 8.4	20.03 ± 2.6	82.34 ± 8.7	2882 ± 31
	S	2411 ± 21	1.35 ± 0.1	4.76 ± 0.1	20 ± 1.2	18.06 ± 2.4	12.68 ± 0.9	165 ± 0.4
	L	8785 ± 27	3.54 ± 1.2	7.35 ± 1.3	47 ± 3.4	9.08 ± 1.4	24.08 ± 2.4	313 ± 1.5
	F	5460 ± 9.1	0.89 ± 0.4	4.94 ± 05	28 ± 2.3	7.65 ± 2.1	15.04 ± 0.1	127 ± 2.8
N. camlikensis	R	2580 ± 21	20.93 ± 5.7	9.13 ± 1.8	91 ± 9.1	13.29 ± 1.8	35.04 ± 3.5	6724 ± 14
	S	2737 ± 18	1.32 ± 0.6	6.98 ± 1.4	24 ± 1.4	9.30 ± 1.4	89.88 ± 7.4	1015 ± 4.2
	L	16 655 ± 31	30.30 ± 9.5	35.00 ± 4.7	260 ± 9.4	19.76 ± 2.1	136.96 ± 12	14 745 ± 24
	F	10 360 ± 28	11.69 ± 2.5	11.21 ± 1.8	31 ± 3.1	8.16 ± 0.4	68.77 ± 8.1	682 ± 2.5
A. acerosa	R	390 ± 10	29.82 ± 8.5	5.41 ± 1.4	541 ± 15	5.90 ± 0.4	24.27 ± 2.8	10 455 ± 41
	S	85 ± 4.1	2.18 ± 1.4	0.57 ± 0.1	185 ± 15	4.70 ± 0.6	17.11 ± 1.5	2213 ± 8.4
	L	45 ± 1.2	14.87 ± 2.4	0.16 ± 0.1	275 ± 8.7	3.20 ± 03	18.70 ± 1.7	870 ± 6.4
	F	91 ± 6.1	35.27 ± 6.4	0.76 ± 0.2	229 ± 9.4	6.10 ± 0.2	30.61 ± 4.6	2330 ± 3.5
S. ozyurtii	R	157 ± 8.4	10.74 ± 1.7	9.63 ± 2.1	411 ± 21	5.40 ± 0.9	33.21 ± 2.4	3293 ± 12
	S	14 ± 2.5	33.08 ± 11.2	3.58 ± 1.0	51 ± 6.4	8.40 ± 2.4	12.03 ± 1.2	305 ± 4.2
	L	30 ± 2.5	13.79 ± 3.1	7.99 ± 1.5	93 ± 6.5	8.70 ± 1.4	15.74 ± 0.8	665 ± 2.4
	F	46 ± 1.4	31.89 ± 5.4	21.31 ± 7.1	163 ± 4.1	10.20 ± 1.4	27.31 ± 2.4	1063 ± 1.8
D. zonatus	R	68 ± 2.1	3.80 ± 0.6	0.92 ± 0.1	284 ± 9.2	9.10 ± 1.4	23.18 ± 1.5	1001 ± 10
	S	19 ± 1.2	1.15 ± 0.1	0.59 ± 0.2	147 ± 12	4.00 ± 0.4	13.09 ± 0.9	181 ± 3.1
	L	38 ± 3.4	1.25 ± 0.4	0.65 ± 0.2	295 ± 11	4.10 ± 1.2	19.44 ± 1.4	191 ± 1.9
	F	20 ± 0.9	1.06 ± 0.3	0.57 ± 0.2	282 ± 8.5	4.80 ± 0.4	16.18 ± 1.2	139 ± 1.6
A. murale	R	5570 ± 17	4.09 ± 0.4	1.72 ± 0.4	34 ± 2.3	5.50 ± 0.8	90.41 ± 6.4	925 ± 9
	S	3938 ± 54	1.80 ± 0.3	0.81 ± 0.1	20 ± 1.4	5.40 ± 0.3	82.75 ± 7.1	361 ± 2.4
	L	12 570 ± 12	2.12 ± 0.2	17.67 ± 3.1	64 ± 5.4	4.00 ± 0.4	94.60 ± 9.1	465 ± 7.4
	F	8290 ± 12	1.58 ± 0.4	7.60 ± 2.1	39 ± 1.7	1.70 ± 0.2	70.30 ± 7.1	172 ± 1.7
D. crinitus	R	143 ± 5.4	9.12 ± 2.1	5.42 ± 0.2	104 ± 4.2	3.30 ± 0.4	13.87 ± 2.1	2747 ± 11
	S	16 ± 1.4	1.17 ± 0.5	0.33 ± 0.1	21 ± 1.2	2.00 ± 0.1	9.39 ± 0.2	225 ± 1.8
	L	33 ± 6.1	1.68 ± 0.5	0.25 ± 0.1	38 ± 2.8	1.80 ± 0.1	13.20 ± 0.8	295 ± 2.8
	F	16 ± 2.4	0.67 ± 0.2	0.17 ± 0.1	47 ± 2.1	1.10 ± 0.1	15.15 ± 0.8	80 ± 1.1

Table 3. Mean ± s.d. total element concentrations (mg kg^{-1}) in serpentine soils of Kızıldağ, (Konya)

Species	Ni	Cr	Co	Mn	Cu	Zn	Fe
Iberis sempervirens	2900 ± 32	153 ± 4.5	144 ± 1.2	1650. ± 15	29.54 ± 0.8	78.98 ± 3.2	63 530 ± 102
Aetionema spicatum	2890 ± 22	162 ± 1.7	104 ± 0.5	1010 ± 11	23.44 ± 0.2	60.27 ± 3.1	75 370 ± 145
Saponaria kotschyi	2420 ± 14	207 ± 6.5	134 ± 0.7	1153 ± 18	12.22 ± 0.1	70.69 ± 3.5	84 500 ± 184
Cerastium macranthum	1830 ± 45	310 ± 1.4	93 ± 1.1	1070 ± 21	8.37 ± 2.1	71.83 ± 6.1	73 920 ± 196
Minuartia anatolica	1960 ± 15	233 ± 1.6	102 ± 2.1	1140 ± 22	10.12 ± 1.2	73.97 ± 2.4	84 780 ± 112
Bornmuelleria kiyakii	1540 ± 18	201 ± 5.1	60 ± 4.3	953 ± 13	8.56 ± 1.0	69.24 ± 5.1	68 400 ± 125
Noccaea camlikensis	1950 ± 52	317 ± 8.9	98 ± 2.5	1146 ± 22	11.49 ± 0.9	75.53 ± 3.1	84 820 ± 154
Arenaria acerosa	2260 ± 64	290 ± 4.5	116 ± 3.4	1154 ± 20	11.65 ± 2.5	70.74 ± 1.2	57 670 ± 123
Silene ozyurtii	1650 ± 33	242 ± 7.5	78 ± 8.1	977 ± 11	7.45 ± 0.8	63.30 ± 5.4	84 870 ± 184
Dianthus zonatus	2010 ± 84	172 ± 5.3	112 ± 4.1	961 ± 10	10.19 ± 0.6	58.91 ± 2.1	58 920 ± 142
Alyssum murale	1530 ± 26	258 ± 2.4	78 ± 2.5	892 ± 14	6.98 ± 1.2	59.86 ± 3.1	53 850 ± 156
Dianthus crinitus	1640 ± 12	194 ± 4.2	85 ± 1.5	950 ± 8.4	8.43 ± 1.0	61.64 ± 2.8	70 650 ± 121

Table 4. Comparisons of total element concentrations (mg kg^{-1}) in serpentine soils of Kızıldağı reported by Reeves *et al.* (2009) and those in the present study

Kızıldağı soil element	Present study	Reeves *et al.* (2009)
Ni	1530–2900	2404–2833
Cr	153–317	404–561
Co	60–144	123–177
Mn	892–1650	1225–1615
Cu	7.5–30	21–60
Zn	59–79	109–214
Fe	53 850–84 870	7.28–8.99%

soils were similar to those of Reeves *et al*. (2009). These authors also reported that the soils were low in the nutrients K and P, and had high concentrations of Mg and low concentrations of Ca.

The Ni concentration in the investigated plants ranged from 16 to 16 650 mg kg^{-1}. Ni concentrations in different plants parts are shown in Table 3. In the dry matter of the leaves, Ni concentration was up to 16 650 mg kg^{-1} in *N. camlikensis*, 12 570 mg kg^{-1} in *A. murale*, and 8780 mg kg^{-1} in *B. kiyakii*. Thus, *N. camlikensis* can be considered as new Ni hyperaccumulator. Nickel accumulation by *B. kiyakii* clearly confirmed this species as a Ni hyperaccumulator (Reeves *et al*. 2009). Extremely high concentrations of Ni have been reported in *B. tymphaea* and *B.* × *Petri* (sterile hybrid) from northern Greece, *B. baldaccii* from Greece and Albania, and in *B. glabrescens* from Masmeneu Mountain (Niğde), near Kayseri in Turkey (Reeves *et al*. 1983).

Bornmuellera tymphaea (31 200 mg kg^{-1}), *B. baldaccii* (27 300 mg kg^{-1}), *B.* × *Petri* (11 400 mg kg^{-1}) and *B. glabrescens* (19 200 mg kg^{-1}) leaves accumulated large amounts of Ni. However, *B. cappadocica* and *B. angustifolia* accumulated very little Ni in their leaves and these species have not been observed on serpentine habitats (Reeves and Adıgüzel 2004). Among the *Alyssum* species in Turkey, the hyperaccumulators include two varieties of *A. murale* subsp. *murale* (var. *murale* and var. *haradjianii*; Reeves and Adıgüzel 2008). *Aethionema spicatum* occurs on serpentine habitats in Turkey, and high-Ni specimens have been recorded from the Hamidiye–Gerdibi region of Seyhan province (Ni concentrations were 764 mg kg^{-1} in 1986 and 1111 mg kg^{-1} in 1988). This species can, therefore, be regarded as marginally Ni hyperaccumulating (Reeves *et al*. 2001). In our study, Ni concentrations in the leaf dry matter reached 472 mg kg^{-1} in *A. spicatum*.

Chromium concentrations in the investigated plants varied between 0.16 and 59 mg kg^{-1}. In the dry matter of the flowers, Cu amount reached concentrations of 59 mg kg^{-1} in *S. kotschyi* (Table 2). Co and Zn in the Ni-hyperaccumulator plants from Kızıldağ were higher than for other reported plants (Table 2).

Reeves *et al.* (2009) studied Co, Cr, Cu, Fe and Zn concentrations of 23 plants (including: *B. kıyakii*, *Alyssum murale* subsp. *murale* and *Thlaspi elegans*, which has recently been described as a new species, *N. camlikensis*) from Kızıldağ. Their findings are compared with those of the present study in Table 5.

The plants sampled from Kızıldağ had Mn concentrations exceeding 15 mg kg^{-1}. The highest value of 626 mg kg^{-1} was measured in *A. spicatum* leaf dry matter (Table 2). The Cu concentrations were within the 1–23 mg kg^{-1} range in all plant samples. However, in the dry matter of flowers of *S. kotschyi*, a concentration of 23 mg kg^{-1} was detected (Table 2). The Fe concentrations were >80 mg kg^{-1} and in the flower dry matter, the concentration of Fe was up to 16 380 mg kg^{-1} in *S. kotschyi* (Table 2). Some investigations have reported unusually high concentrations of metals such as Cr, Mn, Cu, Co and Fe in the flowers, as opposed to roots, leaves and stems of *S. kotschyi* and *Silene ozyurtii* (Tables 2, 5). One possible reason for this is that the flowers of these plants are covered with dense glandular hairs. Heavy-metal particulates released by wind erosion from the soil adhere to the glandular hairs on the plants, leading to surface accumulation and spurious concentrations in the actual dry matter.

The present study has clearly demonstrated that *Noccaea camlikensis* is a Ni hyperaccumulator, and thus, an addition to the existing list of Ni hyperaccumulators. Furthermore, the Ni-hyperaccumulator status of two species, namely, *Alyssum murale* subsp. *murale* var. *murale* and *Bornmuellera kiyakii*, was also confirmed. Some of the Ni-hyperaccumulating species in Turkey could potentially be useful as a plant resource for studies related to phytoremediation and phytomining.

Serpentine soils host a spectacular level of plant endemism in many regions. Furthermore, serpentine soil is an edaphically stressful, low-productivity soil type that hosts stunted vegetation and often a spectacular level of plant endemism (Anacker 2014). The serpentine flora of Kızıldağ has been studied previously (Aksoy *et al.* 2008). These authors found 188 serpentine and 66

Table 5. Comparisons of total element concentrations (mg kg^{-1}) of collected plants of Kızıldağı reported by Reeves *et al.* (2009) and those in the present sutey

Species	Study	Ni	Cr	Co	Mn	Cu	Zn	Fe
Noccaea camlikensis	Present	16 655	30.30	35	260	19.78	136	1474
	Reeves *et al*. 2009	13 340	3.4	8.1	35	1.8	59	1110
Bornmuelleria kiyakii	Present	18 785	3.54	7.35	47	9.8	24	127
	Reeves *et al*. 2009	4400–12 590	–	3.6–253	–	–	8–53	39–408
Alysum murale ssp.	Present	12 575	2.2	17.67	64	4.0	94	172
murale var. *murale*	Reeves *et al*. 2009	7890	2.0	5.8	16	1.3	0	371

endemic species (11 new species recently described from Kızıldağ). Many of the species (hyperacumulators, such as *Noccaea camlikensis* and *Bornmuelleria kiyakii*) are very restricted in their distribution, and some are known from only one locality. These plants grow only in the serpentine soil of Kızıldağ in Turkey. Attention should be paid to the conservation of these unusual and potentially valuable plant resources (Adıgüzel and Reeves 2012).

Conclusions

(i) *Noccaea camlikensis* is now established as a Ni hyperaccumulator.

(ii) Additional analyses have been presented for two other known Ni hyperaccumulators (*A. murale* and *B. kiyakii*), confirming their status as Ni hyperaccumulators.

(iii) Analyses have been presented for some associated non-accumulator plants from the Kızıldağ site, to add to the earlier reported data of Reeves *et al*. (2009) (Table 3).

(iv) The species tolerant to serpentine soil at Kızıldağ can be considered as 'excluders', maintaining relatively low metal concentration in their roots, stems, leaves and flowers, even when the soil metal concentrations are very high.

(v) The serpentine flora of Kızıldağ is rich in species and in endemics, with several examples of Ni hyperaccumulators, and, therefore, efforts should be made to protect the site and to conserve its flora.

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