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The Nickel Hyperaccumulating Plants of the Serpentines of Turkey and Adjacent Areas: A Review with New Data

Roger D. REEVES[1], Nezaket ADIGÜZEL[2]

[1]School of Botany, University of Melbourne, Melbourne - AUSTRALIA

[2]Faculty of Arts and Science, Department of Biology, Gazi University, Ankara - TURKEY

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Abstract: Botanical exploration of serpentine soils in Turkey and neighbouring countries has shown that the region includes at least 59 taxa capable of hyperaccumulating nickel (to >0.1% of plant dry weight). These hyperaccumulators belong to the Brassicaceae (*Aethionema* R.Br., *Alyssum* L., *Bornmuellera* Hausskn., *Pseudosempervivum* (Boiss.) Grossh. (*Cochlearia* L.), and *Thlaspi* L. s.l.) and the Asteraceae (*Centaurea* L.). We review present knowledge of the hyperaccumulators and provide additional data recently obtained. Some species are serpentine-endemic and invariably Ni hyperaccumulating; others show more complex distribution and Ni-accumulating behaviour. Many are good subjects for biochemical studies on the Ni-accumulation and sequestering processes. There is potential in Turkey for exploiting Ni hyperaccumulation for remediation of Ni-contaminated soils ('phytoremediation') and for economical selective extraction of metal compounds by cropping hyperaccumulators ('phytomining'). However, there is a need for further exploration of the natural resources and some further taxonomic work by traditional and DNA methods. Attention must be paid to conservation issues, as some of the relevant species are quite rare.

Key Words: Nickel, serpentine, hyperaccumulation, phytoremediation, phytomining, *Alyssum*, *Thlaspi*, *Centaurea*

Türkiye ve Komşu Ülke Serpantin Alanlarının Aşırı Nikel Biriktiren Bitkileri

Özet: Türkiye ve komşu ülkelerin serpantin topraklarında yapılan botanik araştırmalar göstermiştir ki, bölgede en az 59 takson aşırı nikel biriktirme özelliğine sahiptir (bitkinin kuru ağırlığının > 0,1 % kadar). Bu taksonlar, Brassicaceae (*Aethionema*, *Alyssum*, *Bornmuellera*, *Pseudosempervivum* (*Cochlearia*) ve *Thlaspi* s.l.) ve Asteraceae (*Centaurea*) familyalarına aittir. Biz bu hiperakümülatörlerle ilgili var olan bilgilerimizi yeniden gözden geçirerek son zamanlarda eklenen bilgileri vermekteyiz. Bazı türler serpantin endemiğidir ve her zaman nikel hiperakümülatörüdürler. Diğer türler, daha kompleks bir dağılım ve nikel biriktirme davranışı gösterirler. Çoğu, nikel biriktirme ve ayırma işlemleri üzerinde yapılacak biyokimyasal çalışmalar için güzel konulardır. Türkiye nikel hiperakümülatörler bakımından önemli bir potansiyele sahiptir; nikel bulaşmış toprakların bitkisel yolla temizlenmesi için nikel hiperakümülasyonundan yararlanmada ve hiperakümülatörleri kullanarak ekonomik olarak metal bileşiklerinin çıkarılmasında yapılacak çalışmalar gibi. Gelecekte, geleneksel ve DNA metotlarıyla bazı taksonomik çalışmalara ve doğal kaynakların araştırılmasına gereksinim vardır. İlgili türlerin bazıları oldukça nadirdir, bu nedenle koruma konularına özen gösterilmelidir.

Anahtar Sözcükler: Nikel, serpantin, hiperakümülasyon, fitoremediasyon, bitkisel madencilik, *Alyssum*, *Thlaspi*, *Centaurea*

Introduction

Ultramafic rocks, characterised by high concentrations of Fe and Mg, occur in many parts of the world, and are a notable feature of the geology of some countries and regions, including California, New Caledonia, Cuba, central Brazil, parts of Mediterranean Europe, and Turkey. These rocks, and the soils derived from them, also carry abnormally high levels of other elements such as Ni, Co, and Cr; the mineral assemblage often includes the hydrated Mg silicate mineral known as serpentine, and the soils are often referred to as serpentine soils.

The unusual chemistry of these soils, which generally are moderately to extremely deficient in essential plant nutrients such as Ca, K, and P, often support a flora that is recognisably different from that of adjacent areas of different geology. The serpentine floras can consist of a restricted range of species found nearby, but may also contain some species that are strictly endemic to serpentine soils. Serpentine areas are therefore especially interesting to botanists as well as geochemists. The interaction of plants with serpentine soils has been detailed in several books published during the last 20 years (1-4).

One of the most interesting aspects of plant behaviour on serpentine soils is the way they respond to the elevated levels of nickel in the soil. Normal soils contain about 7-50 mg/kg Ni; plants on these soils generally contain Ni at levels of about 0.2-8 mg/kg in the dry leaf tissue. Serpentine soils can have Ni at levels about 100 times greater, i.e. from about 700 to 5000 mg/kg, and most of the plants that survive on these soils show Ni concentrations about 10 times higher than elsewhere, i.e. from about 2 to 80 mg/kg. However, a small proportion of plant species on serpentine (perhaps 1%-2% of species on serpentine worldwide) show an extraordinarily high uptake of Ni from the soil – well over 1000 mg/kg (0.1%) and sometimes even more than 10,000 mg/kg (1%). Some of these species are discussed in more detail below.

Extreme accumulation of nickel by a serpentine plant was first observed by Minguzzi and Vergnano (5) in Italy in 1948, who found this behaviour in *Alyssum bertolonii* Desv. (Brassicaceae). During the subsequent 20 years a similar observation was made in relation to *A. murale* Waldst. & Kit. growing in Armenia (6) and a subspecies of *A. serpyllifolium* Desf. in north-eastern Portugal (7). In the early 1970s other discoveries of Ni-accumulating plants were made in Rhodesia (now Zimbabwe) (8), Western Australia (9,10), and New Caledonia (11). One of the serpentine species of New Caledonia was the tree *Sebertia acuminata:* Pierre ex Baill, which was reported in 1976 by Jaffré et al. (12) to contain an extraordinary latex with about 20% Ni in the dry matter; this extreme Ni accumulation was described here as 'hyperaccumulation'. The term was clarified later (13,14) by defining as hyperaccumulators those species that can be found with more than 1000 mg/kg Ni in some above-ground tissue (usually leaves, but sometimes latex) in plants growing in their natural habitat.

The 3 scattered early observations about the Ni in *Alyssum* species led Brooks and Radford (15) to examine Ni concentrations in many European species of the genus, a number of which are found on serpentine outcrops. They showed that Ni hyperaccumulation in *Alyssum* was much more widespread than previously known. Extension of this work to almost all of the world's *Alyssum* species by Brooks et al. (16) showed that at least 48 taxa, all in 1 section (sect. Odontarrhena), exhibited Ni hyperaccumulation. The importance of this observation to the study of the Turkish flora is indicated by the fact that just over half of all the *Alyssum* species and just over half of the hyperaccumulators occur in Turkey, with some others in nearby regions (certain Greek islands, the Greek mainland, Bulgaria, Armenia, and parts of Iraq and Iran).

Since the late 1970s, work on serpentine plants worldwide has led to the identification of about 390 species (from more than 90 genera and 40 families) that show Ni hyperaccumulation; about 85% of these discoveries emanated from the Massey University (New Zealand) laboratory of the present senior author and the late Professor Robert Brooks. Lists of these species have been given by Brooks (1), Reeves (14), and more recently Reeves and Baker (17). Much of the early work was carried out on leaf fragments from herbarium specimens kindly provided by curators of collections in many parts of the world, but many of the world's major serpentine areas have also been visited for the collection of additional analytical and herbarium specimens.

It appears that a majority (perhaps 85%-90%) of the Ni hyperaccumulators are serpentine-endemic. However, some occur on a variety of substrates with widely differing Ni concentrations, and show a wide range of plant Ni concentrations as a result. The term 'hyperaccumulator' should be restricted to plant species showing this behaviour in their natural habitats, i.e. not applied to plants that only accumulate Ni from Ni-rich culture solutions or from soils amended with Ni-rich solids or solutions.

In temperate areas of the world (especially Mediterranean Europe and Turkey) the family Brassicaceae contains the largest number of hyperaccumulators, while in tropical areas the Euphorbiaceae is the most important. In Turkey, hyperaccumulation occurs in the Brassicaceae not only in *Alyssum*, but in species of *Bornmuellera, Cochlearia* (the section now separated as *Pseudosempervivum*), *Thlaspi* s.l. (including *Masmenia* F.K.Mey., *Microthlaspi* F.K.Mey., *Noccaea* Moench, and *Thlaspiceras* F.K.Mey.), and *Aethionema* (18-21) and in *Centaurea* (Asteraceae) (20,21). These genera are discussed in more detail below.

Materials and Methods

Analytical data on the Turkish serpentine plants, generally using leaf material, have been obtained using both herbarium material and specimens collected in the field specifically for analytical purposes. Field work carried out by the authors on the Turkish serpentines during the period 1996-2003 has resulted in the collection of nearly 700 specimens, both for analysis and for preservation as herbarium specimens. Specimens have been deposited in the herbaria of Gazi University, Ankara (GAZI), and the Royal Botanic Garden, Edinburgh, Scotland (E). The collection of field specimens has been accompanied by soil sampling and analysis to establish conclusively the ultramafic nature of the substrate. Details of the methods used for sample treatment and analysis can be found elsewhere (21,22).

Results and Discussion

Ni hyperaccumulation in the flora of Turkey and neighbouring areas

In the region of Turkey and its neighbours, serpentine soils are widespread; they occur not only in Turkey itself, but also in some islands (Cyprus, Lesbos, Tinos), in northern Greece, southern Albania and Bulgaria, in the Turkey-Syria border area, and in northern Iraq and north-western Iran. We review below our present state of knowledge of Ni hyperaccumulation in each genus in which this is known to occur.

Alyssum (Brassicaceae)

Among *Alyssum* species of Turkey, the hyperaccumulators include *A. callichroum* Boiss. & Bal., *A. caricum* T.R.Dudley & Hub.-Mor., *A. cassium* Boiss., *A. cypricum* Nyár., *A. dubertretii* Gomb., *A. floribundum* Boiss. & Bal., 2 varieties of *A. murale* Waldst. & Kit. subsp. *murale* (var. *murale* and var. *haradjianii* (Rech.)) T.R.Dudley, *A. pterocarpum* T.R.Dudley, and *A. samariferum* Boiss. & Hausskn. In fact, in western and central Turkey it is rare to find a significant area of serpentine soil without at least 1 Ni-accumulating *Alyssum* species (sometimes as many as 3 or 4), and many of these appear to be endemic to Turkey. Data for Turkish Ni-accumulating species of *Alyssum*, accumulated over the period 1979-2007, are shown in Table 1. The data reported by Brooks et al. (16) were from analysis of herbarium specimens collected over a period of more than 100 years; these data have now been supplemented by subsequent analyses, including particularly those of field specimens collected by the authors since 1996.

Some of the species, such as *A. murale*, are widely distributed; others are very localised and rare. *A. pinifolium* (Nyár.) T.R.Dudley, for example, was known only from 2 gatherings (by Kirk and by Sintenis) in Çanakkale province in the 19th century and some specimens with seeds collected for the first time by Sorger in the 1960s. It was located again by Reeves and Krämer in 1996 and good flowering and fruiting specimens and photographs now exist. Also in 1996 and 1998 we found in several localities in the provinces of Balıkesir and Kütahya (Dursunbey to Harmancık to Tunçbilek and Tavşanlı) a new Ni-accumulating species described in 2001 as *A. dudleyi* N. Adıgüzel & R.D. Reeves (23). On the ultramafic overburden around the Tunçbilek coal mine this can be found as 1 of a mixture of 4 Ni hyperaccumulators (with *A. sibiricum* Willd., *A. corsicum* Duby, and *A. murale*) colonising the disturbed areas.

Other Ni hyperaccumulators in *Alyssum* from countries adjacent to Turkey include, from northern Syria, *A. syriacum* Nyár. (16), and from mainland Greece, *A. smolikanum* Nyár., *A. heldreichii* Hausskn., and the widespread *A. murale* (15). Occurring on serpentines of the Greek islands are *A. lesbiacum* (Cand.) Rech. from Lesbos (16), *A. euboeum* Halácsy from Euboea (15), *A. tenium* Halácsy from Tinos (15), 4 species from Cyprus (16), and a species from Crete earlier recorded as *A. fallacinum* Hausskn. (15) but now regarded as *A. baldaccii* (Vierh.) Nyár. (24).

Ghaderian and co-workers have recently reported on the plants of the serpentines of NW Iran (25,26), and chemical analyses have shown that 3 more species of *Alyssum* sect. Odontarrhena, not previously found with high Ni (16), presumably because they were not collected from serpentine soils, do in fact accumulate Ni from serpentine. It appears that most species of *Alyssum* sect. Odontarrhena from eastern Turkey and adjacent parts of Iraq and Iran are not serpentine endemic, but nevertheless have the capability of surviving on serpentine soils and accumulating Ni from them to levels that may exceed 1000 mg/kg. Species of interest in this context are *A. bracteatum* Boiss. & Buhse, *A. inflatum* Nyár., *A. longistylum* (Somm. & Lev.) Grossh., *A. penjwinense* T.R.Dudley, and *A. singarense* Boiss. & Hausskn. Data for *Alyssum* sect. Odontarrhena in this region have been

Table 1. Turkish Ni hyperaccumulators in *Alyssum*, showing no. of specimens analysed (n), no. with Ni concentration >1000 mg/kg, and range of Ni concentrations (mg/kg): lowest (L), median (M), highest (H).

	Endemism[a]	n	n > 1000	Range of Ni		
				L	M	H
1. *A. anatolicum* Hausskn. ex Nyár.	TE	3	1	<7	10	8170
2. *A. callichroum* Boiss. & Bal.	TE	11	7	33	1970	18,730
3. *A. caricum* T.R.Dudley & Hub.-Mor.	TE/SE	11	11	2820	6130	16,500
4. *A. cassium* Boiss.	SE	14	14	1080	18,260	66,660
5. *A. cilicicum* Boiss. & Bal.	TE/SE	3	3	4260	13,700	14,840
6. *A. condensatum* Boiss. & Hausskn.	--	18	2	<2	17	2390
7. *A. constellatum* Boiss.	--	7	6	13	5380	18,130
8. *A. corsicum*[b] Duby	SE	23	23	1860	7420	21,460
9. *A. crenulatum* Boiss.	TE/SE	8	8	7090	10,280	21,010
10a. *A. cypricum* Nyár. (Turkey)	SE	8	8	3740	5480	20,220
10b. *A. cypricum* Nyár. (Cyprus)	SE	4	4	7670	13,570	23,640
11. *A. davisianum* T.R.Dudley	TE/SE	3	3	6510	11,560	19,570
12. *A. discolor* T.R.Dudley & Hub-Mor.	TE/?SE	8	8	4450	7370	11,710
13. *A. dubertretii* Gomb.	TE/SE	5	5	12,940	16,540	19,250
14. *A. dudleyi* N. Adıgüzel & R.D. Reeves	TE/SE	5	5	2350	5630	22,100
15. *A. eriophyllum* Boiss. & Hausskn.	TE/SE	10	10	4730	11,510	52,910
16. *A. floribundum* Boiss. & Bal.	TE/?SE	17	10	24	5210	22,350
17. *A. giosnanum* Nyár.	TE/SE	4	4	4170	5850	7400
18. *A. huber-morathii* T.R.Dudley	TE/SE	7	7	1220	9820	13,520
19. *A. masmenaeum* Boiss.	TE/SE	14	14	1640	6550	24,360
20. *A. murale* Waldst. & Kit.						
subsp. *murale* var. *murale*	--	29	29	124	4860	21,340
21. var. *haradjianii* (Rech.) T.R.Dudley	SE	7	7	3850	6820	16,220
22. *A. oxycarpum* Boiss. & Bal.	TE	7	5	<7	7290	16,250
23. *A. pateri* Nyár.subsp. *pateri*	TE	18	3	<5	85	17,090
24. *A. peltarioides* Boiss.						
subsp. *peltarioides*	TE	9	4	2	31	19,270
25. subsp. *virgatiforme* (Nyár.) T.R.Dudley	TE/?SE	5	5	3130	7600	34,690
26. *A. pinifolium* (Nyár.) T.R.Dudley	TE/SE	7	7	4520	9330	21,800
27. *A. pterocarpum* T.R.Dudley	TE/SE	8	8	1190	9980	22,200
28. *A. samariferum* Boiss. & Hausskn.	SE	9	9	2820	6650	24,350
29. *A. sibiricum* Willd.	--	21	5	<1	132	8810
30. *A. syriacum*[c] Nyár.	TE?/SE?	3	3	3380	5250	10190
31. *A. trapeziforme* Bornm. ex Nyár.	TE/SE	5	5	2820	6990	11,930
32. *A. virgatum* Nyár.	TE/SE	4	4	1830	4280	6230

[a]Endemism indicated by TE (endemic to Turkey) and SE (serpentine endemic)
[b]Specimens from Turkey only; for specimens from Corsica see ref. 2.
[c]Specimens analysed were all 19th century specimens from 'Syria', probably from 'Mt. Cassius' on the border of present-day Turkey and Syria. The species has also been collected from within Turkey in the Amanus mountains, Hatay province; the Ni accumulation of specimens from here needs confirmation.

summarised (26) and further work is in progress. *A. penjwinense*, for example, has been recorded with high Ni from Iran and with both high and low Ni from Iraq (16); it has also been collected in 2002 in eastern Turkey, but the nature of the substrate and the Ni content of the Turkish plants are not known to us.

Thlaspi (Brassicaceae)

One species of *Thlaspi* (Brassicaceae) in Europe was known as a zinc-accumulating plant on Zn/Pb mine waste areas since the 1860s, but in the early 1980s it was shown (27) that a number of European species accumulated Zn from a variety of soils, and that a number of species that grew on serpentine soils were Ni accumulators. Other publications (18,28) reported Ni hyperaccumulation by *Thlaspi* species from serpentine soils in Turkey, Japan, and the USA.

The Turkish species include *T. elegans* Boiss., *T. oxyceras* (Boiss.) Hedge, and *T. jaubertii* Hedge, as shown in Table 2. The discovery and description of the new species, *T. cariense* A. Carlström, from Marmaris (29) led to the prediction, confirmed in 1999 (20,30), that it would also be a Ni-accumulating plant. It has subsequently been recorded from the area of Lake Köyceğiz and from the mountains of Sandras dağ. The present authors have collected and analysed specimens from Marmaris and Sandras dağ; the results are included in Table 2.

Attempts at classification of species within *Thlaspi* s.l. have presented many problems and a wide diversity of opinion, which make it particularly difficult to discuss Ni accumulation by species of this genus. A broad view of *Thlaspi* has been taken in publications such as Flora Europaea and Flora of Turkey, contrasting with the subdivision of the genus by Meyer (31,32) into 12 and then 13 separate genera (*Noccaea* being the largest) and more than 100 species. Meyer's separations were rejected in the publication of Flora of Turkey, Vol. 10, in 1988 (33), but have received some support from the subsequent molecular work by Koch, and Mummenhoff and co-workers (34,35). A recent assessment by Al-Shehbaz et al. (36) seems to adopt a middle position in accepting some of the changes proposed by Meyer, while

Table 2. Turkish Ni hyperaccumulators in *Bornmuellera*, *Pseudosempervivum*, *Thlaspi* s.l., and *Aethionema* (Brassicaceae), showing no. of specimens analysed (n), no. with Ni concentration >1000 mg/kg, and range of Ni concentrations (mg/kg): lowest (L), median (M), highest (H).

	Endemism[a]	n	n > 1000	Range of Ni		
				L	M	H
Bornmuellera						
1. *B. glabrescens* (Boiss. & Bal.) Cullen & T.R.Dudley	TE/SE	3	3	14,800	18,000	19,240
2. *B. kiyakii* Aytaç & Aksoy	TE/SE	16	16	4490	7370	12,590
Pseudosempervivum (*Cochlearia*)						
1. *P. aucheri* (Boiss.) Pobed.	TE/SE	11	11	3030	14,800	21,550
2. *P. sempervivum* (Boiss. & Bal.) Pobed.	TE/SE	10	10	2210	6720	34,130
Thlaspi s.l.						
1. *T. cariense* A. Carlström	TE/SE	14	14	9260	13480	23,960
2. *T. eigii* (Zohary) Greuter & Burdet subsp. *eigii*	TE/SE	2	2	7910		20,000
3. subsp. *samuelssonii* (F.K.Mey.) Greuter & Burdet	TE/SE	4	4	8810	13,330	20,200
4. *T. elegans* Boiss.	TE/SE	10	10	8800	14,670	20,800
5. *T. jaubertii* Hedge	TE/?SE	6	6	2870	5520	26,900
6. *T. ochroleucum*[b,c] Boiss. & Heldr.	--	7	3	11	70	6050
7. *T. oxyceras* (Boiss.) Hedge	TE/SE	22	20	509	18,000	56,020
8. *T. perfoliatum*[b] L.	--	11	5	8	406	8120
9. *T. rosulare* Boiss. & Bal.	TE/?SE	6	6	3550	6600	31,940
Aethionema						
1. *A. spicatum* Post	TE?	2	1	764		1110

[a] Endemism indicated by TE (endemic to Turkey) and SE (serpentine endemic).
[b] Specimens from Turkey only.
[c] Most specimens are probably not from serpentine soils. All 3 high values are from different specimens of the collection Sintenis 277 (1883) from Uludağ, Erenköy, Çanakkale province; this specimen has been taken by Meyer (31) as an example of *Noccaea versicolor*.

recognising that more work needs to be done. Details of Turkish *Thlaspi* nomenclature and changes proposed at various times can be followed from the original Flora of Turkey (37) through the work by Meyer (31) and Greuter and Raus (38) and subsequent publications (33,36).

The data for *Thlaspi* s.l. shown in Table 2, derived from published work (18,20,21,30) and recent unpublished studies, use the nomenclature as updated in Vol. 10, but further comment on some of the species is given below. We note also the recent description (39) of *Noccaea camlikensis* Aytaç, Nordt & Parolly from Kızıldağ near Çamlık (Konya). We think that this is also likely to prove to be a Ni-accumulating species: further collections and chemical analyses of specimens from this site and comparison with *Thlaspi cariense* are desirable.

Several entries in Table 2 under *Thlaspi* s.l., and other *Thlaspi* occurrences in Turkey, deserve further comment.

(i) *T. perfoliatum* L., which is a widespread weed on many substrates throughout Turkey, Europe, North Africa, and SW Asia, does occur on serpentine in Turkey. Collections made by the authors from non-serpentinitic soils have shown Ni <40 mg/kg, but serpentine occurrences had Ni ranging from 270 to 8120 mg/kg. These collections were generally made at times of the season when only senescent or dead leaves were available.

(ii) *T. ochroleucum* Boiss. & Heldr. is a well established species of Greece and Turkey. Meyer's transfer to *Noccaea ochroleuca* (Boiss. & Heldr.) F.K.Mey. has been accepted by Al-Shehbaz et al. (36). On various substrates this species has shown a wide variety of concentrations of both Ni and Zn (18,27), each element exceeding 1000 mg/kg on occasion. In particular, we note here that fragments from 3 separate plants belonging to the 1883 collection Sintenis 277, from the mountains of Ulu dağ near Erenköy (Çanakkale province) have all shown Ni in the range 3760-6050 mg/kg. One of the examples of this collection, however, has been provided to us by Meyer as an example of *Noccaea versicolor* (Stoj. & Kit.) F.K.Mey.

(iii) All analysed specimens of *T. rosulare* Boiss. have shown high Ni. This includes material collected by Balansa in 1855, by Siehe in 1906, and by the present authors more recently. These specimens would be regarded as *Masmenia rosularis* (Boiss. & Bal.) F.K.Mey. according to Meyer's revision. High Ni (15,800 mg/kg) is also found in the specimen Akman 203, listed here under *T. rosulare* but regarded by Meyer as the type of *M. crassiuscula* F.K.Mey.

(iv) For *Thlaspi oxyceras*, apart from 2 samples of a collection from a site near Refahiye with Ni in the range 500-1000 mg/kg, all show clear Ni hyperaccumulation, with more than 3000 mg/kg. The specimens listed in Table 2 under *T. oxyceras* include material collected recently by the present authors, as well as earlier herbarium specimens (data summarised in ref. 18), some of which were regarded by Meyer as examples of new species in his genus *Thlaspiceras*. In the event that Meyer's species become widely recognised, we give details of these specimens and their Ni concentrations in his putative new species.

T. bovis F.K.Mey.: Eig & Zohary 1.vii.1932 – 14,200 mg/kg

T. cappadocicum (Boiss. & Bal.) F.K.Mey.: Balansa 1004 (1856) – 24,300 mg/kg; Gombault 2102 (1933) – 3080 mg/kg.

T. capricornutum F.K.Mey.: Wall 17.v.1933 – 18,000 mg/kg

T. crassifolium Hub.-Mor. & F.K.Mey.: Huber-Morath 16241 – 35,600 mg/kg

T. dolichocarpum (Zohary) F.K.Mey.: Eig & Zohary 1.vii.1932 – 34,700 mg/kg

T. huber-morathii F.K.Mey.: Walther 9183 (1971) – 7880 mg/kg

T. rechingeri F.K.Mey.: Haradjian 3637 (1911) – 30,000 mg/kg

T. triangulare F.K.Mey.: Akman 244 (1968) – 25,000 mg/kg

(v) A *Thlaspi* specimen collected by Davis & Coode in 1962 (D.36781) from rocky slopes of Murat dağ above Gediz (Kütahya province) became the type for *Noccaea edinensium* F.K.Mey., and was included in *Thlaspi* as *T. edinensium* (F.K.Mey.) Greuter & Burdet in 1983 (38). It is listed by Davis et al. (33) under *Species Incertae Sedis*, but *N. edinensium* is accepted by Al-Shehbaz et al. (36). With 1490 mg/kg Ni it qualifies as a Ni hyperaccumulator.

(vi) A leaf sample forwarded to the senior author by Professor Y. Akman under the name "*Thlaspi austroamanicum* Hub.-Mor." and referred to by him in his study of the flora of the Amanus mountains (40) contains

17,700 mg/kg Ni. The name has not been published formally, and it is uncertain whether this represents a new species or falls within the scope of one already described.

(viii) We have collected the recently described *T. leblebici* Gemici & Görk from serpentine in the mountains of Sandras dağ and have found it to contain only 11 mg/kg Ni.

(ix) Specimens of *T. violascens* Boiss. have been collected from a variety of substrates and analysed. The Ni concentrations range from <1 mg/kg to 966 mg/kg; those from serpentine soil are in the range 365-966 mg/kg, thus falling just short of hyperaccumulator status.

Pseudosempervivum (*Cochlearia*) (Brassicaceae)

Cochlearia in Turkey is represented by sect. *Pseudosempervivum*, raised to genus status by Pobedimova (41). It was shown in the 1980s that, of the 3 Turkish species, 1 is not found on serpentine soils and has low Ni concentrations. The other 2, now listed as *P. aucheri* (Boiss.) Pobed. and *P. sempervivum* (Boiss. & Bal.) Pobed., are apparently serpentine-endemic and have high levels of Ni in their leaves (18). The 1980s work was carried out with herbarium specimens, but we have now collected both hyperaccumulators in several places in the field, and confirmed the earlier findings, as shown in Table 2. We have not found *P. amanum* (Contandr. & Quézel) Al-Shebaz, Mutlu & Dönmez, originally described as *Cochlearia amana* Contandr. & Quézel from the Amanus mountains (42), but we predict that this will prove to be another serpentine-endemic Ni hyperaccumulator.

Bornmuellera (Brassicaceae)

This genus of a few species is restricted to Turkey, Greece, S. Albania, and the Kosovo province of Serbia. Some of the species appear to be serpentine-endemic, and analytical work on herbarium specimens in the 1980s (19) showed these to be Ni hyperaccumulators. The three Turkish species known at that time are all uncommon or extremely rare. One of them, *B.* glabrescens (Boiss. & Bal.) Cullen & T.R.Dudley, from Niğde province, was found to be a Ni hyperaccumulator, as were all the taxa from serpentine in northern Greece. The report by Aytaç and Aksoy (43) about a new species of *Bornmuellera* on the ultramafic mountain Kızıldağ in Konya province caused us to visit this locality in 2003 to take samples for analysis, in the expectation that it would prove to be another hyperaccumulator. This has been found to be the case (44). Data for the 2 Turkish Ni hyperaccumulators in *Bornmuellera* are also summarised in Table 2.

Some information about other plant species occurring on the serpentine of Kızıldağ (Konya) has already been provided (43). However, this ultramafic mountain deserves much further detailed study, as it also hosts other Ni-accumulating species in genera such as *Pseudosempervivum* (*Cochlearia)*, *Thlaspi* s.l., and *Alyssum* (44).

Aethionema (Brassicaceae)

Several species of *Aethionema* have been recorded from serpentine soils in Turkey; these include *A. armenum* Boiss., *A. coridifolium* DC., *A. grandiflorum* Boiss. & Hohen., A. *membranaceum* DC., *A. saxatile* (L.) R.Br. subsp. *creticum* (Boiss. & Heldr.) I.A.Andersson et al., *A. schistosum* Boiss. & Kotschy, *A. speciosum* Boiss. & Huet subsp. *compactum* Hartvig & Strid, and *A. spicatum* Post. However, their Ni uptake has been found to be unremarkable, except for the record of 764 and 1110 mg/kg in specimens of *A. spicatum* (20) from the Hamidiye-Gerdibi area of Niğde province (Table 2). The same species has been found by the present authors and by Aytaç and Aksoy (43) at Kızıldağ near Çamlık (Konya); the level of its Ni accumulation there should be studied in detail. This species appears to be widely scattered in S and E Anatolia and N Syria. From the localities recorded it is possible that it may occur often on serpentine, or even be serpentine-endemic.

Centaurea (Asteraceae)

On a visit to ultramafic areas in Seyhan province with A.R. Kruckeberg in 1998 we collected the extremely rare *Centaurea ptosimopappoides* Wagenitz, and were very surprised to find that it was a Ni-accumulating plant (20). Up to this time, all the reliable cases of extreme Ni accumulation from the Mediterranean region had been in the Brassicaceae, and serpentine samples of *Centaurea* species (e.g., from Greece and Italy) had shown no unusual Ni levels (R.D. Reeves, unpublished work). Since then we have found high Ni in 13 *Centaurea* species in Turkey (21), although only some of them seem to be serpentine endemic and invariably Ni-accumulating. Table 3 gives an updated summary of relevant species, following further collecting in 2001 and 2003 and subsequent analysis.

Much more work is needed on serpentine occurrences of *Centaurea* species in Turkey before we understand fully

Table 3. Turkish Ni hyperaccumulators in *Centaurea*, showing no. of specimens analysed (n), no. with Ni concentration >1000 mg/kg, and range of Ni concentrations (mg/kg): lowest (L), median (M), highest (H).

	Endemism[a]	n	n > 1000	Range of Ni		
				L	M	H
1. *C. aladaghensis* Wagenitz	TE/?SE	1	1		9900	
2. *C. amanicola* Hub.-Mor.	TE/?SE	3	3	11,050	11,430	11,550
3. *C. antitauri* Hayek	TE/?SE	2	2	20,280		24,990
4. *C. arifolia* Boiss.	TE/?SE	3	2	10	17,540	22,500
5. *C. cataonica* Boiss. & Hausskn.	TE	3	2	282	4320	7840
6. *C. cheirolopha* (Fenzl) Wagenitz	--	8	2	2	228	2020
7. *C. haradjianii* Wagenitz	TE	1	1		4770	
8. *C. ensiformis* P.H.Davis	TE/SE	7	7	9390	24,400	37,750
9. *C. ptosimopappa* Hayek	TE/SE	14	14	1080	13,980	27,200
10. *C. ptosimopappoides* Wagenitz	TE/SE	6	6	7320	8240	11,660
11. *C. sericea* Wagenitz	TE/?SE	1	1		14,830	
12. *C. spicata* Boiss.	--	7	5	94	5870	24,040
13. *C. tomentella* Hand.-Mazz.	TE	5	1	17	59	1510

[a] Endemism indicated by TE (endemic to Turkey) and SE (serpentine endemic)

their distribution and behaviour in relation to the Ni concentrations in the soil. Some species (e.g., *C. tomentella* Hand.-Mazz., *C. cheirolopha* (Fenzl) Wagenitz) appear to have very variable Ni-accumulation, even among their serpentine occurrences. However, species that are probably serpentine endemic and always Ni-accumulating include *C. ptosimopappoides*, *C. ptosimopappa* Hayek, and *C. amanicola* Hub.-Mor. from the Amanus mountains and *C. ensiformis* P.H.Davis from the mountains of Sandras dağ in Muğla province. When more material becomes available for analysis it is possible that a few other species may prove to be Ni hyperaccumulators, e.g., *C. doddsii* Post and *C. foliosa* Boiss. & Kotschy.

Applications of Ni hyperaccumulators

There are several possible applications of Ni hyperaccumulator plants. First, there is their use as geobotanical indicators: the Ni hyperaccumulation in their leaves is quickly established by a simple field test with filter paper impregnated with the Ni-specific reagent dimethylglyoxime (14), and the distribution of these plants can be used to delineate or delimit areas of Ni-rich serpentine soils. However, interest is also developing in the use of Ni accumulator plants as phytoextraction agents, for either phytoremediation or phytomining. Phytoremediation involves extracting Ni from the soil to remediate contaminated land around Ni smelters (45). Detailed work on the parameters governing Ni uptake in this type of environment has been carried out by Chaney and co-workers (46,47), investigating the behaviour of *Alyssum murale* on contaminated soils from around the smelter at Port Colborne, Ontario, Canada. Phytomining involves extraction of Ni as a crop product from natural (or contaminated) soils that are Ni-rich but not rich enough to be treated as an ore material for direct smelting (48). Many of the issues involved in the commercial development of phytoextraction have been discussed by Angle et al. (49) and Chaney et al. (50).

There are possibilities for phytomining to be developed on a large scale in Turkey, for many reasons:

1. Several Ni hyperaccumulators (e.g., *Alyssum corsicum, A. murale, Centaurea ptosimopappa, C. ensiformis*) regularly exceed 1% Ni in the dry matter and 10% Ni in the ash, and produce good biomass in 12-18 months.

2. The *Alyssum* species, at least, become established easily, rapidly colonising disturbed ground (road cuttings, edges of crop fields, abandoned fields, and other ultramafic 'waste land'), and produce abundant seed.

3. There are no biosecurity problems with growing species native to the country, and in using native species there should be negligible problems with pests.

4. Considerable areas of flat arable ultramafic land exist.

5. The value of the extracted Ni was similar to that of the non-optimum wheat crops obtained from ultramafic soils in the 1980s when this calculation was first done and the Ni price was about US$15/kg. Recent large increases in the Ni price have greatly improved the economics of Ni phytoextraction.

6. There is the possibility of energy generation from burning of dry harvested biomass, and the Turkish climate makes low-cost drying possible.

7. Some optimisation of growth, Ni uptake, and process efficiency of the Turkish Ni hyperaccumulators can be expected as the concept of developing them as agronomic crops is pursued. This can be achieved via studies of planting density, planting techniques, soil modification including fertilisation, and harvesting strategies (49).

Conservation Issues

Many of the Ni hyperaccumulator plant species are very restricted in their distribution, and some are known from only 1-3 collections or 1-3 localities (e.g., *Alyssum pinifolium*, *Centaurea ptosimopappoides, Bornmuellera kiyakii, B. glabrescens, Thlaspi cariense*, and *Pseudosempervivum* (*Cochlearia*) *amanum*). There is therefore a need to pay attention to the conservation of these unusual and potentially valuable species. More exploration is needed to establish their distributions and rarity more exactly, and strategies put in place to ensure their conservation. In the context of the subject of the present paper, there seems to be a special need for more detailed collection and study of serpentine occurrences of species of *Thlaspi* and *Centaurea*, in particular, using both traditional morphometric and DNA methods.

Even plants that may be locally abundant at one time can be seriously threatened: we note the case of *Alyssum corsicum*, first described from Bastia, Corsica, in 1828, but now known to be a plant of serpentines of western Anatolia that became naturalised in this one serpentine location in Corsica many centuries ago. It was still abundant there in 1978 but could not be found in the same area in 1990. Although it is quite abundant at many locations on the serpentines of western Turkey, its continued existence on the island that gave it its name is in doubt.

Increasing urbanisation, as at Bastia, is just one of several threats that may be identified. Others include fire (accidental or deliberate), the development of ultramafic soil areas for agriculture or forestry, and even the activities of overenthusiastic plant collectors. A strong case can be made for increased protection of certain key ultramafic areas containing the rare plants noted above.

Corresponding author:
Nezaket ADIGÜZEL
Faculty of Arts and Science,
Department of Biology,
Gazi University,
Ankara - TURKEY

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