

This is a post-print version of an article published in:

Audet, P., & Charest, C. (2007). Heavy metal phytoremediation from a meta-analytical perspective. *Environmental Pollution*, 147(1), 231-237.  
doi: 10.1016/j.envpol.2006.08.011.

# **Heavy metal phytoremediation from a meta-analytical perspective.**

**Patrick Audet & Christiane Charest**

Ottawa-Carleton Institute of Biology  
Department of Biology  
University of Ottawa  
30 Marie-Curie St.  
Ottawa, ON, K1N 6N5, Canada

E-mail: [ccharest@science.uottawa.ca](mailto:ccharest@science.uottawa.ca) (corresponding author)  
[paude086@uottawa.ca](mailto:paude086@uottawa.ca)

Tel: (613) 562-5800 Ext.6359

Fax: (613) 562-5486

# Heavy metal phyto remediation from a meta-analytical perspective.

## ABSTRACT

We conducted a literature survey and correlated heavy metal (HM) uptake and plant growth factors from published data to estimate the effectiveness of phytoextraction. The indicators of the actual plant HM uptake showed positive correlations with soil-HM concentrations, while the relative plant HM uptake showed negative correlations. Plant growth was negatively correlated with both the plant and soil-HM concentrations. These significant relationships were found for the majority of HM tested (e.g. Zn, Cd, Pb, Cu, Cr, and Fe) with a few exceptions (e.g. Ni, Co, and Mn). After fitting the correlation coefficients, the highest proportion of variance among the studies was mainly due to the experimental parameters or the plant species. When the metabolic costs of HM uptake are taken into account, the phytoextraction appears to be less effective beyond critical HM concentrations. Despite these constraints, it is emphasized that HM phytoextraction can play an important role in bioremediation.

**“Capsule”:** This meta-analytical approach has revealed a compromise between growth and HM uptake when plants are subjected to toxic soil-HM levels.

**Key words:** Bioconcentration factor; Specific extraction yield; Tolerance index.

## 1     **1.     INTRODUCTION**

2           Phytoremediation is defined as the use of plants to remove pollutants from the  
3 environment (Cunningham et al. 1995; Salt et al. 1998). Inorganic pollutants, such as plant trace  
4 elements (e.g. Cr, Cu, Fe, Mn, Ni, and Zn) and non-essential elements (e.g. Cd, Co, and Pb),  
5 have been shown to be more difficult to remediate from contaminated soils as they cannot be  
6 degraded (Pilon-Smits 2005). Still, plants have been shown to take up and sequester heavy  
7 metals (HM) in roots and/or shoots and, therefore, to significantly contribute to their removal  
8 from the environment through a mechanism of phytoextraction. This mechanism occurs despite  
9 important growth challenges, including HM toxicity, changes to soil pH, and mineral  
10 imbalances.

11           For phytoextraction to be effective plants must take up HM from the soil, tolerate high  
12 plant or soil-HM levels, and produce sufficient harvestable biomass (Chaney et al. 1997;  
13 Meagher 2000; Pilon-Smits 2005; Salt et al. 1995, 1998). Using a meta-analytical approach, our  
14 objectives were (1) to describe the relationship between the levels of soil-HM and actual or  
15 relative plant HM uptake, (2) to describe the relationship between plant growth and plant HM  
16 uptake, and (3) to evaluate whether these relationships are the same for all the HM selected.  
17 Thus, we have tested the hypothesis that HM phytoextraction is an effective means of  
18 phytoremediation for highly polluted environments, using meta-analysis as a useful and  
19 meaningful approach for summarizing relationships from multiple studies (Lipsey and Wilson  
20 2001). From the current body of phytoremediation literature, we have quantitatively evaluated  
21 the key plant physiological relationships influencing the effectiveness of HM phytoextraction  
22 and have detected, with high statistical power, broad-scale trends which have been  
23 underestimated by conventional or qualitative review analyses.

## 319 2. METHODS

### 320 2.1. Meta-analysis

321 In this meta-analytical study, based on the methods of Hedges & Olkin (1985) and Lipsey  
322 & Wilson (2001), we have tested the correlations between (1) the soil-HM concentration with  
323 actual or relative plant HM uptake and (2) the plant growth with actual plant HM uptake or soil-  
324 HM concentration, using combined results from multiple studies. The studies from which data  
325 were used have been selected through searching of library journal directories and online  
326 academic literature networks. In total, 36 articles were selected for having studied herbaceous  
327 plants and measured biomass and HM uptake, whether under laboratory or field conditions. All  
328 the HM with the soil concentration ranges and the 50 different plant species included in our  
329 study are appended (Supplementary Data). The distinguishing features required for inclusion in  
330 our analyses were that the soil mineral composition be described and the data be presented in  
331 tables. Key variables included soil-HM concentration ( $\text{mg kg}^{-1}$  dry soil), plant HM concentration  
332 ( $\text{mg kg}^{-1}$  dry mass) and/or content ( $\text{mg plant}^{-1}$ ) for shoots and/or roots, and plant dry mass (g) for  
333 shoots and/or roots.

### 334 2.2. Metrics

335 Total plant HM content ( $\text{HM}_{\text{plant}}$ ) and plant HM concentration ( $[\text{HM}_{\text{plant}}]$ ) were used to  
336 measure the actual plant HM uptake. The specific extraction yield percentage ( $\text{SEY}_{\%}$ ) and  
337 bioconcentration factor (BCF) were used to measure the plant HM uptake relative to the HM in  
338 soil. The  $\text{SEY}_{\%}$ , representing the percent ratio of plant HM content to soil-HM concentration  
339 ( $[\text{HM}_{\text{soil}}]$ ) (adapted from Audet & Charest 2006), is defined as:

340 (1)

$$341 \text{SEY}_{\%} = \frac{\text{HM}_{\text{plant}}}{[\text{HM}_{\text{soil}}]}$$

342

343 The BCF, representing the ratio of plant HM concentration to soil-HM concentration (Dowdy  
344 and McKone 1997), is defined as:

$$345 \quad (2) \quad BCF = \frac{[HM_{plant}]}{[HM_{soil}]}$$

346 Typically, the BCF is an indication of the magnification of contaminants from a lower to a  
347 higher trophic level (Newman and Unger 2003). For plants, the BCF has been used as a measure  
348 of HM accumulation efficiency, whereby values greater than 1 are an indication of potential HM  
349 phytohyperaccumulator species (Zhang et al. 2002). The tolerance index (TI), representing the  
350 ratio of biomass for plants grown in HM-soil to plants grown in non-HM control-soil for roots  
351 and shoots separately (Wilkins 1957, 1978), is defined as:

$$352 \quad (3) \quad TI = \frac{biomass_{HM}}{biomass_{control}}$$

353 TI values lower than 1 indicate a net decrease in biomass and suggest that the plants are stressed,  
354 whereas TI values equal to 1 indicate no difference relative to non-HM control treatments. Also,  
355 TI values greater than 1 indicate a net increase in biomass and suggest that plants express a  
356 growth dilution effect.

### 357 **2.3. Statistical analyses**

358 The Pearson product-moment correlation test (Zar 1999) was used to calculate the  
359 significance and strength of the following correlations: between the total HM tissue content, HM  
360 tissue concentration, SEY%, BCF, or TI and soil-HM concentration, and between the TI and total  
361 HM tissue content or concentration. The correlation coefficients (r) were determined and fitted  
362 for variance attributable to differences in HM type, plant species, reference source, plant tissue  
363 type (either shoot or root), and study type (either field or laboratory study). This was done by  
364 adding these terms to the statistical model and solving for the coefficient of determination ( $r^2$ )  
365 (data not shown). The correlations were also calculated for each HM (e.g. Zn, Cd, Pb, Cu, Ni,

366 Cr, Co, Mn, and Fe) for all comparison variables representing the HM-specific correlation  
367 coefficients, with the exception of the comparisons involving the TI that did not show any  
368 significant HM-specific correlations (data not shown). The empty coefficient fields for the  
369 individual HM (Tables 2 and 3) indicate that the correlation model cannot be fitted with any  
370 variables since the data analyzed were taken from either one plant species, reference source,  
371 plant tissue type, or study type only. The Fisher correlation comparison test was used to  
372 compare coefficient values (Zar 1999). We applied logarithmic transformations to each of the  
373 variables in order to detect any linear relationship between the variables, and to meet normal  
374 distribution and homoscedasticity assumptions during analysis. We analyzed the residual rather  
375 than the raw values of SEY<sub>%</sub> and BCF in order to detect any trend underlying the negative  
376 relationship between [HM<sub>soil</sub>] with SEY<sub>%</sub> or BCF. All of the p-values were determined using S-  
377 Plus® 7.0 (Insightful 2005).

378

### 379 **3. RESULTS**

380 The total plant HM content (Fig.1a) and plant HM concentration (Fig.1b) were plotted  
381 versus the soil-HM concentration; their correlation coefficients with [HM<sub>soil</sub>] were 0.53 and 0.50,  
382 respectively (Table 1). The correlation coefficients for the total plant HM content and  
383 concentration were significantly increased once fitted for heavy metal type (0.65 and 0.61), and  
384 the strongest values were observed after fitting the reference source (0.75 and 0.73), or species  
385 type (0.76 and 0.82). The fitted coefficients for the study type showed no significant differences  
386 from the unfitted values. The HM-specific correlation coefficients for the total plant HM content  
387 and concentration were all significant and positive, with the exception of Cr and Mn showing no  
388 significant correlations (Table 2). Once fitted for reference source or species type, the strength  
389 of correlation significantly increased in all cases. Likewise, the HM-specific correlation

390 coefficients for total plant HM content and soil-HM concentration were all significant and  
391 positive, with the exception of Cr and Fe showing no significant correlations (Table 2). Again,  
392 the coefficients significantly increased in all cases once fitted for reference source and species  
393 type.

394 The residual values for the  $SEY_{\%}$  (Fig.2a) and BCF (Fig.2b) were plotted against the soil-  
395 HM concentration; their correlation coefficients were -0.54 and -0.52, respectively (Table 3).  
396 The correlation coefficients for the  $SEY_{\%}$  and BCF were significantly decreased once fitted for  
397 the HM type (-0.64 and -0.61), and the strongest once fitted for the reference source (-0.75 and -  
398 0.80) and the species type (-0.74 and -0.81). The fitted coefficients for the study type showed  
399 no significant differences from the unfitted values. The HM-specific correlation coefficients for  
400 residual  $SEY_{\%}$  and residual BCF were mostly all significant and negative (Table 3). However,  
401 the  $SEY_{\%}$  coefficients of Pb, Ni, Cr, and Mn indicated non-significant correlations, while Co  
402 showed a significant and positive correlation with soil-HM concentration. Furthermore, the BCF  
403 coefficients of Cr and Fe showed non-significant correlations, while Ni, Co, and Mn showed  
404 significant and positive correlations with soil-HM concentration. For the  $SEY_{\%}$  and BCF  
405 correlations, the coefficients for nearly all the HM were the strongest once fitted for the reference  
406 source and species type.

407 The TI values plotted against the soil-HM concentration (Fig.3a), total plant HM content  
408 (Fig.3b), and plant HM concentration (Fig.3c) showed significant and negative correlations with  
409 soil-HM concentration (-0.21) or plant HM concentration (-0.19), whereas the soil-HM content  
410 showed no significant correlation (Table 4). All of these coefficients were significant and  
411 strongest once fitted for species type (-0.49, -0.44, and -0.49) and reference source (-0.55, -0.49,  
412 and -0.54). Only the correlation between plant HM content and TI showed non-significant  
413 coefficients when fitted for HM type, plant tissue type, or study type.

414

415 **4. DISCUSSION**

416 We observed that both plant HM content and concentration, which are indicators of  
417 actual plant HM uptake, strongly and significantly increase as soil-HM concentration increases;  
418 this trend being found for each individual HM studied. This is remarkable considering that some  
419 plants tolerate high tissue HM content or concentration, with levels as high as 325 mg [Ni] DM<sup>-1</sup>  
420 for *Alysum corsicum* (Li et al. 2003) and 125 000 mg [Pb] kg<sup>-1</sup> DM for *Raphanus sativus* (Chen  
421 et al. 2003a), while soil-HM concentration increased by approximately three to five orders of  
422 magnitude. In this regard, the predictive model for actual plant HM uptake from our meta-  
423 analytical results suggests that plants are able to accumulate heavy metals at higher soil-HM  
424 concentrations, and then an even greater potential for phytoremediation purposes than indicated  
425 in published reports so far. This is in agreement with the criterion that an effective HM  
426 phytoextraction requires that plants be increasingly tolerant to high plant-HM and soil-HM  
427 concentrations (Chaney et al. 1997; Meagher 2000; Pilon-Smits 2005; Salt et al. 1995, 1998).  
428 On the other hand, both SEY<sub>%</sub> and BCF, indicators of relative plant HM uptake, were shown to  
429 strongly and significantly decrease as soil-HM concentration increases; this trend being found for  
430 each HM studied, with few exceptions. Hence, HM phytoextraction was declining relative to  
431 increasing soil-HM concentration, even though the actual HM uptake was linearly increasing.  
432 This response of decreased relative uptake is likely linked to the increased cost associated with  
433 tolerance to high plant HM levels, for example the cost of phytochelatin production or HM  
434 sequestration (Cobbett 2000; Maier et al. 2003; Wang et al. 2005). Furthermore, the decrease in  
435 relative plant HM uptake could also be the result of direct and/or indirect challenges such as HM  
436 toxicity causing plant poisoning, soil pH changes, and mineral imbalances (Foy et al. 1978;  
437 Marschner 1986), all of which similarly affecting the soil microbiota and their interactions with

438 plants (Giller et al. 1998; Hayman and Tavares 1985; Leyval et al. 1997; McGrath et al. 1995).  
439 From our results, the predictive model for relative plant HM uptake suggests that HM  
440 phytoextraction becomes less effective as soil-HM concentration increases when the metabolic  
441 costs of HM uptake and sequestration are taken into consideration. This, therefore, challenges  
442 the aforementioned criteria for effective phytoextraction.

443 As for the individual HM studied, all share, at varying strengths, the general trend of  
444 positive correlation between plant HM content or concentration and soil-HM concentration,  
445 despite some non-significant correlations (e.g. Cr, Mn, and Fe with  $df < 28$ ). In this case, non-  
446 significant correlations may be attributed to the small sample size or the narrow soil-HM  
447 concentrations less than one order of magnitude. For these reasons, the actual uptake correlation  
448 values for Cr, Mn, and Fe cannot be considered representative of any significant biological  
449 trends until more data are available. As for the correlations between residual values of  $SEY_{\%}$  or  
450 BCF with soil-HM concentration, all of the HM studied show negative correlations, with the  
451 exception of Ni, Co, and Mn. The non-significant correlations observed can be attributed to the  
452 effects of sample size or soil concentration range as previously stated, particularly for Co and  
453 Mn. However, any positive  $SEY_{\%}$  or BCF correlations imply that plants show higher relative  
454 uptake of Ni, Co, and Mn under increasing soil-HM concentrations, thus indicating their greater  
455 phytoremediation potential compared to the other HM studied. In this regard, the relative plant  
456 HM uptake may be affected by edaphic conditions, particularly soil-HM bioavailability (Walker  
457 et al. 2003). For example, a plant uptake likely increase as soil-pH becomes acidic, relating to  
458 increased HM bioavailability when colloidal sorption decreases (Apak 2002). Hence, plant HM  
459 levels may be higher when grown in more acidic soil conditions, then explaining differences in  
460 HM-specific uptake.

461

462 From our meta-analytical results, the TI values, which represent relative plant growth,  
463 decreased as the plant or soil-HM concentrations increased while there was no significant  
464 correlation between TI and total plant HM content. Accordingly, the potential for  
465 phytoextraction is likely affected by the rate of HM uptake rather than the level of HM tolerance,  
466 meaning that high biomass species may take up greater total HM content than low biomass  
467 species while possibly tolerating equal plant HM concentration. Nevertheless, we have provided  
468 evidence that plants subjected to soil-HM conditions are in the zone of nutrient toxicity and that  
469 any further HM uptake would eventually result in plant death; this being in agreement with the  
470 generalized relationship between plant growth and nutrient concentration (Epstein 1972). This is  
471 an indication that plants are becoming increasingly stressed, with their overall health declining  
472 under such soil-HM conditions. In our study, there is some incidence of increased plant growth  
473 under HM relative to non-HM conditions, yet this was not observed in conjunction with any  
474 decrease in plant HM concentration. Therefore, it may be interpreted that plants do not use any  
475 mechanism of growth dilution effect in tolerating soil-HM stress, a process in which the  
476 concentration of any compound decreases subsequent to its distribution in the growing biomass  
477 (Newman and Unger 2003). Instead, our findings strongly suggest a compromise with regard to  
478 plant resource allocation, this affecting plant capacity for HM uptake, tolerance, and growth  
479 under soil-HM conditions. In view of these metabolic costs, high biomass plants (e.g. *Zea mays*  
480 and *Nicotiana* sp.) have seldom been shown to take up higher HM concentration than some low  
481 biomass plants (e.g. *Alysum corsicum* and *Raphanus sativus*). Therefore, HM phytoextraction  
482 under increasing soil-HM concentrations would decline, and be limited to only better adapted or  
483 hyperaccumulator species (Xue et al. 2004; Yanai et al. 2006).

484 As for the fitted correlation coefficients, these values can also be interpreted as measures  
485 of variance between the different plant species chosen or the different experimental parameters

486 (e.g. HM, plant tissue, or study type), as compared with the unfitted values. Notably, the  
487 correlation values were significantly strongest once fitted for reference and plant species type;  
488 therefore, the highest proportion of variance is attributable to the different methods or treatments  
489 used in each study as well as the different plant species studied. It has been reported that  
490 chelating agents enhance plant HM uptake (Blaylock et al. 1997; Chen et al. 2003b; Cui et al.  
491 2004; Jiang and Yang 2004). It has also been shown that hyperaccumulators often tolerate and  
492 take up higher HM levels compared to non-hyperaccumulator species (Delorme et al. 2001;  
493 Marchiol et al. 2004; Shen et al. 2002). Moreover, the correlation values fitted for plant tissue or  
494 study type were mostly not different from the unfitted values, and therefore account for only a  
495 small proportion of the variance in our study. This has occurred even though plant HM uptake  
496 levels were not necessarily the same in both shoots and roots for different plant species or HM  
497 type (Chaney et al. 1997), and despite the fact that these plant HM levels differed between  
498 laboratory and field conditions (Huang and Cunningham 1996).

499

## 500 **5. CONCLUSION**

501 Our meta-analytical study has quantified key relationships involving the physiology of  
502 plants and the HM phytoextraction process. From these results, we should reject the assertion  
503 that HM phytoextraction is an effective means of soil remediation under increasing soil-HM  
504 levels. In this regard, it would be important to better understand the metabolic compromises in  
505 plants between investing in HM tolerance and growth in a bioremediation perspective.

## 506 **ACKNOWLEDGMENTS**

507 The authors wish to thank the Editor-in-Chief and the two anonymous referees for this  
508 publication. This research was funded by a grant from the Natural Sciences and Engineering  
509 Research Council of Canada (NSERC) to Ch Ch.

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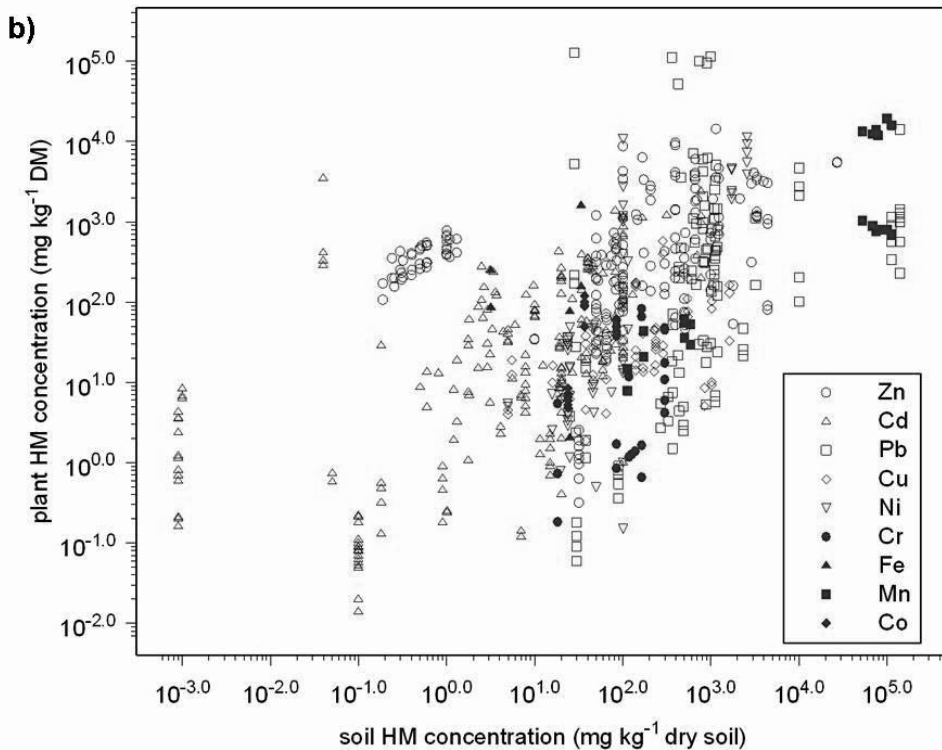
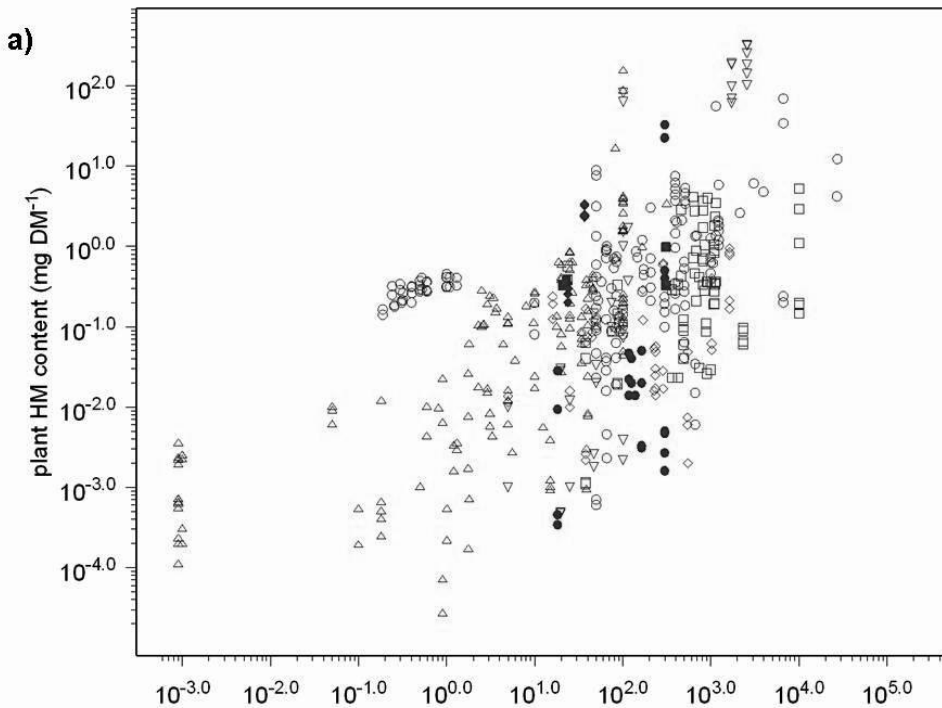
606 Figure 1. Plant HM content ( $\text{mg DM}^{-1}$ ) (a) and concentration ( $\text{mg kg}^{-1} \text{DM}$ ) (b) in relation with  
607 soil-HM concentration ( $\text{mg kg}^{-1}$  dry soil).

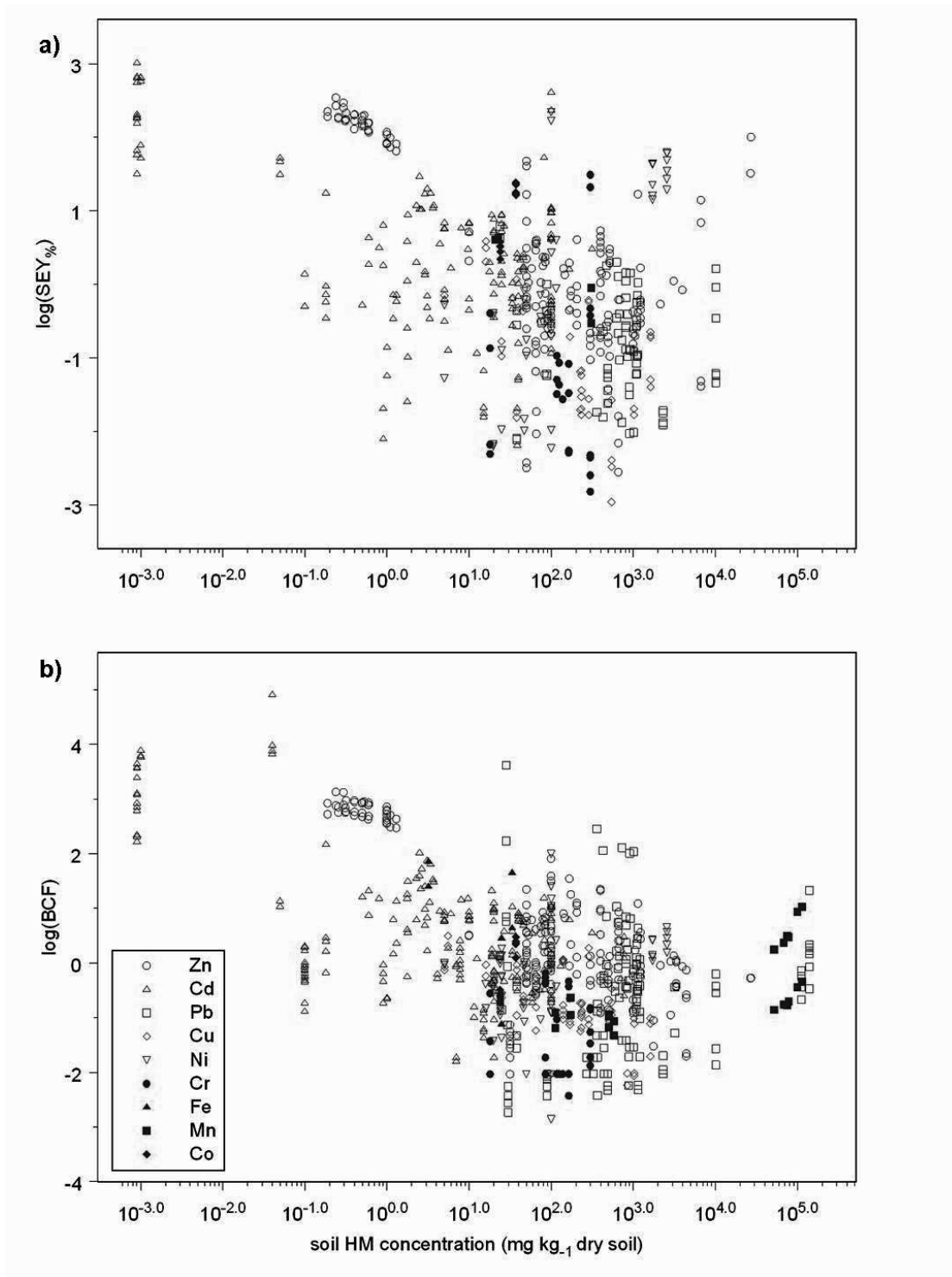
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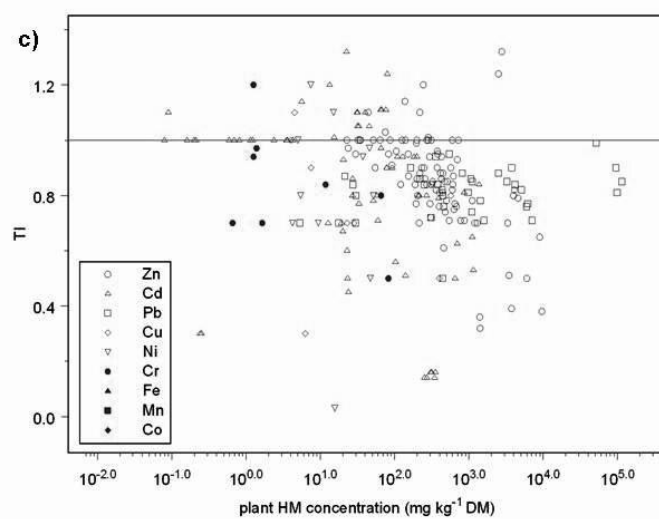
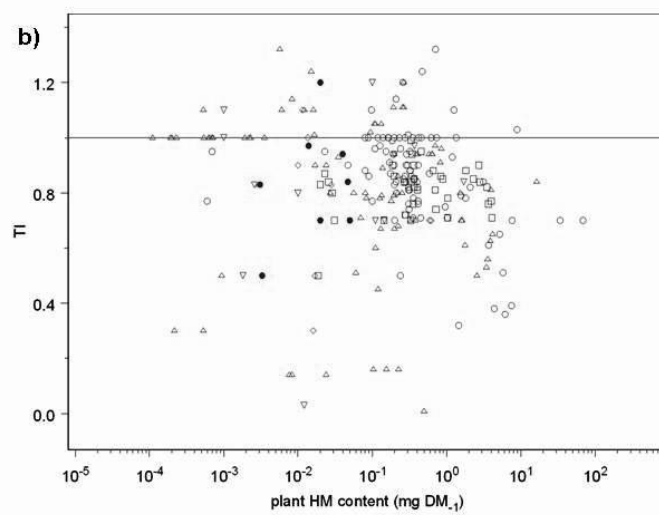
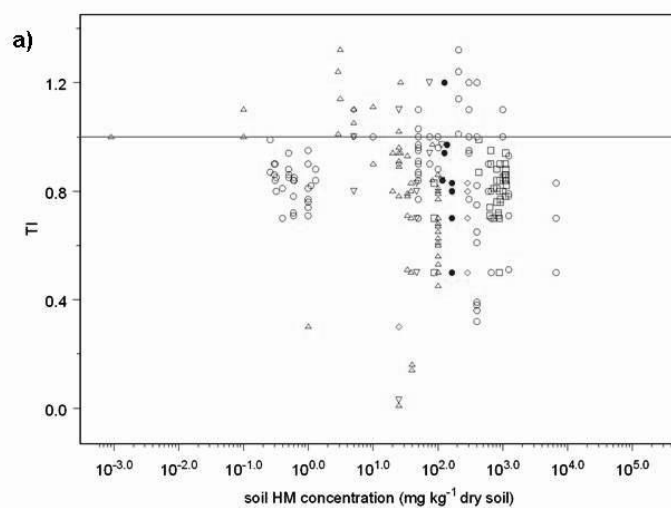
609 Figure 2. Residual SEY% (a) and residual BCF (b) in relation with soil-HM concentration  
610 ( $\text{mg kg}^{-1}$  dry soil).

611

612 Figure 3. TI in relation with soil-HM concentration ( $\text{mg kg}^{-1}$  dry soil) (a), plant HM content ( $\text{mg}$   
613  $\text{DM}^{-1}$ ) (b), and plant HM concentration ( $\text{mg kg}^{-1} \text{DM}$ ) (c). The reference line indicates  
614 the TI value of 1.







618 Table 1. Correlation coefficients ( $r$ ) for the plant HM content ( $HM_{\text{plant}}$ ), plant HM concentration ( $[HM_{\text{plant}}]$ ), residual  
 619 specific extraction yield percentage ( $SEY_{\%}$ ), and residual bioconcentration factor (BCF) in relation with the soil-HM  
 620 concentration ( $[HM_{\text{soil}}]$ ). The  $r$  values for raw and fitted coefficients (heavy metal type,  $r_{\text{HM}}$ ; reference,  $r_{\text{r}}$ ; species,  $r_{\text{s}}$ ;  
 621 plant tissue type,  $r_{\text{t}}$ ; study type,  $r_{\text{st}}$ ) and degrees of freedom (df) are shown.

Variables	df	$r$	$r_{\text{HM}}$	$r_{\text{sp}}$	$r_{\text{r}}$	$r_{\text{t}}$	$r_{\text{st}}$
$HM_{\text{plant}}$	508	0.53 <sup>c</sup>	0.65 <sup>b</sup>	0.75 <sup>a</sup>	0.76 <sup>a</sup>	0.56 <sup>bc</sup>	0.55 <sup>c</sup>
$[HM_{\text{plant}}]$	761	0.50 <sup>d</sup>	0.61 <sup>c</sup>	0.73 <sup>b</sup>	0.82 <sup>a</sup>	0.59 <sup>c</sup>	0.51 <sup>d</sup>
$SEY_{\%}$	508	-0.54 <sup>c</sup>	-0.64 <sup>b</sup>	-0.75 <sup>a</sup>	-0.74 <sup>a</sup>	-0.55 <sup>c</sup>	-0.54 <sup>c</sup>
BCF	761	-0.52 <sup>c</sup>	-0.61 <sup>b</sup>	-0.80 <sup>a</sup>	-0.81 <sup>a</sup>	-0.52 <sup>c</sup>	-0.59 <sup>c</sup>

622 All p-values <0.01. Different letters within each row indicate significant differences between correlation  
 623 coefficients according to Fisher's comparison test at  $p < 0.05$ .

Table 2. HM-specific correlation coefficients ( $r$ ) for the plant HM content ( $HM_{\text{plant}}$ ) and concentration ( $[HM_{\text{plant}}]$ ) in relation with the soil-HM concentration ( $[HM_{\text{soil}}]$ ). The  $r$  values for raw and fitted coefficients (reference,  $r_r$ ; species,  $r_s$ ; plant tissue type,  $r_t$ ; study type,  $r_{st}$ ) and degrees of freedom (df) are shown.

HM	$HM_{\text{plant}}$						$[HM_{\text{plant}}]$					
	df	$r$	$r_r$	$r_{sp}$	$r_t$	$r_{st}$	df	$r$	$r_r$	$r_{sp}$	$r_t$	$r_{st}$
Zn	186	0.29 <sup>c</sup>	0.73 <sup>a</sup>	0.59 <sup>b</sup>	0.39 <sup>c</sup>	0.33 <sup>c</sup>	202	0.24 <sup>c</sup>	0.90 <sup>a</sup>	0.84 <sup>a</sup>	0.25 <sup>c</sup>	0.71 <sup>b</sup>
Cd	156	0.71 <sup>b</sup>	0.85 <sup>a</sup>	0.85 <sup>a</sup>	0.71 <sup>b</sup>	0.75 <sup>b</sup>	211	0.56 <sup>b</sup>	0.90 <sup>a</sup>	0.86 <sup>a</sup>	0.57 <sup>b</sup>	0.67 <sup>b</sup>
Pb	80	0.40 <sup>b</sup>	0.44 <sup>b</sup>	0.76 <sup>a</sup>	0.55 <sup>b</sup>	0.56 <sup>b</sup>	142	0.05 <sup>d</sup>	0.85 <sup>a</sup>	0.77 <sup>b</sup>	0.52 <sup>c</sup>	0.44 <sup>c</sup>
Cu	44	0.34 <sup>b</sup>	0.57 <sup>b</sup>	0.80 <sup>a</sup>	0.60 <sup>ab</sup>	0.48 <sup>b</sup>	64	0.39 <sup>b</sup>	0.73 <sup>a</sup>	0.61 <sup>b</sup>	0.55 <sup>ab</sup>	0.43 <sup>b</sup>
Ni	36	0.89 <sup>a</sup>	0.90 <sup>a</sup>	0.89 <sup>a</sup>	0.89 <sup>a</sup>	0.79 <sup>a</sup>	64	0.78 <sup>b</sup>	0.81 <sup>b</sup>	0.89 <sup>ab</sup>	0.79 <sup>b</sup>	0.78 <sup>b</sup>
Cr	20	0.43 <sup>ns</sup>	0.48 <sup>ns</sup>	0.46 <sup>ns</sup>	0.52 <sup>ns</sup>	0.46 <sup>ns</sup>	28	0.35 <sup>ns</sup>	0.51 <sup>a</sup>	0.46 <sup>ns</sup>	0.76 <sup>a</sup>	0.46 <sup>ns</sup>
Co	10	0.99					10	0.99 <sup>a</sup>				
Mn	2	0.52 <sup>ns</sup>	0.99 <sup>ns</sup>		0.53 <sup>ns</sup>		20	0.91 <sup>a</sup>	0.89 <sup>a</sup>	0.89 <sup>a</sup>	0.91 <sup>a</sup>	0.90 <sup>a</sup>
Fe							4	-0.06 <sup>ns</sup>	0.77 <sup>ns</sup>	0.77 <sup>ns</sup>	-0.06 <sup>ns</sup>	

All p-values <0.01 except those indicated with ns, non-significant. Different letters within each row indicate significant differences between correlation coefficients according to Fisher's comparison test at  $p < 0.05$ . Empty coefficient fields indicate that the correlation model cannot be fitted with variables since the data analyzed were taken from either one plant species, reference source, plant tissue type, or study type only.

Table 3. HM-specific correlation coefficients for the residual specific extraction yield percentage (SEY<sub>%</sub>) and residual bioconcentration factor (BCF) in relation with the soil-HM concentration ([HM<sub>soil</sub>]). The r values for raw and fitted coefficients (reference, r<sub>r</sub>; species, r<sub>s</sub>; plant tissue type, r<sub>t</sub>; study type, r<sub>st</sub>) and degrees of freedom (df) are shown.

HM	SEY <sub>%</sub>						BCF					
	df	r	r <sub>r</sub>	r <sub>sp</sub>	r <sub>t</sub>	r <sub>st</sub>	df	r	r <sub>r</sub>	r <sub>sp</sub>	r <sub>t</sub>	r <sub>st</sub>
Zn	186	-0.73 <sup>c</sup>	-0.89 <sup>a</sup>	-0.82 <sup>b</sup>	-0.75 <sup>bc</sup>	-0.73 <sup>c</sup>	202	-0.73 <sup>c</sup>	-0.96 <sup>a</sup>	-0.92 <sup>a</sup>	-0.73 <sup>c</sup>	-0.83 <sup>b</sup>
Cd	156	-0.55 <sup>b</sup>	-0.79 <sup>a</sup>	-0.79 <sup>a</sup>	-0.56 <sup>b</sup>	-0.62 <sup>b</sup>	211	-0.63 <sup>b</sup>	-0.91 <sup>a</sup>	-0.88 <sup>a</sup>	-0.64 <sup>b</sup>	-0.72 <sup>b</sup>
Pb	80	-0.18 <sup>ns</sup>	-0.61 <sup>ab</sup>	-0.67 <sup>a</sup>	-0.38 <sup>b</sup>	-0.56 <sup>ab</sup>	142	-0.21 <sup>c</sup>	-0.79 <sup>a</sup>	-0.68 <sup>b</sup>	-0.23 <sup>c</sup>	-0.23 <sup>c</sup>
Cu	44	-0.55 <sup>b</sup>	-0.81 <sup>ab</sup>	-0.84 <sup>a</sup>	-0.69 <sup>ab</sup>	-0.61 <sup>b</sup>	64	-0.68 <sup>b</sup>	-0.84 <sup>a</sup>	-0.77 <sup>b</sup>	-0.74 <sup>ab</sup>	-0.69 <sup>b</sup>
Ni	36	0.74 <sup>ns</sup>	0.77 <sup>a</sup>	0.76 <sup>a</sup>	0.75 <sup>a</sup>	0.75 <sup>a</sup>	64	0.34 <sup>b</sup>	0.48 <sup>b</sup>	0.73 <sup>a</sup>	0.39 <sup>b</sup>	0.36 <sup>b</sup>
Cr	20	0.11 <sup>ns</sup>	-0.79 <sup>a</sup>	-0.21 <sup>ns</sup>	-0.33 <sup>b</sup>	-0.22 <sup>ns</sup>	28	-0.17 <sup>ns</sup>	-0.42 <sup>a</sup>	-0.36 <sup>ns</sup>	-0.73 <sup>a</sup>	-0.35 <sup>ns</sup>
Co	10	0.98					10	0.98				
Mn	2	-0.94 <sup>ns</sup>	-0.94 <sup>ns</sup>		-0.94 <sup>ns</sup>		20	0.70 <sup>a</sup>	0.71 <sup>a</sup>	0.71 <sup>a</sup>	0.86 <sup>a</sup>	0.70 <sup>a</sup>
Fe							4	-0.50 <sup>ns</sup>	-0.83 <sup>ns</sup>	-0.83 <sup>ns</sup>	-0.50 <sup>ns</sup>	

All p-values <0.01 except those indicated with ns, non-significant. Different letters within each row indicate significant differences between correlation coefficients according to Fisher's comparison test at p<0.05. Empty coefficient fields indicate that the correlation model cannot be fitted with variables since the data analyzed were taken from either one plant species, reference source, plant tissue type, or study type only.

1 Table 4. Correlation coefficients ( $r$ ) for the soil-HM concentration ( $[HM_{soil}]$ ), plant HM content ( $HM_{plant}$ ), and plant  
 2 HM concentration ( $[HM_{plant}]$ ) in relation with the TI. The  $r$  values for raw and fitted coefficients (heavy metal type,  
 3  $r_{HM}$ ; reference,  $r_r$ ; species,  $r_s$ ; plant tissue type,  $r_t$ ; study type,  $r_{st}$ ) and degrees of freedom (df) are shown.

Correlation comparison	df	$r$	$r_{HM}$	$r_{sp}$	$r_r$	$r_t$	$r_{st}$
$[HM_{soil}]$	236	-0.21 <sup>b</sup>	-0.29 <sup>b</sup>	-0.49 <sup>a</sup>	-0.55 <sup>a</sup>	-0.27 <sup>b</sup>	-0.24 <sup>b</sup>
$HM_{plant}$	236	-0.12 <sup>ns</sup>	-0.23 <sup>ns</sup>	-0.44 <sup>a</sup>	-0.39 <sup>a</sup>	-0.21 <sup>ns</sup>	-0.15 <sup>ns</sup>
$[HM_{plant}]$	220	-0.19 <sup>b</sup>	-0.32 <sup>b</sup>	-0.49 <sup>a</sup>	-0.54 <sup>a</sup>	-0.24 <sup>b</sup>	-0.20 <sup>b</sup>

4 All p-values <0.01 except those indicated with ns, non-significant. Different letters within each row indicate  
 5 significant differences between correlation coefficients according to Fisher's comparison test at  $p < 0.05$ .

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7 **SUPPLEMENTARY DATA**

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**Heavy metals and soil concentration ranges comprised in the meta-analysis.**

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HM	soil HM range (mg kg <sup>-1</sup> dry soil)	Reference
Zn	0.2 - 27 413	Audet & Charest 2006; Ayoub et al 2003; Bi et al. 2003; Barazani et al 2002; Bi et al. 2003; Chen et al. 2003a, 2004; Cui et al. 2004; Delorme et al. 2001; Freeman et al. 2005; Gildon & Tinker 1983; Hammer & Keller 2002; Kubota & Takenaka 2003; Li & Christie 2001; Marchiol et al. 2004a, b; Mereno et al. 2002; Shen et al. 2002; Wang et al. 2005; Weissenhorn et al. 1995; Wu et al. 2004; Xia 2004; Yanai et al 2006.
Cd	0.001 - 770	Ayoub et al 2003; Barazani et al 2002; Chen et al. 2003b, 2004; Citterio et al. 2003; Delorme et al. 2001; Gildon & Tinker 1983; Hammer & Keller 2002; Hutchinson et al. 2000; Kubota & Takenaka 2003; Marchiol et al. 2004a, b; Pichtel et al. 2000; Riverra-Becerral et al. 2002; Shen et al. 2002; Wang et al. 2005; Weissenhorn et al. 1995; Wu et al. 2004; Xia 2004; Yanai et al 2006.
Pb	24 - 140 500	Barazani et al. 2002; Blaylock et al. 1997; Chen et al. 2003b; Cui et al. 2004; Huang et al. 1997; Kubota & Takenaka 2003; Marchiol et al. 2004a, b; Mereno et al. 2002; McGrath et al. 1997; Pichtel et al. 2000; Rydlova & Vosatka 2003; Shen et al. 2002; Vivas et al. 2003; Wang et al. 2005; Weissenhorn et al. 1995; Wu et al. 2004; Xiong et al. 1997.
Cu	5 - 1 631	Barazani et al. 2002; Gildon & Tinker 1983; Hammer & Keller 2002; Jiang & Wang 2004; Kubota & Takenaka 2003; Marchiol et al. 2004a, b; Mereno et al. 2002; McGrath et al 1997; Shen et al. 2002; Wang et al. 2005; Weissenhorn et al. 1995; Wu et al. 2004; Yanai et al 2006.
Ni	5 - 2 570	Barazani et al. 2002; Citterio et al. 2003, 2005; Freeman et al. 2005; Gildon & Tinker 1983; Marchiol et al. 2004a, b; McGrath et al. 1997; Li et al. 2003.
Cr	18 - 300	Citterio et al. 2003, 2005; Marchiol et al. 2004a, b.
Fe	3 - 34	Barazani et al. 2002, Kubota & Takenaka 2003.
Co	24 - 37	Li et al. 2003.
Mn	21 - 11 4000	Barazani et al. 2002, Kubota & Takenaka 2003, McGrath et al. 1997; Weissenhorn et al. 1995, Xue et al. 2004.

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11 Plants species comprised in the meta-analysis.

Species	Reference	Species	Reference
<i>Achillea millefolium</i>	Pichtel et al. 2000	<i>Pennisetum glaucum x P. Purpureum</i>	Xia 2004
<i>Aesculus glabra</i>	Pichtel et al. 2000	<i>Phytolacca acinosa</i>	Xue et al. 2004
<i>Agrostemma githago</i>	Pichtel et al. 2000	<i>Pisum sativum</i>	Huang et al. 1997; Riverra-Becerril et al. 2002.
<i>Agrostis capillaris</i>	Rydlova & Vosatka 2003	<i>P. pratense</i>	Bi et al. 2003, Chen et al. 2003a, Li & Christie 2001
<i>Allium cepa</i>	Gildon & Tinker 1983	<i>Platanus occidentalis</i>	Pichtel et al. 2000
<i>Alyssum corsicum</i>	Li et al. 2003	<i>Potentilla norvegica</i>	Pichtel et al. 2000
<i>Ambrosia artimissifolia</i>	Pichtel et al. 2000	<i>Raphanus sativus</i>	Chen et al. 2003b; Marchiol et al. 2004a, b
<i>Anfropogon virginicus</i>	Pichtel et al. 2000	<i>Rosa multiflora</i>	Pichtel et al. 2000
<i>Arabis gemmifera</i>	Kubota & Takenaka 2003	<i>Sonchus oleraceus</i>	Xiong 1997
<i>Brassica carinata</i>	Marchiol et al. 2004a	<i>Stenotaphrum secundatum</i>	Xia 2004
<i>B. juncea</i>	Blaylock et al. 1997; Cui et al. 2004; Marchiol et al. 2004a, b; Su & Wong 2004; Wu et al. 2004.	<i>Taraxacum officinale</i>	Pichtel et al. 2000
<i>B. napus</i>	Marchiol et al. 2004a, b	<i>Thlaspi arvense</i>	Freeman et al. 2005
<i>B. napa</i>	Shen et al. 2002	<i>T. caerulescens</i>	Ayoub et al. 2003; Delorme et al. 2001; Freeman et al. 2005; Hammer & Keller 2002; Hutchinson et al. 2000; McGrath et al. 1997; Yanai et al. 2006.
<i>B. pekinensis</i>	Mereno et al. 2002	<i>T. ochroleucum</i>	McGrath et al. 1997
<i>Cannabis sativa</i>	Citterio et al. 2003, 2005.	<i>T. officinale</i>	Ayoub et al. 2003
<i>Elsholtzia splendens</i>	Jiang & Yang 2004; Wang et al. 2005	<i>T. oxyceras</i>	Freeman et al. 2005
<i>Glechoma hederacea</i>	Pichtel et al. 2000	<i>T. perfoliatum</i>	Freeman et al. 2005
<i>Hordeum vulgare</i>	Ayoub et al. 2003	<i>T. pratense</i>	Delorme et al. 2001
<i>Lepidium heterophyllum</i>	Hutchinson et al. 2000	<i>T. rosulare</i>	Freeman et al. 2005
<i>Medicago lupulina</i>	Pichtel et al. 2000	<i>Trifolium pratense</i>	Vivas et al. 2003
<i>Mullen verbascum</i>	Pichtel et al. 2000	<i>Triticum aestivum</i>	Huang et al. 1997; Shen et al. 2002; Cui et al. 2004
<i>Nicotiana glauca</i>	Barazani et al. 2002	<i>Vetiveria zizanoides</i>	Xia 2004
<i>N. rustica</i>	Audet & Charest 2006	<i>Vigna radiata</i>	Shen et al. 2002
<i>Paspalum notanum</i>	Xia 2004	<i>Zea mays</i>	Chen et al. 2004; Weissenhorn et al. 1995

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