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POINTS OF REFERENCE

Points of Reference are part of a regular series intended to address emerging or controversial topics of interest to the scientific community.

Feasibility of Metal(loid) Phytoextraction from Polluted Soils: The Need for Greater Scrutiny

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The goal of phytoextraction is to remove contaminants—for example, metal(loid)s—from polluted soils through root uptake and accumulation in the harvested plant parts. Many articles propound phytoextraction as a low-cost means of cleaning up such polluted soils. However, if legislation is based on total soil metal(loid) concentrations, phytoextraction is generally infeasible because of unrealistically long time frames required for success in this process (Robinson et al. 2015).

Nevertheless, articles on phytoextraction continue to appear in scientific journals, although few contain any calculations showing the likely time span and mass balance of the metal(loid)s in the soil–plant system. As of April 2020, there were approximately 4000 and 12 500 articles in the Web of Science database containing the words "phytoextraction" and "phytoremediation," respectively, in the title, abstract, or keywords. Only 227 of them contained the abbreviations "g" or "kg" and "ha^{-1}" or "hectare" or "ac^{-1}" or "acre" (or "g/ha" or "kg/ha" or "g/ac" or "kg/ac") in their abstracts, despite these units being the primary measures for assessing metal phytoextraction rate. Likewise, only 87 of them contained the term "mass balance" in their abstracts. It is likely that the bulk of publications on phytoextraction are authored by academic researchers with limited specific industry experience. On the other hand, industry scientists who ask themselves the right questions and find the right answers through their practical work in remediating polluted sites may be less likely to publish the results of their studies. Therefore, the mostly perfunctory allusions to phytoextraction may cause some researchers to overlook any article with words relating to "phyto" technologies in the title.

Table 1 illustrates cleanup time-scale calculations required to achieve a 50% reduction in total soil metals assuming a constant rate over time. For instance, *Sauropus androgynus* may be useful in cleaning up Zn from soils within a reasonable time span, that is, within less than one human generation of <25 yr (Xia et al. 2013). However, it would take >1000 yr to clean up Pb using this plant species. Meanwhile, chelate-enhanced phytoextraction, where chelating agents such as ethylenediaminetetraacetic acid are added to the soil to increase plant-metal uptake, can reduce cleanup time in some cases. However, such chelate application almost invariably leads to groundwater contamination, unless carried out ex situ or in arid areas (Nowack et al. 2006). Although biodegradable chelating agents (e.g., methylglycinediacetic acid) may reduce metal leaching, they are expensive and still require impractically long times for cleanup (González et al. 2014).

Moreover, this extraction rate decreases as bioavailable soil metal declines, which may double the phytoextraction time. Another factor increasing the phytoextraction time is the spatial variability of contaminants on sites. Furthermore, high metal concentrations in soil are likely to be associated with the formation of precipitates that are not readily bioavailable or easily dissolved, particularly in the long term, which is highly relevant in the context of this article. It is for this reason that Swiss soil protection laws, to give but one example, account for both total and labile (salt-extractable) soil metals. When the primary

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TABLE 1: Estimates of time required to halve total soil metal concentrations, based on experimental metal extraction rate in field conditions[a]

Reference, country	Metal	Metal content (mg kg^{-1})	Soil layer (m)	Species	Rate (g ha^{-1} yr^{-1})	Time (years)
González et al. (2014), Chile	Cu	678	0.05	*Oenothera picensis*	212	959
Mench et al. (2018), France	Cu	1169	0.11	*Helianthus annuus*	88	8768
Xia et al. (2013), China	Zn	548	0.10[b]	*Sauropus androgynus*	15 662[c]	21
Xia et al. (2013), China	Pb	2568	0.10[b]	*Sauropus androgynus*	1225[b]	1284

[a]Soil bulk density was assumed to be 1200 kg m^{-3}.
[b]Assumed value.
[c]For aboveground biomass.

goal is to phytoextract only labile metal(loid) fractions, that is, bioavailable contaminant stripping (BCS), phytoextraction may be appropriate owing to a short time span of only a few years (e.g., Herzig et al. 2014).

Yet studies on the efficiency of phytoextraction at reducing available soil metal(loid)s are scarce. So far, few have reported the phytoextraction rate of bioavailable soil metal(loid)s, and thus, we were unable to include it in Table 1. Mench et al. (2018) reported that the annual shoot Cu removal ranged from 2.6 to 9% of 1 M NH_4NO_3-extractable topsoil Cu. Thus, approximately 5 to 20 yr will be required to halve bioavailable topsoil Cu, which is more feasible than the timeline to halve total topsoil Cu (Table 1). Determining the role of phytoextraction for BCS is complicated by other rhizosphere processes that affect bioavailability, such as changes in pH and organic carbon. A key aspect of BCS is to determine the factors affecting the replenishment of the labile pool of the targeted metal(loid)s. Metal phytotoxicity and uptake might depend on both bioavailable and total soil metal pools that are capable of supplying metal to the soil solution at the same time as plant roots take up ions (e.g., Lillo et al. 2020).

For applying the BCS concept in practice, there must be support from legislation in countries where laws governing mandatory threshold values are still based solely on total soil metal(loid)s, rather than bioavailable pools. Globally, the risk-intolerant contaminated land management approach based on total metals (which often necessitates exhaustive remediation) is being gradually replaced by the concept of risk-based sustainable land management (Reinikainen et al. 2016). Currently, the most advanced soil remediation frameworks are considering site-specific risk-based assessment of pollutant linkages and future land use, rather than promoting legislation based only on mandatory threshold values. For instance, site-specific assessment using leafy and root vegetables can be carried out. If metal(loid) concentrations in edible parts of vegetables are below the threshold values, there might be no need to remediate this soil. However, vegetable consumption rate and other exposure pathways (e.g., incidental soil ingestion) also should be considered in human health risk assessment (e.g., Lizardi et al. 2020).

Practical phytoextraction research has been incorporated into the concept of phytomanagement, which includes growing nonfood crops on contaminated soils to source biomasses for various bioeconomy sectors, such as bioenergy, biofuels, timber, fiber, ecomaterials, green chemistry, and essential oils (Mench et al. 2018). Likewise, phytomanagement can change the composition and structure of microbial communities, thus restoring soil ecological functions (Burges et al. 2020).

The current challenge is how to bridge plant biomass production for the purposes of financial returns with the remediation of contaminated soils in a feasible time span. There is a need to integrate metal(loid) phytoextraction into the concepts of BCS and phytomanagement. Furthermore, it should be noted that contaminated soil can hinder plant biomass production. Therefore, finding plants with both economic value and capacity to tolerate high metal exposure is important.

In summary, we encourage authors, reviewers, and editors to be more stringent with phytoextraction articles, demanding that they include information on metal(loid) phytoextraction rates to reach an acceptable level of residual risks in a site-specific risk-based assessment of pollutant linkages according to future land use.

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