OECD PROCEEDINGS

Sources
of Cadmium
in the Environment

ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

Natural Sources of Cadmium

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Abstract

Cadmium is a naturally occurring element that falls within Group IIB of the periodic table, its average abundance in the earth's crust is 0.1 to 0.2 mg Cd/kg. On average it is present in many soils at slightly higher levels, 0.2 to 0.3 mg Cd/kg, due to weathering and biological processes that lead to relative concentration in the finer size fractions and decomposed vegetal matter. The average crustal composition masks actual geological variability, averages for individual non-phosphatic rocks vary from 0.01 to 4 mg Cd/kg, while phosphatic rocks can contain in excess of 200 mg Cd/kg. Three important physical properties, ionic radius and charge and electronegativity, influence cadmium behaviour in both the abiotic and biotic natural environments in comparison with cadmium and zinc. Natural processes lead to regional differences in background cadmium levels and careful interpretation is required to determine their relative roles, together with anthropogenic processes, in influencing the cadmium content of surficial materials. Of critical importance in environmental studies is the bioavailability of cadmium, it is this portion of the cadmium that can enter the food chain. Chemical speciation determines bioavailability; pH, carbonate, organic carbon and chloride levels are particularly important controls. There are less data concerning bioavailability than for total cadmium determinations. Studies of Canadian prairie chernozemic soils indicates that <25 per cent of the total cadmium present is actually bioavailable to wheat. Procedures to manage the risk of cadmium accumulation in agricultural products in the soil part of the soil-plant relationship have to focus on all sources of bioavailable cadmium to the soils, and in sustainable agricultural practices that provide a suitable environment for plant growth, but one that is unfavourable to the formation of mobile and bioavailable cadmium compounds.

Introduction

Cadmium is a naturally occurring element that falls in Group IIB of the periodic table, it is a member of the loosely defined group known as the heavy metals. Although life on earth has developed in the presence of background levels of cadmium there is little evidence of its essentiality, though cadmium deficiency in some animal species can hinder growth or reproduction (Markert, 1994). However, high levels of cadmium in the diet or atmosphere can lead to human health problems, e.g., Itai-Itai disease, renal dysfunction, and for smokers increased cancer risk (Hutton, 1987).

149

Cadmium is present in most geological materials at readily detectable levels using modern geoanalytical procedures, e.g., Graphite Furnace Atomic Absorption Spectrophotometry (GF-AAS) and Inductively Coupled Plasma Mass Spectrometry (ICP-MS). The majority of the data are for the total, or near-total, amounts of cadmium released by strong acid mixtures, e.g., hydrofluoric-perchloric-nitric acids and aqua-regia. However, a significant amount of data exists arising from geochemical exploration programmes around the world where the cadmium content of materials has been determined using a variety of partial leaches (weak acid mixtures, chelating agents, etc.) to map the natural distribution of cadmium in the environment in order to find mineral deposits. Similarly, there are data derived in agronomy studies using similar non-total decompositions and leaches that attempt to estimate the bioavailable amounts of cadmium in soils.

Bioavailability is controlled by chemical speciation, the mineral or chemical form in which cadmium is present in any media. Speciation controls the manner in which cadmium is transferred from one environmental compartment to another. In natural systems cadmium is most mobile and bioavailable in its soluble forms. In the solid phase cadmium can be removed and sequestered for geologically significant periods of time (e.g., >100,000 yrs), by being buried in sediment columns. Changes in the physical environment, i.e. Eh and pH, can resolubilize cadmium that had previously been immobile. These processes of mobilization and immobilization form the biogeochemical cycle of cadmium in which both physicochemical (abiotic) and biological (biotic) processes play important roles.

Physicochemical characteristics of cadmium

The distribution and mobility of cadmium in the abiotic and biotic environments is closely associated with the behaviours of Ca and Zn. In this context the ionic radii and electronegativity are important properties, Table 1, as will be discussed below.

Table 1

Atomic properties

	Ionic radius, Å	Electronegativity
Calcium, Ca	0.99	1.0
Cadmium, Cd	0.97	1.7
Zinc, Zn	0.74	1.7

Source: Krauskopf (1967)

150

All three elements are divalent, and cadmium may behave similarly with respect to cadmium or zinc depending upon the particular circumstances. Different cadmium compounds form and are stable due to the manner in which cadmium is bound in oxygen-rich (e.g., carbonate and phosphate) and sulphur-rich (e.g., sulphide) environments. Their behaviour in the abiotic and biotic environments have been discussed by Krauskopf (1967) and Nieboer and Richardson (1980) respectively.

Cadmium in the crust

In most primary (bedrock) environments cadmium behaves as a chalcophile element, i.e. one that combines with sulphur to form sulphide minerals. Pure cadmium minerals are rare, e.g., greenockite, CdS, cadmoselite, CdSe, and monteponite, CdO. However, cadmium replaces zinc in up to percentage levels in many minerals due to the similar covalent bonding behaviours of cadmium and zinc. This is most commonly seen in sphalerite, (Zn, Fe) S, smithsonite (var. otavite), $ZnCO_3$ and tetrahedrite, $Cu_{12}Sb_4S_{13}$, where Fe, Zn and other minor constituents, e.g., Ag, cadmium and Hg, replace Cu. It is often a moot point as to whether these trace constituents are in true solid solution or present as minute exsolved blebs of minerals such as cadmium carrying sphalerite. Minerals, such as sphalerite, occur as exsolution grains in common sulphide minerals, e.g., pyrite (fool's gold), FeS_2, and it is by this mechanism that cadmium is present in many rocks at trace levels of the order of 0.1 to 0.2 mg Cd/kg (ppm).

While average abundance levels, known as Clarkes to geochemists, are useful as a general guide they mask the fact that averages for individual rock types can vary over four orders of magnitude (Table 2). Darker melanocratic rocks and certain leucocratic volcanic rocks that contain sulphide minerals tend to contain higher levels of cadmium, whereas most sandstones and carbonates, with the notable exception of phosphatic sediments, contain levels up to an order of magnitude lower. In general zinc:cadmium ratios remain relatively constant at approximately 450:1 in rocks, but in the sulphide environment this ratio decreases to 250:1. It is in the latter environments that zinc mineralization, containing cadmium, can be sufficiently concentrated to permit the commercial extraction of zinc and the co-production of cadmium.

Elevated cadmium levels in black organic-rich shales, as old as 1 billion years, occur due to the presence of both sulphide minerals and organic matter. The sediment starved deep marine basins in which these rocks formed provided a euxinic environment where sulphides once precipitated were preserved and organic matter decomposition was severely retarded. The decomposing organic matter provided abundant ligands for the sequestration of a wide range of metals (Nieboer and Richardson, 1980), including cadmium. These chemical processes coupled with a lack of normal clastic sedimentation lead to high levels of the heavy metals, to the extent that some black shales are considered an environmental hazard (Reichenbach, 1993; Dunn and Irvine, 1993). These same processes are operative today in deep ocean basins which are sinks removing cadmium from the biosphere.

Table 2

Variations in average cadmium content (mg/kg or ppm) for different rock types

Ultrabasic rocks	0.1
Basic rocks	0.2
Felsic rocks	0.1
Archean metamorphic and igneous rocks	0.1
Sandstones	0.02
Carbonates	0.05
Shales	0.2
Black organic-rich shales (North America)	4
Permian phosphatic shale (Wyoming, USA)	200
Examples of Commercial Phosphate Rocks	
Igneous - Russia and South Africa	0.1
Sedimentary - Jordan	5
Sedimentary - Khneifiss, Syria	6
Sedimentary - Florida, USA	8
Sedimentary - Khourigba, Morocco	16
Sedimentary - Negev, Israel	20
Sedimentary - Bou Craa, Morocco	35
Sedimentary - North Carolina, USA	40
Sedimentary - Gafsa, Tunisia	50
Sedimentary - Togo	53
Sedimentary - Senegal	80
Sedimentary - Western USA	100

Sources: Love (1961), Turekian and Wedepohl (1961), Horn and Adams (1966), Goodfellow et al. (1980), Bøckman et al. (1990), Wedepohl (1991), Kongshaug (1992), Reichenbach (1993), Dunn and Irvine (1993)

Other than in sulphide ores, the highest cadmium levels in a really extensive rock units occur in phosphatic shales and limestones, the commercial source of a major part of the world's rock phosphate resource. In the special case of phosphates, e.g., hydroxy-apatite, francolite and collophane, the similarity of ionic radii between cadmium and calcium permits cadmium to replace calcium in its octahedral coordination structure with oxygen. Thus, hydroxy-apatite, $Ca_5(PO_4)_3(F,Cl,OH)$, francolite where carbonate replaces some of the phosphate, and collophane the cryptocrystalline variety, bearing rocks can contain average levels as high as 200 mg Cd/kg (Table 2). Sedimentary phosphorites can

be formed by at least two processes. Firstly, direct deposition on the outer parts of marine continental shelves where cold nutrient rich waters up-well from deep ocean basins, warm and enter disequilibrium with the resulting deposition of calcium phosphate. And secondly, phosphorites resulting from the subaerial erosion of older phosphatic rocks, this process can lead to formation of in situ residual phosphate richer rocks, or through transport the formation of detrital deposits where phosphatic pebbles are concentrated.

Cadmium in soils

In a global context, the weathering of rocks and glacial sediments, soil parent materials, containing sulphides is the major source of cadmium to the secondary[1] environment. The fate of liberated cadmium largely depends on other minerals (e.g., clays), ions and ligands present in the local environment and the level of biological activity. Soluble cadmium compounds, e.g., sulphate, chlorides and nitrates, and a variety of stable chloride, hydroxide and bicarbonate complexes aid the movement of cadmium in the secondary environment. However, if the soil is alkaline, and carbonate is available, insoluble $CdCO_3$ will be formed. Clays minerals, through their ability to exchange cations, will incorporate cadmium, together with other heavy metals, onto their surfaces. Precipitating Fe and Mn hydrous sesquioxides will sequester Cd^{2+} ions, these are incorporated into the mineral lattices on desiccation and become largely unavailable for resolubilization in natural soil solutions. The role of organic compounds in complexing or chelating cadmium is less well understood, however, it is complexed by both humic and fulvic acids. These processes form that part of the biogeochemical cycle at the surface-atmosphere interface, where due to similar divalency and electronegativity cadmium follows closely the behaviour of zinc.

Average abundance levels in soils are in the 0.2 to 0.3 mg Cd/kg range, but can vary significantly regionally due to differing parent material geochemistries and the above mentioned pedological processes. The main factor determining the cadmium content of soil is the chemical composition of the parent material; however, Kabata-Pendias and Pendias (1984) were incorrect in stating that levels in excess of 0.5 mg Cd/kg indicate anthropogenic impact, such levels are possible in areas of natural geochemical enrichment (e.g., Garrett, 1994). Moreover, soils developed on rocks containing similar levels of cadmium may have significantly different cadmium levels by virtue of the amount of clay minerals (the cation exchange capacity), Fe and Mn sesquixoides, and organic matter present in different horizons within the developing soil profile.

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[1] The secondary environment, as defined here, includes soils, stream and lake sediments, waters and vegetation.

Table 3

Variations in average cadmium content (mg/kg or ppm) for surface soils

Canada	- Prairies	0.28
	- Ontario	0.56
U.S.	- Western Region	0.33
	- North-Central Region	0.37
	- Northeast	0.17
	- Southern	0.15
Austria		0.2
Belgium		0.3
Denmark		0.3
England and Wales		0.24
France		0.74
Germany		0.52
Netherlands		1.76
Norway		0.95
Scotland		0.47
Sweden		1.17

Sources: Frank et al. (1976), Page et al (1987), Angelone and Bini (1992), Kabata-Pendias et al (1992), Holmgren et al. (1993), Garrett (1994)

Soil chemistry is not static, ions and materials are added both from above through the deposition of rain (snow), dust, and dead vegetation, and from below by capillary action, bioturbation, and the cycling of nutrients, including trace elements, from plant roots to leaves, woody parts, etc. Ions and materials may also be completely removed from the "volume" under consideration by erosional processes or leaching to deep groundwater levels, and, in the case of agricultural land use, cropping. Examples of the total cadmium levels reported for a number of regions are presented in Table 3.

The above data are grouped by national boundary, however, within each region the data are heterogeneous by virtue of the different soil orders that have developed as a result of the parent material, climate and local biological processes. Data presented by Holmgren et al. (1993) and Kabata-Pendias et al. (1992) clearly demonstrate the impact of these processes. When grouped by soil order United States soils vary in average cadmium

154

content by over an order of magnitude from 0.049 to 0.622 mg/kg for ultisols and histosols respectively. Similarly, in Poland, average cadmium contents vary from 0.35 to 0.48 mg/kg for luvisols and fluvisols respectively.

Organic chemical based processes play an important role in the biogeochemical cycle in causing elevated cadmium, and other heavy metal, levels in plants and the surface organic rich layers of the soil (Goldschmidt, 1937; Rose, Hawkes and Webb, 1979; Fortescue, 1980; Jeffrey, 1987; Kubovics and Nagy, 1989; Nuorteva, 1990). Failing to consider these processes can lead to the false conclusion that a significant part of the heavy metal content of the organic rich surface layer of a soil is present due to deposition from anthropogenic sources. That there are anthropogenic components is not disputed, only their magnitude relative to the natural background already present; close to anthropogenic point sources they can be major contributors. In agriculture, some soil amendments have led to a build up of cadmium in soils, but comparisons between soils need to be made under conditions of comparable matrix chemistry, including organic carbon content (e.g., Johnston and Jones, 1995; Table 7), when seeking evidence of build up due to anthropogenic processes. Vegetation, particularly deep rooted plants, in cycles metals from mineral soils to the organic rich and surface litter horizons where they are arrested in the cycle and accumulate. Except in heavily polluted areas the major part of the heavy metal present in surface soils will be from natural sources. Where anthropogenic additions have been made the metals may enter the local cycle either through deposition on the land surface or via absorption into the plant and then litter fall to the surface. Thus heavy metal patterns observed in the surface layers of soils are the result of both natural biogeochemical and anthropogenic processes.

The roles of parent material geochemistry, mineralogy through the abundance of clays and sesquioxides, and organics in providing a matrix control on the levels of cadmium, and the other heavy metals, in the soil have to be taken into account during regional studies where the source of metals to the surficial environment is being investigated. Climate controls biological productivity and the amount of organic material in surface soils and lake sediments. This in turn has a major influence in determining heavy metal levels in surficial materials as demonstrated by Garrett et al. (1990) in a 900 km latitudinal study that crossed the tree-line in Labrador, Canada.

Bioavailability of cadmium

In the context of cadmium in the food chain, or tobacco smoke, i.e., non-occupational exposure for the general public, what are most important are the levels of bioavailable cadmium in soils, not the total amounts present.

Many investigators, e.g., Chaney and Hornick (1977), Jastrow and Koeppe (1980), Page et al. (1987), Jackson and Alloway (1992) and McLaughlin et al. (1994), have reported on the links between cadmium in plants and the pH, carbonate, organic carbon, calcium, zinc and chlorine contents and sorptive capacity of soil. High pH and

155

carbonate levels inhibit cadmium uptake, the situation with organic carbon is more complex as some chemical species appear to be able to lock up cadmium and reduce its bioavailability, but others enhance its bioavailability. High calcium levels appear to inhibit cadmium uptake, whilst low zinc levels encourage it in some cases. The presence of free chlorine ions permits the presence of the soluble $CdCl_2$ in soil that is readily bioavailable. All these factors effect the bioavailability of cadmium to plants. In addition, plants are not passive occupants of the soil, by root exudates they modify the immediate microrhizomal environment, and thus may be able to encourage or inhibit nutrient and metal uptake.

Cadmium behaviour in plants and animals is closely related to that of zinc in that they both have a strong affinity for sulphur containing, particularly sulphydryl, groups. However, the similarity of cadmium to calcium may well be important in carrier mechanisms involving carboxylate and phosphate groups that effect translocation across cellular boundaries (Nieboer and Richardson, 1980).

An average (reference) cadmium level for plants of 0.05 mg/kg (dw) has been proposed by Markert (1993). However, like the Clarke for rocks, this single value hides a large amount of natural variability. Average cadmium levels in different plants, and plant parts vary over three orders of magnitude from a few mg/kg to a few mg/kg, and levels an order of magnitude higher have been reported for some vegetable foodstuffs (Kabata-Pendias and Pendias, 1984; Page et al., 1987; Angelone and Bini, 1992). Local spatial variability for a single plant species can be as extreme, i.e., three orders of magnitude. Dunn (1995) reports on Sitka alder twigs in the Kimberley area, southwestern B.C., Canada, where Pb-Zn mineralization is present and cadmium levels in plant ash range over two orders of magnitude from 0.6 to 60 mg/g within a few kilometres of each other in response to bedrock sources of cadmium.

Total cadmium contents of soil are not good predictors of plant cadmium, though there has to be sufficient cadmium in the soil for uptake. A variety of chemical procedures have been proposed and employed to attempt to directly estimate the bioavailable amounts of cadmium, e.g., EDTA, DTPA and $CaCl_2$ solutions; however, none of these are accepted as being universally applicable. This problem may be further confounded by the possibility that different plant species operate in different manners, and a particular chemical species in the soil may be more available to one plant than to another. Work by the author in the Canadian prairies using DTPA and $Na_4P_2O_7$ soil extractions indicates that the fraction of the total cadmium that is bioavailable to wheat in the dominantly alkaline to neutral chernozemic agricultural soils studied is less than 25 per cent.

Bioavailability depends on chemical speciation. The question is, for any particular soil, can cadmium be partitioned to the liquid phase by abiotic processes, or by biotically instigated processes in the microrhizomal environment, to be available for plant uptake? An obvious cadmium risk management procedure in areas where cadmium is present due to both natural (Reichenbach, 1993; Garrett, 1994) or anthropogenic, e.g., fertilizer or sludge applications (Webber and Singh, 1995), processes is to ensure that the soil chemistry is such that these reactions favour cadmium in the solid phase. Related to this

156

issue is the problem of determining the source, natural or anthropogenic, of the bioavailable cadmium. For example, let us assume that the effect of some soil amendment which contained cadmium was to stimulate plant growth so that the plant took up more of the bioavailable cadmium in the soil. If the cadmium in the amendment was bioavailable it would be advisable to reduce its level in the amendment. However, if the bioavailable cadmium was present from some other source, natural or anthropogenic, reducing the cadmium levels in the amendment would have no effect, some other action would be more appropriate to manage the risk of increased plant cadmium uptake. Because cadmium is a naturally occurring element present in all agricultural soils there will always be a pool of bioavailable cadmium. Thus, the careful control of amendments and fertilizer from all sources, phosphatic, manure, slurry and sludge is essential. The first three fertilizer sources are closely related to natural sources if farm stock eating feed are considered a part of the biogeochemical cycle.

Thus knowledge of the speciation of cadmium in natural and anthropogenically sourced materials, and the chemical species' bioavailability, is essential in planning effective risk management procedures. It is a fact that our knowledge in this area is incomplete, and can be acquired and developed.

Transboundary movements from natural sources

The transboundary movement of minerals and rock fragments occurs due to natural fluvial and aeolian processes, sometimes over long distances. Rivers transport sediments across international boundaries, major storms can move dust distances in excess of 1000 km from their sources, and volcanic eruptions are capable of putting millions of tonnes of particulates into the atmosphere. Some volcanic debris can reach the upper atmosphere and severely effect the global environment, viz. Mt. Pinatuba and ensuing northern hemisphere cold-weather summers, before being deposited back to the surface. Transboundary movement of rocks, except due to natural processes such as landslides in the immediate proximity of international boundaries, is limited to trade in raw-materials, and purchasers have the option of buying products from sources with cadmium contents compatible with their needs. Involuntary transboundary movement occurs when cadmium emissions to the atmosphere associated with the primary use of natural materials, e.g., fossil fuel burning, particularly low-grade sulphur-rich coals, base-metal smelting, and other activities, cross international boundaries.

Scale and distance are important factors, what is transboundary to some regions is only internal to some large countries unless close to an international boundary. There is considerable discussion in Canada concerning the significance of the long range transport of cadmium and other heavy metals by atmospheric processes and the relative importance of natural and anthropogenic sources. Recent Geological Survey of Canada studies of humus geochemistry within a 200 km radius of the base-metal smelter complex at Flin Flon, Manitoba, have shown that cadmium levels fall rapidly for 40 km, and drop to regional background levels somewhere between 80-120 km away from the smelter (I.

McMartin, pers. comm.). Similar results indicating a rapid decrease in levels from point sources over 40 km have been reported for Hg (Pirrone et al., 1995; Henderson and Martin, 1995). Unarguably particulates can be transported long distances, but what falls back to the surface at any point is a mixture of naturally and anthropogenically sourced materials, derived from a variety of sources and distances. However of more relevance to agriculture and the biosphere is the impact of this deposition on the land or water surfaces it falls on and the bioavailability of cadmium in the different deposited constituents.

In the terrestrial context it is useful to remember that a volume of soil of density 1.3 g/cc and containing 0.2 mg Cd/kg that is 20 cm thick covering 1 ha contains 520 g cadmium. The addition of 1 g cadmium/ha/yr through imported fertilizers, as is typical in the Canadian prairies, leads to an increase of cadmium in soils to 0.23 mg Cd/kg after 100 years assuming one year in three is unfertilized fallow. Atmospheric deposition rates for cadmium in this region are likely less than one half of this amount, assuming one third, atmospheric deposition into this soil volume would raise the level to 0.21 mg Cd/kg over 100 years. In either event, these changes in cadmium levels are insignificant in the light of the natural variability present due to geological and pedological processes. Deposition and accumulation have to be considered in the context of the reality of the naturally present cadmium, and other natural and anthropogenic processes leading to the removal of cadmium from this volume.

Risk management strategies

The level of total cadmium present in any surficial environmental compartment is controlled by a variety of natural and anthropogenic processes, and the plant bioavailable amounts of cadmium are controlled by a further set of physicochemical factors. The most important task is to reduce the levels of bioavailable cadmium so that foodstuffs grown in soils have sufficiently low cadmium levels so as not to cause a health hazard. Thus attention is focused on both the plants, by finding or breeding low cadmium accumulator cultivars, and the soils

In the context of soils two strategies are available. Firstly to reduce the amounts of bioavailable cadmium added to soils either by amendments, e.g., chemical fertilizers, manures, slurries, sludges, etc., or inadvertent addition. To accomplish this and ensure that the most effective decisions are made it is essential that there is a sufficient body of knowledge on the bioavailability of cadmium in materials purposefully or inadvertently added to soils. Secondly, it is important that the bioavailable amounts of cadmium be kept appropriately low. In regions where cadmium is naturally high due to geological and pedological factors reductions on the input side will have little effect. However, the bioavailability of cadmium in soils can be reduced by ensuring that the physicochemical environment whilst remaining favourable for plant growth is kept unfavourable for the formation of soluble bioavailable cadmium species that can be absorbed by plant root systems. This last strategy has equal efficacy for controlling naturally bioavailable

158

cadmium and that which has resulted from some anthropogenic soil amendment or inadvertent addition.

If controls are to be implemented they must focus on cadmium from all sources in the knowledge of the bioavailability of cadmium in those sources. It would be ineffective and inappropriate to focus only on chemical fertilizers when manures, slurries and sludges could also be significant contributors to the already present natural bioavailable pool of cadmium in soils. It becomes important that sustainable agricultural practices be encouraged, agricultural soils cannot be pushed and abused indefinitely without eventual degradation.

Summary

Natural levels of cadmium in the bedrock, soil and vegetation compartments of the environment can vary more than three orders of magnitude. Dominant control in all but the most anthropogenically polluted environments is exerted by cadmium abundance in the rocks and glacial sediments that provide the parent material for the soil in which the vegetation or crops are rooted. In the primary bedrock environment cadmium levels are closely associated with the abundance of sulphide and phosphate minerals, and in the case of black shales fossil organic matter. In the secondary environment factors such as the cation exchange capacity, the abundance of Fe and Mn sesquioxides and organic matter can exert local controls, both spatially and in profile, on the amounts of cadmium present in soils. Plants, particularly trees, play an important role in cycling cadmium, and other metals and nutrients, from deeper levels in the soil into the surface layers.

There is a significant pool of cadmium present in agricultural soils due to natural processes. The interpretation of cadmium levels in the surficial environment must be undertaken in the light of these natural processes as well as anthropogenic processes, such as soil amendments in agriculture and atmospheric deposition, and the removal of cadmium by erosion, leaching and cropping. With respect to the plant uptake of cadmium, it is important that a better understanding be obtained of the bioavailability of cadmium in natural and agriculturally amended or polluted soils. What are the controls on bioavailability? A complete picture has not yet been obtained, and what, particularly in the case of anthropogenic additions, are the bioavailabilities of cadmium in the materials being added to soils? It is through a knowledge of these factors that effective and appropriate risk management procedures can be defined in terms of all sources of additional cadmium to soils, so encouraging sustainable agricultural practices that preserve a physicochemical soil environment conduce to plant growth and reduce cadmium accumulation in plants.

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