Fact Sheet on Environmental Risk Assessment

Published by the International Council on Metals and the Environment (ICME)

2

MARCH 2001

How Organisms Live with Heavy Metals in the Environment

by Professor Steve P. McGrath

How do organisms cope with increased metal exposure in the environment? Before this question can be answered, it is important to distinguish between elements that are essential to life and those that are not, or at least have no known function at present. Box A shows some of the most common essential and non-essential metals.

Box A

Metals and Metalloids Classified by Their Known Essentiality to Living Organisms

ESSENTIAL	NON-ESSENTIAL
Chromium	Arsenic
Cobalt	Antimony
Copper	Cadmium
Iron	Lead
Manganese	Mercury
Molybdenum	Thallium
Nickel	Tin
Selenium	Silver
Zinc	

Some environments have too small a supply of certain essential elements. Under such conditions, organisms suffer from nutrient deficiencies, which reduce the activities of various biological functions or can even threaten the organisms' survival. It should not be surprising, therefore, if growth in the size and number of organisms is stimulated when the external supply of an essential metal increases above the deficient level (Figure 1).

Homeostasis

All organisms try to maintain their activities by controlling the concentrations of essential and non-essential elements inside their tissues — a concept known as homeostasis. Some reports even show stimulation of biological activity from small amounts of non-essential elements. This may be because some non-essential metals can substitute for the deficient nutrient to a small extent.

The flat part of Figure 1 shows a zone in which, depending on the element of interest and the particular type of organism, no apparent response occurs. However, homeostatic processes are still taking place, even though the supply of the element may be at optimal or even "luxury" levels. Simultaneously with the organism's own control mechanisms, the environment also contributes to this apparent "no change" zone, through physical and chemical processes known as "**buffering**." As the concentration of metals increases, especially in soils and sediments, various solids or dissolved materials can bind the metals chemically or even physically inside their structure. In Figure 1, curve A represents a species that is less able to withstand increasing metal concentrations in the environment, whereas curve B is a species that is more resistant to or tolerant of metals.

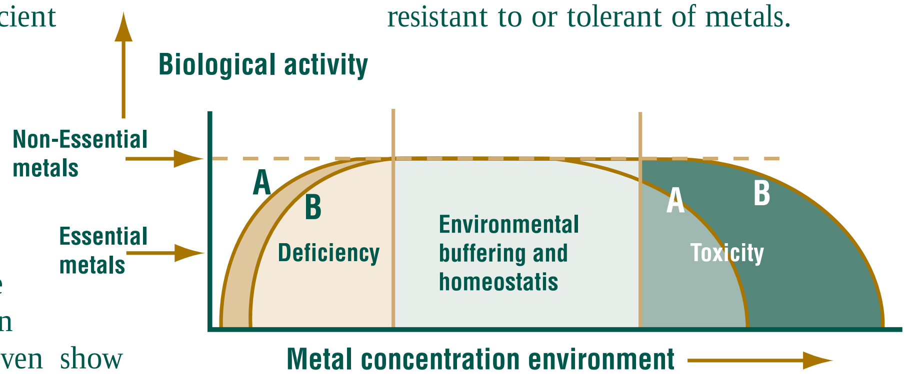

Figure 1

General Dose Responses of Organisms to Metals

ICME

Finally, at very high environmental supplies, most elements become toxic and biological activity decreases.

Acclimation and Adaptation

Organisms attempt to resist toxicity and can **acclimate to**, **tolerate** and even genetically **adapt** to high exposure. These terms are often used interchangeably to refer to the responses of organisms to metal stress; however, strictly speaking, they differ in definition and meaning (see Box B).

Acclimation (here also termed "resistance") is a non-heritable trait and is seen as the *response of an individual* to stress. Acclimation may employ either the same or different mechanisms that contribute to homeostasis. All organisms have evolved in environments that vary over time in the amount of metals present and so have mechanisms to resist metal overload. Even without genetic change, an individual or population may be resistant enough to continue to function normally upon increased metal exposure. This is referred to as **phenotypic plasticity**. This type of non-genetic resistance can easily be lost when the exposure to metals decreases. For example, the metal resistance of some grass clones as measured by the ability of roots to grow in high concentration metal solutions decreases if the clones are first grown in low-metal soil.

Box B

General Terms and Features of How Organisms Cope with Increased Metals in the Environment

ACCLIMATION	ADAPTATION
Resistance	Tolerance
Responses by the individual to stress	Genetic, heritable adaptation resulting from natural selection
Responses induced	Mechanisms often continually present
Traits can be lost	Traits not normally lost
Phenotypic plasticity	genotypic plasticity

Genetic adaptation, here termed "metal tolerance," means that the traits have evolved through natural selection in response to high metal exposure in the environment and can therefore be passed on through the genes to subsequent generations. Genetic tolerance cannot be lost in the individual, except in the case of mutations in single-celled organisms. Genetic tolerance may even render the individual less fit to survive in non-contaminated environments. However, the exact "costs" to organisms that are metal-tolerant have been difficult to identify and are not proven.

Tolerance is an organism's ability to maintain homeostasis when exposed to a particular array of environmental factors.

Mechanisms of Resistance and Tolerance

There may be overlap between tolerance and acclimation as the mechanisms used often are the same. Tolerance and acclimation are caused by change in a normal function, such as uptake of a metal, or the development of a new mechanism. This may be a result of activation of previously silent genes or simply the consequence of a range of available phenotypes coded by active genes. Basic mechanisms that occur across the different groups of organisms can be distinguished (Figure 2). Avoidance — the ability to move elsewhere (such as earthworms moving out of contaminated layers) or to limit contact with the contaminated soil (such as earthworms lining their burrow with materials that are less toxic) — may appear to be limited to animals.

However, some plant phenomena can be thought of as avoidance, such as trees allocating their roots into deeper uncontaminated layers, plant roots growing around contaminated zones, or "excluder" plants that limit the movement of metals from roots to the sensitive metabolic tissues present in leaves.

Additionally, **animals are known to change their life cycle**, e.g., altering the period to maturity, while plants may flower sooner in response to stress or may reproduce vegetatively instead. **Both plants and animals can excrete metals**. Animals do this through the gut or into hair and feathers that later are lost during molting; plants drop old leaves containing high metal levels or **excrete metals** into hairs on the leaves. At a cell or organ level, the types of resistance mechanisms in different organisms can be similar.

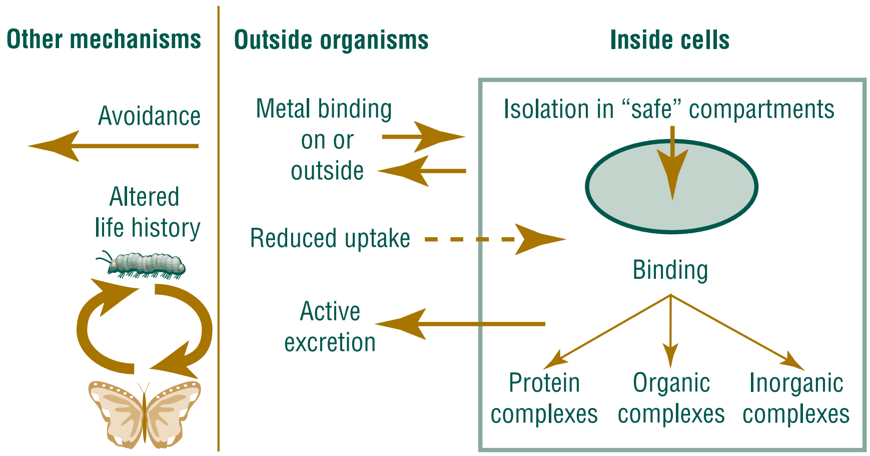

Figure 2

Metal Tolerance Mechanisms

Plants

Of special interest is the development of specialized **"metalliferous" flora** in parts of the globe that are characterized by longstanding natural occurrence of high metal concentrations in the soil. Tolerant plants originating in these locations can be either **"excluders"** or **"accumulators"** of metals (Figure 3). It was discovered some 40 years ago that metal-tolerant excluder plants can evolve rapidly at human-made polluted sites. On the other hand, metal **"hyperaccumulating"** plants do not occur on recently polluted sites unless carried there by humans. These plants accumulate metals and store them in structures such as vacuoles and leaf hairs, outside the metabolically active parts of cells. This adaptation is more effective than exclusion at highly toxic sites and has led to the term **"hypertolerance."** Hyperaccumulators can, for example, accumulate up to 3% Ni or Zn and 1% Cd into the plant and still remain healthy or continue to grow well, under conditions with solutions of 59, 65 and 56 mg/L of these metals respectively at the root surface.

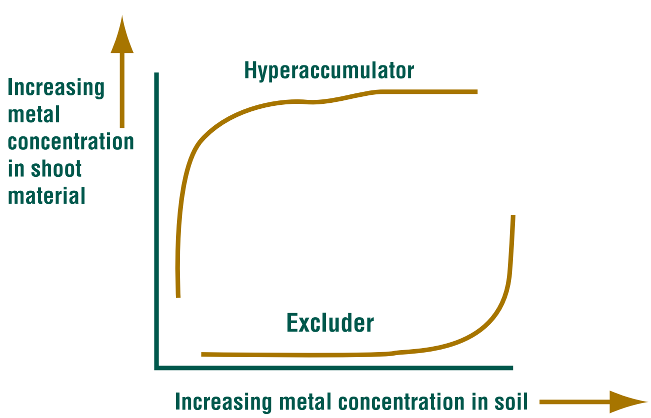

Figure 3

Strategies of Plants Towards Metals in Soil

Animals

Animals do not exhibit adaptive tolerance to high metal exposures in the same habitats in which tolerant plants are found. Animals that persist at such sites appear to use acclimation or avoidance mechanisms. If the metal stress is too severe, animals may be absent at sites where plants and microbes are still found. Tolerance has been reported in some invertebrates such as flies, isopods and spiders, but has not been proven in animals ranging from earthworms to mammals. Some animals are genetically sensitive even to "normal" levels of metals; examples are certain breeds of sheep (e.g. the Texel breed) that are extremely sensitive to copper, and humans with Wilson's disease, a rare genetic disorder that causes copper accumulation in tissues.

Microbes

Effects of increased metal exposure on soil microbes are largely hidden but also important, as global ecosystems ultimately depend on microbes for the cycling of nutrients present in organic remains. Microbes have innate control mechanisms for metals and provide a few good examples of adaptive mechanisms, such as mercury tolerance due to reduction of divalent mercury ions to elemental mercury, reduction of arsenate, and pumps for Cd, Zn, As, Cu, Co and Ni. Some general statements can be made about the differences in sensitivity of different groups of microbes: fungi are more resistant than bacteria, and gram negative bacteria which possess thicker cell walls are more resistant than gram positive bacteria. These generalizations are based on observations of the relative abundance of these groups of organisms in highly metal-stressed soils, but this does not necessarily infer genetic tolerance.

Risk Assessment Implications

Terrestrial organisms have the means to exist in environments with differing metal concentrations. Because metals are naturally occurring substances, genetically based physiological mechanisms are in place to allow organisms to respond to changing environments. Metal tolerance genes may be silent or found at very low frequency in populations of organisms inhabiting areas that have relatively low concentrations of metals. Such populations, when challenged with the addition of metals to the environment, may be exterminated. The more severe the contamination, the more individuals will be killed initially and the longer it will take for adaptive organisms to repopulate the environment. In areas with less severe metal contamination, complex communities of plants, animals and microbes are likely to redevelop quickly, or to remain viable even in the face of increased metal loads. Thus, elevated metals in soils will change the natural plant and animal communities, but will not necessarily result in a depauperate landscape. Because of this innate capacity of organisms to respond to metals in the environment, ecological costs and adverse consequences of metal enrichment (whether due to natural processes or anthropogenic sources) cannot be assumed without a clear definition of what desirable environmental attributes are at risk.

About the Author:

Professor Steve P. McGrath is Senior Principal Scientist and Programme Leader of the Soil Protection and Remediation Group at the Institute for Arable Crops Research at Rothamsted, UK. His research concerns the biogeochemistry of nutrients, heavy metals and xenobiotic pollutants and has developed sensitive biological indicators of pollution and methods for remediation of polluted soils. Professor McGrath has published over 120 papers in international peer-reviewed journals and 150 other publications. He collaborates with numerous research groups and international bodies in Europe, the US, Asia and Australia.

Fact Sheet on Environmental Risk Assessment

This is the second in an occasional series of *Fact Sheets* to be produced by ICME on metal-specific issues in environmental risk assessment. Authorship selection and editorial review are coordinated by Dr. Anne Fairbrother of Parametrix, Inc. Each *Fact Sheet* is reviewed for technical merit by Dr. Erik Smolders of Katholieke Universiteit (Catholic University) Leuven, Belgium, and by a panel of experts in metal-related regulatory issues. While the *Fact Sheets* reflect the views of the authors, they are intended to provide an objective review of each topic. ICME hopes these publications provide insights into complex issues in regulatory science, and welcomes questions and comments.

These *Fact Sheets* are also available on the ICME Web site. For additional information, please contact:

The International Council on Metals and the Environment

294 Albert Street, Suite 506
Ottawa, Ontario, Canada K1P 6E6
Tel.: (+1 613) 235-4263 Fax: (+1 613) 235-2865
E-mail: info@icme.com
Web site: www.icme.com

INTERNATIONAL COUNCIL ON METALS AND THE ENVIRONMENT
Promoting policies and practices towards sustainable development
ICME