



Plant uptake of elements in soil and pore water: Field observations versus model assumptions



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ARTICLE INFO

Article history:

Received 3 October 2012
Received in revised form
6 March 2013
Accepted 31 March 2013
Available online 28 May 2013

Keywords:

Transfer factor
Element transport
Plant uptake
Field observation
Model validity
Environmental risk assessment
Radioactive waste management
Phytoremediation

ABSTRACT

Contaminant concentrations in various edible plant parts transfer hazardous substances from polluted areas to animals and humans. Thus, the accurate prediction of plant uptake of elements is of significant importance. The processes involved contain many interacting factors and are, as such, complex. In contrast, the most common way to currently quantify element transfer from soils into plants is relatively simple, using an empirical soil-to-plant transfer factor (TF). This practice is based on theoretical assumptions that have been previously shown to not generally be valid. Using field data on concentrations of 61 basic elements in spring barley, soil and pore water at four agricultural sites in mid-eastern Sweden, we quantify element-specific TFs. Our aim is to investigate to which extent observed element-specific uptake is consistent with TF model assumptions and to which extent TF's can be used to predict observed differences in concentrations between different plant parts (root, stem and ear). Results show that for most elements, plant-ear concentrations are not linearly related to bulk soil concentrations, which is congruent with previous studies. This behaviour violates a basic TF model assumption of linearity. However, substantially better linear correlations are found when weighted average element concentrations in whole plants are used for TF estimation. The highest number of linearly-behaving elements was found when relating average plant concentrations to soil pore-water concentrations. In contrast to other elements, essential elements (micronutrients and macronutrients) exhibited relatively small differences in concentration between different plant parts. Generally, the TF model was shown to work reasonably well for micronutrients, whereas it did not for macronutrients. The results also suggest that plant uptake of elements from sources other than the soil compartment (e.g. from air) may be non-negligible.

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1. Introduction

Adverse impacts of environmental pollution on health are often quantified using dose–response models that rely on estimates of dose contributions from different pathways of exposure (Fryer et al., 2006; Törnqvist et al., 2011; U.S. EPA, 1989). In particular, ingestion of foods can lead to considerable dose contributions. Contaminant concentrations in fruits, berries, vegetables, crop grains and other edible plant parts transfer hazardous substances from the environment to animals and humans. Experimental observations of plant uptake of heavy metals (Intawongse and Dean, 2006; Kozlov et al., 2000; Ranieri, 2012), radionuclides (Choi et al., 2011; Ehlik and Kirchner, 2002), nutrients (Shtangeeva et al., 2011; Smith, 2002) and emerging contaminants including pharmaceuticals and personal care products (e.g. Calderón-Preciado et al., 2011; Tanoue et al.,

2012) emphasize the different and sometimes contrasting uptake processes of various plant types, plant parts, substance groups and various elements of the same substance group.

Hydrological and biogeochemical cycling of elements imply that plants take up elements that have been transported through coupled groundwater– surface water systems from upstream source zones in urban, industrial, mining, and agricultural areas (Baresel et al., 2006; Destouni et al., 2010; Jarsjö et al., 2005; Malmström et al., 2008). Contaminant transport models are needed at catchment scale to assess source-zone impacts and effects of possible remediation measures. Flow velocities of water, contaminant retention and natural attenuation processes along transport pathways govern the timing of contaminant breakthrough and total loads of downstream pollution (Bayer-Raich et al., 2006; Destouni et al., 2010; Jarsjö and Bayer-Raich, 2008; Malmström et al., 2008; Persson et al., 2011; Thorslund et al., 2012). Considering actual field conditions, models thus need to couple flows of water and matter through the landscape with corresponding flows

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through, and accumulation in, various linked ecosystems. Such models have been developed to quantify impacts on ecosystems of accidental radionuclide releases from a planned deep repository of high-level radioactive nuclear waste (Avila Moreno et al., 2006; Lindborg et al., 2006). These developments were based on detailed site data and models of hydrology, geochemistry, and ecology (e.g. Darracq et al., 2010; Jarsjö et al., 2008; Lindborg, 2008; Werner et al., 2006). A different aspect of element uptake by plants, which has attracted considerable scientific interest in recent years, is represented by phytoremediation applications (Manzoni et al., 2011; Mench et al., 2009; Salt et al., 1998). In phytoremediation, plants and wetland vegetation are used to reduce net pollutant flows of e.g. heavy metals and arsenic (Nyquist and Greger, 2009; Widerlund et al., 2004; Zhang et al., 2002) and organic contaminants (Gao et al., 2007). Of particular interest is the total removal of contaminants by the plants and their interactions with the ambient soil–water systems.

The element uptake by a plant, or by a plant part, needs to be predicted in all the different applications described above. However, it has been shown to be a challenge to develop models that estimate element concentrations in plants on the basis of what can be measured in the soil system. Although some authors consider mechanistic soil–plant transfer models to be preferable or even irreplaceable (Ehlken and Kirchner, 2002; Vandenhove et al., 2009), the most common method to currently quantify the transfer of specific elements from soils into plants is by means of an empirical soil-to-plant transfer factor (TF; see e.g. Section 2 of this article, Uchida et al., 2007b; Ghosh et al., 2012 for its definition and use). From its conception in the 1960's, it has been continuously used under many different names, including: the vegetable/soil TF, the transfer ratio (TR), the soil-to-plant concentration ratio (CR), the soil-to-plant concentration factor (CF), the plant uptake factor, the uptake ratio, the relative ratio, the plant bioconcentration factor and the discrimination factor. All of these names however refer to the same concept (Napier, 2006). We address the following main questions regarding the method's applicability and possible generality, given similar, well-defined ambient conditions. (i) If and, if so, how do observed concentrations of 61 selected chemical elements differ in Spring barley in agricultural fields? (ii) In which cases (e.g. considering the different elements or different soil compartments), are observed processes consistent with basic assumptions of the TF-theory? (iii) To which extent do models need to account for plant-internal translocation processes that create element-specific concentration gradients within the plants when comparing root, stem and ear concentrations?

2. Plant uptake of elements: theory, assumptions and hypotheses

The most common method to model transfer of elements from soil and pore water into plants is the use of empirical transfer factors (TFs), which are constants by definition and based on the assumption of a linear relationship between plant and soil concentrations (e.g. Sheppard and Evenden, 1988, 1990; Vera Tome et al., 2003; International Atomic Energy Agency (IAEA), 2010). They are often expressed as a ratio:

$$TF_{\text{ratio}} = C_{\text{plant}}/C_{\text{soil}} \quad (1)$$

where C_{plant} is the element concentration in plant tissues [$\text{mol kg}_{\text{dry}}^{-1} \text{weight}$] and C_{soil} is the element concentration in the soil compartment. Most previous studies have considered concentrations in the solid phase of the soil compartment, in which case C_{soil} can preferably be expressed in units of [$\text{mol kg}_{\text{dry}}^{-1} \text{weight}$], such that the TF becomes dimensionless [–]. Here, we additionally consider

concentrations in the pore water part of the soil compartment, expressing C_{soil} in units of [mol m^{-3}], which results in TF units of [$\text{m}^3 \text{kg}_{\text{dry}}^{-1} \text{weight}$]. If several measurements at different concentration levels are available, Trapp and Legind (2011) proposed that the relationship between soil and plant concentrations can be quantified using linear regression:

$$C_{\text{plant}} = C_0 + TF_{\text{slope}} \cdot C_{\text{soil}} \quad (2)$$

where C_{plant} is the dependent or response variable, C_{soil} is the independent or explanatory variable, TF_{slope} is the regression coefficient (slope of the regression line), and C_0 is the regression constant (y -axis intercept of the regression line). Trapp and Legind (2011) suggest that C_0 , which equals C_{plant} when $C_{\text{soil}} = 0$, can be interpreted as a background concentration in the plant due to uptake of elements from air, e.g. through atmospheric deposition on above-ground plant parts.

The assumed linearity between soil and plant concentrations has been questioned due to observed violations for various elements (Simon and Ibrahim, 1987; Vasconcellos et al., 1987). Such non-linear processes have been attributed to the effect of heterogeneous soil and contaminant concentration profiles (Centofani et al., 2005; Ehlken and Kirchner, 2002), and non-linear interactions with the rhizosphere and co-existing elements (Ehlken and Kirchner, 2002; Simon and Ibrahim, 1987). Hence, various soil compartments (e.g. bulk soil, soil pore water, and the rhizosphere) may show different relationships with plant concentrations, some of which may be more non-linear than others. In addition, plants concentrations can show systematic differences between different plant parts (Greger, 2006), such as roots, stems and ears of crops, since they can be affected by (potentially non-linear) plant-internal translocation processes to various degrees. Concentrations in some plant parts may therefore exhibit a more non-linear relationship with soil compartment concentrations than others.

In absence of common practice, available TF-datasets are based on a range of observations in different plant parts and soil compartments (Vandenhove et al., 2009). Furthermore, the methods that have been used to chemically analyse soil samples differ in terms of the degree of digestion, and may reflect different parts of the soil (e.g. grain surfaces versus whole grains; Tröjbom and Nordén, 2010). Results from such different datasets of TFs are often combined in long-term dose assessment models. This means that above-mentioned observations of e.g. concentration variation between plant parts and/or soil compartments are in effect neglected; assuming that values obtained from a study of a particular soil-plant system are sufficiently consistent with values obtained from studies that consider other plant parts or soil compartments. We here depart from the hypothesis that this assumption is true. The hypothesis is tested through analysis of novel field measurement data on element concentrations in different soil compartments and plant parts (see Section 3 and Fig. 1). If the hypothesis is correct, it supports the practice of using TF-values from different datasets in state-of-the-art dose assessment models, even if different procedures were used to produce the datasets. However, a rejection of the hypothesis implies that predictions could improve if TF-values used in models were based on more well-defined experimental procedures, considering for instance only certain plant parts or soil compartments.

3. Material and methods

3.1. General approach, data sources and processing

We consider element uptake in crops – specifically spring barley, which is a frequently investigated plant group (e.g. Uchida

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