Science of the Total Environment 461–462 (2013) 240–257

Contents lists available at SciVerse ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Modeling the cadmium balance in Australian agricultural systems in view of potential impacts on food and water quality

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HIGHLIGHTS

- Cadmium concentrations in soils and plants are predicted with a mass balance model.
- Predictions are made for four Australian agricultural systems for the period 1900–2100.
- Predicted soil concentrations exceeded critical soil Cd concentrations only in two systems.
- Critical Cd/P ratios in P fertilizers are comparable to those in currently used fertilizers in Australia.

ARTICLE INFO

Article history:
Received 5 December 2012
Received in revised form 23 April 2013
Accepted 23 April 2013
Available online 2 June 2013

Editor: Charlotte Poschenrieder

Keywords:
Cadmium
Food quality
Water quality
Modeling
Critical loads
Critical limits

ABSTRACT

The historical build up and future cadmium (Cd) concentrations in top soils and in crops of four Australian agricultural systems are predicted with a mass balance model, focusing on the period 1900–2100. The systems include a rotation of dryland cereals, a rotation of sugarcane and peanuts/soybean, intensive dairy production and intensive horticulture. The input of Cd to soil is calculated from fertilizer application and atmospheric deposition and also examines options including biosolid and animal manure application in the sugarcane rotation and dryland cereal production systems. Cadmium output from the soil is calculated from leaching to deeper horizons and removal with the harvested crop or with livestock products. Parameter values for all Cd fluxes were based on a number of measurements on Australian soil–plant systems. In the period 1900–2000, soil Cd concentrations were predicted to increase on average between 0.21 mg kg^{-1} in dryland cereals, 0.42 mg kg^{-1} in intensive agriculture and 0.68 mg kg^{-1} in dairy production, which are within the range of measured increases in soils in these systems. Predicted soil concentrations exceed critical soil Cd concentrations, based on food quality criteria for Cd in crops during the simulation period in clay-rich soils under dairy production and intensive horticulture. Predicted dissolved Cd concentrations in soil pore water exceed a ground water quality criterion of 2 μg l^{-1} in light textured soils, except for the sugarcane rotation due to large water leaching fluxes. Results suggest that the present fertilizer Cd inputs in Australia are in excess of the long-term critical loads in heavy-textured soils for dryland cereals and that all other systems are at low risk. Calculated critical Cd/P ratios in P fertilizers vary from <50 to >1000 mg Cd kg P^{-1} for the different soil, crop and environmental conditions applied.

1. Introduction

Inputs of phosphorus (P) fertilizers and soil amendments in Australian agricultural systems may cause accumulation of contaminants, such as arsenic (As), cadmium (Cd) fluorine (F), lead (Pb) and mercury (Hg) in soils. After consideration of the behavior of these contaminants in the soil–plant system, McLaughlin et al. (1996) concluded that only Cd in fertilizers poses a potential risk of accumulating to concentrations exceeding food quality standards in agricultural crops. A comparable conclusion is made by Chaney (2012) who presented an overview on the risks of adding selenium (Se), molybdenum (Mo), cobalt (Co), Cd and Pb. The increase in soil Cd concentrations is associated with increased Cd concentrations in crops with time (Anderson and Bingefors, 1985; Jones et al., 1992), thus causing concern for the long-term human dietary intake of Cd. In view of the risk of elevated Cd inputs to soils, Cd concentrations in foodstuffs have been monitored in Australia since 1970 to assess whether exceedances of regulatory maximum levels

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http://dx.doi.org/10.1016/j.scitotenv.2013.04.069

(MLs, formerly maximum permitted concentrations) occur, specified for certain food categories by the Australian Food Standards Code (FSANZ, 2005). Literature data show that some Australian crops such as potatoes (McLaughlin et al., 1994, 1997), peanuts (Bell et al., 1997) and leafy vegetables (Jinadasa et al., 1997) demonstrated in the past exceedances of the Australian ML of 0.1 mg kg^{-1} (fresh weight basis) in certain areas. Contrary to several European countries (Anderson and Bingefors, 1985), the same ML for wheat and other cereals is hardly ever exceeded in Australia. This even holds for the previous ML of 0.05 mg kg^{-1} (e.g. Oliver et al., 1993, 1995; McLaughlin et al., 2006), but there is still concern about possible future exceedances. In pastoral systems, exceedances are also found in animal produce. About 20% of the animals slaughtered in New Zealand had Cd concentrations in the kidney exceeding 1.0 mg kg^{-1} (Loganathan et al., 2003). Up to 2002, the ML for Cd in kidney in New Zealand was 1.0 mg kg^{-1} but since then the ML has been changed to 2.5 mg kg^{-1}, being also the current value in Australia, thus causing less exceedances of the food standard. The kidney is the critical organ for long-term Cd exposure in both animals and humans, where it irreversibly impairs re-absorption of proteins, sugars and amino acids. Extreme cases of chronic Cd toxicity lead to bone fractures, as observed in industrially polluted areas in Japan (Itai itai disease) (Kasuya, 1988).

The high concentrations of Cd in Australian superphosphates were first identified by Walkley (1940) and the environmental consequences for soil and food quality were first highlighted in Australia by Williams and David (1973). The historically high Cd concentrations in Australian phosphate fertilizers resulted from the use of island sources of high Cd phosphate rock for fertilizer manufacture (Tiller et al., 1994). The metal concentration in the rock phosphate varies with origin with low Cd concentrations (<100 mg Cd kg P^{-1}) found in igneous P rocks originating from South Africa and Russia (Kola) and high concentrations (200–450 mg Cd kg P^{-1}) in sedimentary rocks from Oceania, Africa and western USA (McLaughlin et al., 1996). Since approximately 1980, a strong decline in Cd/P ratios has been observed in the P fertilizers used in Australia, due to a shift in the source of phosphate rocks used for manufacturing locally, and a shift in the source of imported manufactured fertilizers (Zarcinas and Nable, 1992). With the exception of animal grazing systems, high (P) analysis fertilizers such as mono-ammonium phosphate (MAP) and di-ammonium phosphate (DAP) (and blends or variants based on these) with low Cd concentrations are now typically used in Australian agriculture.

Despite these reductions in Cd inputs by fertilizers, accumulation may still be ongoing, specifically in certain agricultural systems where Cd is added to soils by the application of biosolids (sewage sludge and other waste materials), soil amendments and/or animal manure. Several studies have shown that present inputs in Europe and North America still lead to net positive metal balances, including Cd, in agricultural systems (Keller et al., 2001; De Vries et al., 2002; Keller et al., 2002; Keller and Schulin, 2003; Sheppard et al., 2009). High manure application rates, mainly from the poultry industry, occur in Australia in some intensive horticultural areas, such as the greater Sydney region (Jinadasa et al., 1997). Even though the Cd concentrations are generally low in these products (<10 mg kg^{-1}), the high product application rates used can result in significant accumulation of Cd in soils and horticultural produce (Jinadasa et al., 1997). Finally, atmospheric Cd deposition, which is generally very low in Australia, may be of local importance, particularly in the proximity to urban areas or certain industries. For example, Merry and Tiller (1991) measured Cd deposition up to 3 g ha^{-1} yr^{-1} downwind from the Adelaide metropolitan area in South Australia.

Considering the above, it is pertinent that future trends in Cd accumulation in soils and crops be estimated for key Australian agricultural systems. Unfortunately, Australia lacks long-term data on soil Cd concentrations, but data on concentrations of Cd in fertilized and unfertilized rural soils show that substantial Cd accumulation of fertilizer-derived Cd has taken place already (Merry and Tiller, 1991).

This paper presents a model analysis, predicting Cd concentrations in top soils, soil solution and in crops of four key Australian agricultural systems in response to changes to Cd inputs for the period 1900–2100, to assess potential risks. The agricultural systems represent extremes in terms of Cd inputs by fertilizer and hydrology, i.e.:

- Dryland cereals: a 4 year rotation of wheat, canola, barley, and wheat; typical for Southern and Western Australia in areas with very low rainfall;
- Sugarcane and rotational crops: a rotation of sugarcane (4 years) followed by a single grain legume crop (peanuts or soybeans; 1 year); typical for coastal Queensland in areas with very high rainfall;
- Intensive rotational horticulture: a 4 year rotation of potatoes, carrots, onions, and broccoli; typical for areas nearby the larger Australian cities with average rainfall;
- Dairy production: grazing of dairy cattle on regenerated pastures in high rainfall areas or irrigated areas in Australia.

The risk is evaluated by comparing the soil concentration predictions, made with a dynamic mass balance model, with critical soil limits that were derived from the MLs for Cd in food products for the various crops involved in each system and soil–plant relationships developed for Cd uptake and transfer to harvested food. In the dairy production system, MLs for Cd in sensitive animal organs (kidney and liver) of cows were used to assess the critical soil limits. The analysis focuses on the period 1900–2100. The historic period (1900–2000) is included to evaluate the models' ability to reconstruct observed increases in soil Cd in Australia over natural background values. The future predictions are evaluated in view of the potential risks (if any) posed by Cd in fertilizer for accumulating in soils to levels where it could cause Cd concentrations in agricultural produce exceeding food quality criteria. By making the reconstructions and predictions for each of the four agricultural systems in two areas, representing the variation of agricultural practices and biophysical conditions (typical ranges in water fluxes and soil properties) affecting Cd inputs, leaching and crop uptake, we also assess which parameters are most likely to affect future soil Cd concentrations. The approach is, however, not meant to identify 'hot-spots', requiring a coupling with geographic information systems (e.g. De Vries et al., 2008), nor can it be used to assess specific management impacts at the scale of biophysical regions, farms or field scales (e.g. Moolenaar and Lexmond, 1998). The mass balance analysis was specifically carried out to assess what quality of fertilizer might be needed to safeguard food quality, given various soil and management assumptions.

2. Modeling approach

2.1. General approach

The annual accumulation (or depletion) of Cd in the mineral topsoil (Cd_{ac}) was calculated from the total annual input to the soil (Cd_{in}) minus annual crop uptake (Cd_{up}) and annual leaching from the topsoil (Cd_{le}) according to (see also (all fluxes in g ha^{-1} yr^{-1})):

$$Cd_{ac} = Cd_{in} - E_{up} - Cd_{1e}. \quad (1)$$

The following assumptions apply to the model:

(i) The soil system is homogeneously mixed which implies that both soil properties such as organic matter content and concentrations of the pollutant do not show vertical variation within the observed soil compartment. We recognize that vertical variation may occur especially in undisturbed pasture soils (McLaughlin et al., 1990), but this is less important in tilled soils. The assumption of homogeneous mixing implies that the modeling only applies for a distinctive homogeneous layer up to the depth of soil cultivation, which is the case in the present application.