Science of the Total Environment 639 (2018) 608–616

Contents lists available at ScienceDirect

Science of the Total Environment

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

Impact of organic and conventional farming systems on wheat grain uptake and soil bioavailability of zinc and cadmium

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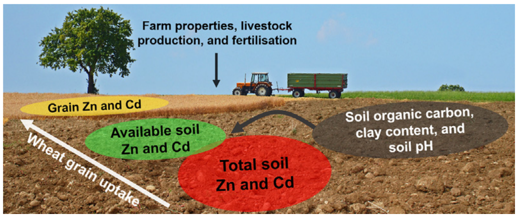
HIGHLIGHTS

- Soil Zn and Cd were promoted by soil organic matter due to higher input and binding.
- Organic farming with compost had more available soil Cd than conventional farming.
- Grain Zn was decoupled from soil Zn.
- Livestock production increased soil and grain Cd indicating contamination.
- In the field, a combination of management and soil properties influenced Zn and Cd.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 8 December 2017
Received in revised form 15 May 2018
Accepted 15 May 2018
Available online xxxx

Editor: Charlotte Poschenrieder

Keywords:
Soil organic matter
Compost application
Heavy metal
Organic matter management
Livestock production
Agronomic Zn biofortification

ABSTRACT

Zinc (Zn) deficiency is a widespread problem in human nutrition and wheat grains are a major source of Zn intake in large parts of the population. It remains unclear to what extent organic and conventional farming practices, differing in organic matter management, influence Zn availability and uptake by wheat grains. Factors leading to an increased Zn uptake may also increase the Cd uptake in wheat grains, which can be harmful for humans. Here, we investigated the effects of different farming practices on Zn and Cd concentrations in wheat grains and their relationships with total and available soil Zn and Cd concentrations, and other soil properties. In northern Switzerland, 28 farms were sampled including 11 organic farms with compost use, 10 organic farms without compost use, and 7 conventional farms without compost use. Soil organic matter was a key factor for soil Zn and especially Cd concentrations across all three farming systems. Total and available soil Cd concentrations as well as soil organic carbon concentration (SOC) were significantly higher on the organic farms with compost use than on the conventional farms. However, only the compost farms with livestock showed significantly higher grain Cd concentrations in comparison to conventional and organic farms without compost use, although a nested effect of cultivar within the system also had an influence. In contrast to Cd, the soil and grain Zn concentrations showed no significant farming system effect although there was a correlation between total soil Zn and SOC when all farms were pooled. Grain Zn was decoupled from soil Zn indicating that under agricultural field conditions the farming systems are a minor factor in increasing grain Zn. Our study suggests that the Zn and Cd soil and grain concentrations were mediated by a combination of on-farm organic matter management, soil properties, cultivar, and livestock production.

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https://doi.org/10.1016/j.scitotenv.2018.05.187
0048-9697/

1. Introduction

Increasing zinc (Zn) in edible plant parts is a strategic aim in agricultural systems to combat widespread Zn deficiency in human nutrition (Cakmak, 2008; Cakmak and Kutman, 2017; White and Broadley, 2011). The HarvestPlus program has set a target concentration of 38 mg kg^{-1} Zn in wheat grains (Bouis and Welch, 2010). In agricultural soils, the availability of soil Zn for uptake by crop plants is limited by its solubility, which is governed primarily by adsorption to mineral surfaces, complexation with organic matter and formation of precipitates (Baird and Cann, 2005; Smolders and Mertens, 2013). Due to its chemical similarity with Zn, the availability of soil cadmium (Cd) is affected in a similar manner by the same soil factors (Hart et al., 2002). However, Cd threatens human health and the environment and, thus, interactions between Zn and Cd availability and uptake should be carefully monitored. In particular, the availability of Zn and Cd in the soil is dependent on soil organic matter (SOM), oxides, clay particles, and pH (Schulin et al., 2009; Smolders and Mertens, 2013). The affinity of Zn and Cd for sorption on soil particles can be >10 times higher on organic matter than on mineral particles (Lair et al., 2007b). As agricultural practises can have a major impact on SOM and soil pH (Bolan et al., 2001; Six et al., 2000), it is important to understand how they influence available Zn and Cd concentrations in agricultural soils. For food safety reasons it is especially important to relate soil Zn and Cd to their uptake by wheat grains to determine how availability translates into the edible parts of crop plants. Previous studies showed that for some cultivars the Zn and Cd accumulation in grains might be more strongly affected by soil properties than others (Gao et al., 2011) whereas the different soil properties of sites had a higher impact than crop cultivars (Oliver et al., 1995; Wångstrand et al., 2007).

Various studies investigated how organic compounds affect Zn and Cd uptake by crop plants. In a hydroponic experiment, the addition of citrate and histidine increased Zn uptake of wheat due to soluble complex formation of Zn with these organic acids, comparing nutrient solutions with the same free Zn concentration (Gramlich et al., 2013). Soil microorganisms can increase soil Zn availability by exuding organic ligands (Altomare and Tringovska, 2011). Mycorrhizal plants were observed to have more Zn available, while Cd toxicity was reduced due to a potential discrimination of the arbuscular mycorrhiza between Zn and Cd (Janoušková et al., 2006). These greenhouse and pot experiments provided important insights, however, the impact of SOM management on Zn and Cd availability remains elusive in real farm environments.

In addition to the complexation by organic ligands and sorption at organic matter surfaces, Zn and Cd can also be sorbed and complexed at mineral surfaces like clay minerals or (hydr-)oxides (Fonseca et al., 2011; Sipos et al., 2008). Organo-mineral associations were shown to provide important interfaces for the binding of heavy metals and can be prominent factors for the binding and mobilisation of soil Zn and Cd (Arias et al., 2005; Leinweber et al., 1995).

The addition of fertilisers or amendments containing organic matter can enrich soils with heavy metals due to metal contents of the applied materials exceeding natural inputs (Facchinelli et al., 2001). Animal feed is supplemented with Zn to improve animal health and livestock productivity and the majority of the supplemented Zn is not retained by the animals and excreted (Bolan et al., 2004; Gubler et al., 2015; Schultheiß et al., 2004). The heavy metal concentrations in manure vary depending on the farming system and the feed and supplements used (Keller et al., 2002; Menzi and Kessler, 1998; Menzi et al., 1999; Möller and Schultheiß, 2015). In German dairy production, on-farm grown fodder introduced 39% of the added Zn and 71% of the Cd into cow sheds, whereas protein-rich external feed accounted for a similar range of Zn and much less Cd (Schultheiß et al., 2004). In addition, the recycling of plant residues and land management was found to influence metal dynamics and plant uptake (Düring et al., 2003; Mench, 1998; Oliver et al., 1993). While many studies have looked at the on-farm flows of heavy metals in livestock production, only a few studies have investigated to what extent heavy metals are retained and mobilised in agricultural soils (Helfenstein et al., 2016).

In this study, we investigated how agricultural cropping and livestock production systems influence Zn and Cd concentrations in wheat grains and how these effects relate to soil Zn and Cd availability and other soil factors. We sampled soils and wheat grains on farms in northern Switzerland categorised in three differing farming systems, with and without livestock production: organic farms with compost use, organic farms without compost use, and conventional farms without compost use. The objectives of the study were (i) to relate total and available soil Zn and Cd concentrations to wheat grain Zn and Cd concentrations and (ii) to assess the role of management practices and soil properties in these relationships.

2. Methods

2.1. Study site and farm characteristics

The 28 farms included in this survey were located at elevations between 340 and 954 m above sea level around Zurich in northern Switzerland (Fig. 1). The sampled soils were Cambisols (WRB) with an average clay-sized particle content of 25 ± 1.2% and a range of 16–41%. The sampled soils did not significantly differ in texture, cation exchange capacity (CEC), pH, and bulk density between the three farming systems we distinguished in this study. The climate is temperate and humid. The annual mean temperature at the centrally located city Zurich is 8.5 °C and the average annual precipitation 1136 mm. The 28 farms were classified as organic farms with compost use (COMP; $n = 11$ with 6 livestock farms), organic farms with use of uncomposted manure (ORG; $n = 10$ with 8 livestock farms) and conventional farms with integrated fertilisation of synthetic fertilisers and minor amounts of uncomposted manure (CON; $n = 7$ with 6 livestock farms).

We assessed the management practices used on the whole farms as well as those applied specifically on the sampled fields, where farmers grew winter wheat (*Triticum aestivum* L.) or spelt (*Triticum aestivum* subsp. *spelta* L.), in 2015. In particular, the winter wheat cultivars Camedo, Fiorina, Ludwig, Forel, and Siala were grown on the organic farms with compost use. On the organic farms without compost use, farmers grew Wiwa, Bockris, Titlis, Claro Bio, and Oberkulmer Rotkorn, whereas one farmer grew spelt. The conventional farmers grew the cultivars Aszita, Scaro, Arina, Zürcher Oberländer Rotkorn, Wiwa, Tengri, Titlis, Runal, Fiorina, and Claro Bio. By means of questionnaires, the following data were recorded: plot and farm size, livestock production, and fertilisation. The organic C (C_{org}), total N (N_{tot}), and mineral N (N_{min}) inputs during the whole crop rotation as well as during wheat cultivation were estimated based on fertiliser input and using standard values for nutrient contents of the various fertilisers according to Flisch et al. (2009) and Schleiss (2015; Table A.1). The N input from inorganic fertilisers was calculated from data provided by the fertiliser suppliers, whereas the total N content was assumed to equal the mineral N contents (Table A.2). The individual data of the farms is given in Table A.3.

2.2. Sampling and analysis

We collected soil and grain samples approximately 3 days prior to harvest from fields cultivated with wheat in 2015. One field was sampled per farm. Soil cores were extracted 4 times at 0–20 cm depth within 10 m distance to a representative location and merged to one composite sample per farm. The soil samples were dried for 48 h at 40 °C until constant weight, sieved <2 mm, and ground. The bulk density of 100 cm^3 soil cores was analysed in triplicates at 2.5–7.5 cm and 12.5–17.5 cm respectively and averaged across the replicates and both depths.

We analysed the clay content by treating 10 g of each sample with an excess of H_2O_2 (30%) until no further oxidation was observed. The