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CADMIUM IN NEW ZEALAND'S AGRICULTURE AND FOOD SYSTEMS

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Abstract

We summarise up-to-date data related to the management of cadmium in New Zealand's agriculture and food systems, including: cadmium concentrations reported in phosphate fertilisers used in New Zealand since 2003, with a comparison to agreed voluntary limits; soil cadmium concentrations from soil samples collected by the fertiliser industry, regional councils and other researchers between 2006 and 2015 from across a broad range of land uses and soil types; trends in soil cadmium accumulation from the long-term flood irrigation fertiliser trials at Winchmore Research Station in Canterbury, New Zealand; and cadmium concentrations in food from the 2009 New Zealand Total Diet Study, with a comparison to international standards. The analysis showed that the monthly averaged concentration of cadmium (Cd) in phosphate (P) fertiliser, ready for dispatch, has remained below the voluntary limit of 280 mg Cd/kg P, with a long-term average of 184 mg Cd/kg P. The soil cadmium data showed that for many New Zealand territorial authorities (32 of the 62 that have been sampled), there were no farms with soil cadmium concentrations beyond the range that naturally occurs in New Zealand. In four districts in the Waikato region (Matamata-Piako, Waipa, Waitomo, and Otorohanga), over 5% of the farms had soil cadmium concentrations that require active management to prevent accumulation above the voluntary soil cadmium limit of 1.8 mg Cd/kg. Of the 1980 farms sampled to date, four (0.37%) had soil cadmium concentrations that exceed this limit. Data from the long-term irrigation trials at Winchmore Research Station showed that accumulation of cadmium has slowed since the early 1990s, with modelling of cadmium concentration in an irrigated treatment suggesting a recent decline in soil cadmium concentrations. The 2009 New Zealand Total Diet Study found that cadmium intake by different age and gender groups of New Zealanders was 50% or less of the Provisional Monthly Tolerable Intake recommended by the World Health Organisation.

Introduction

Cadmium (Cd) is a heavy-metal contaminant of phosphate (P) fertiliser. Where there is sustained application of fertiliser, cadmium may accumulate in topsoil. From there, cadmium may be taken up into agricultural produce, and enters the food system. In this paper, we summarise data that are used to monitor cadmium concentrations in New Zealand's agriculture and food systems. There were three main points of focus, including cadmium in phosphate fertiliser, cadmium in agricultural soil, and cadmium in the diet of New Zealanders.

Until the 1990s, most of New Zealand's phosphate fertiliser was derived from Nauru rock phosphate, which had high cadmium concentrations. Since then, rock phosphate with lower cadmium concentrations has been sourced from elsewhere. In 1995, the fertiliser industry established voluntary limits for cadmium concentrations in fertiliser. Initially, a limit of 420 mg Cd/kg P was introduced, with a planned phased reduction in the limit. From July 1995, the cadmium concentration in fertiliser was restricted to be below 340 mg Cd/kg P. Fertiliser companies were rapidly able to manufacture fertiliser within this range, reducing the upper limit to 280 mg Cd/kg P from January 1997. Since 2001, this limit on cadmium concentrations in fertiliser has been monitored and audited through the Fertmark programme, a New Zealand fertiliser quality assurance scheme.

Management of cadmium concentration in agricultural soils is carried out through the Tiered Fertiliser Management System (TFMS; Warne 2011, Fertiliser Association of New Zealand 2014, Sneath 2015). The TFMS is a voluntary system managed by the fertiliser industry. It is part of the Cadmium Management Strategy, approved by the Cadmium Management Group (a group with representation from the fertiliser industry, primary sector organisations, regional councils, and central government agencies). The intent of the TFMS is to ensure that cadmium concentrations in agricultural soils remain within a range that allows for long-term sustainable agricultural production. The TFMS establishes concentrations of soil cadmium at which management actions should occur (Table 1). At the lowest level (Tier 0), cadmium soil concentrations are within the range of background values found in soils that have not been fertilised. No accumulation of soil cadmium is allowed by the TFMS beyond 1.8 mg Cd/kg (Tier 4), without a detailed site-specific investigation to identify risks and pathways for potential harm.

Table 1. Soil cadmium concentrations specified by the Tiered Fertiliser Management System, voluntary system managed by the fertiliser industry.

Tier	Soil cadmium (mg Cd/kg)	Management required
Tier 0	< 0.6	Soil cadmium is within the range of natural background concentrations. No restriction on phosphate fertiliser type or application.
Tier 1	0.6 to <1.0	Some restrictions on phosphate fertiliser application rates, and implementation of appropriate management practices.
Tier 2	1.0 to <1.4	Increased restrictions on phosphate fertiliser type and application rates, and implementation of appropriate management practices.
Tier 3	1.4 to <1.8	Further restrictions on phosphate fertiliser type and application rates, and implementation of appropriate management practices.
Tier 4	≥ 1.8	No further cadmium accumulation allowed unless a detailed site-specific investigation is undertaken to identify risks and pathways for potential harm.

The primary method for evaluating risk to human health from soil cadmium is through food standards and the New Zealand Total Diet Study (NZTDS, Vannoort and Thomson 2009). The NZTDS samples foods that have been purchased from supermarkets and were prepared as they would be by consumers. A range of agricultural residues and contaminants, including cadmium, are measured in these foods, and information on typical New Zealand diets is then used to estimate the total dietary intake. The World Health Organisation (2011) has established a Provisional Monthly Tolerable Intake of dietary cadmium, and data from NZTDS may be used to monitor the dietary intake of cadmium by New Zealanders relative to this concentration. There have been seven studies carried out to date, the first in 1974/75 and the most recent in 2009. A further study is currently underway, but the results are not yet available.

In this paper, we summarise the available data on cadmium concentrations in phosphate fertiliser, agricultural soil, and the diet of New Zealanders. The results of this research will be used to support the Cadmium Management Group's continuing risk management of cadmium in New Zealand's agriculture and food systems, and inform the planning for the forthcoming review of the national Cadmium Management Strategy in 2017.

Methods

Cadmium in fertiliser

The cadmium concentration in phosphate fertiliser (measured in mg Cd/kg P) is monitored using samples from the main manufacturing sites of the fertiliser companies Ballance and Ravensdown (currently at Mount Maunganui, Awarua, Ravensbourne, Awatoto, and Hornby). The two fertiliser companies carry out weekly composite sampling of fertiliser that is ready for dispatch, at each manufacturing site, with data available since January 2003 (3188 samples). Samples are taken of each of the main phosphate fertiliser products, and an average cadmium concentration for each manufacturing site is calculated, weighted by the production of each sampled product. The sampling is carried out as part of the Fertmark fertiliser quality assurance programme, which specifies the sampling and analytical methods (Fertiliser Quality Council 2015). The industry sampling programme is audited by Quality Consultants of New Zealand Limited (QCONZ), who also collate the data, in a spreadsheet. In the present study, the weekly data were averaged to determine the monthly mean concentration of cadmium between January 2003 and July 2015. The average was an unweighted average across the manufacturing sites, and was not weighted by relative fertiliser production volumes, as these data were not available. The 5th and 95th percentiles of the data were calculated to indicate the range of variation in the spot samples.

Cadmium in soil

Cadmium concentrations in soil were measured by the fertiliser industry, as part of on-farm nutrient sampling. The samples were typically from composite samples collected along a transect or a grid, generally to a depth of either 7.5 cm or 15 cm, depending on land use. The TFMS requires the composite sample to comprise 15 to 20 soil cores collected along a transect, or a grid, so that the cores are representative of a land management unit. Metadata associated with each sample include a customer identifier (allowing repeated samples from the same farm to be identified—in the analysis, the customer identifier was assumed to represent a farm), a soil type, a land use, the date of the sample, and a locality. Due to customer confidentiality requirements, the precise location of the samples was not made available, and the localities were standardised by identifying the associated Territorial Authority. The land use and soil type categories were also standardised, with soil types of Sedimentary, Ash, Pumice, or Peat/Organic, and land use categories of dairy, sheep and beef, arable cropping, horticultural cropping, background, or other. A land use of background was used for conservation land, while a land use of other included forestry, turf, and urban land. Ballance and Ravensdown provided data from 6840 soil samples, taken in 2007 and over the period 2012–2015. Of the industry samples, 3492 (51%) were from 2014.

In addition to the industry data, soil cadmium data from other sources (such as regional councils and researchers) were collated by Landcare Research and included with the industry data. The land use, soil type and other metadata were standardised in the same way as the industry data. There were 1996 samples from other sources (1463 from regional councils and 533 from researchers), collected in the period 2006–2012.

In an analysis of cadmium concentration by territorial authority, the industry data were first averaged by customer identifier (to provide a mean cadmium concentration per farm), before the proportion of customers within each territorial authority that was above each level of the TFMS was calculated. Data from 3936 samples from 1980 different farms (based on customer identifier) were used from the period 2012–2015. During this period, the fertiliser industry collected an additional 1360 samples without an available farm identifier, and these samples were not included in the present analysis. Of the 1980 farms, 75 farms had insufficient information to allow the assignment of a territorial authority. In addition, when there was no cadmium data in some territorial authorities, they were merged with adjacent territorial authorities for the purpose of this analysis. For this approach, Wellington, Lower Hutt City, and Porirua District were merged with Upper Hutt City, and Kawerau was merged with Whakatane.

Cadmium in food
Data on the concentration of cadmium in food are collected by the Ministry for Primary Industries as part of the NZTDS. The latter samples foods, following a simulated New Zealand diet, and these foods are then analysed for selected agricultural residues, contaminants, and nutrient elements. The foods are bought at supermarkets, and prepared as they would be by consumers. The study includes an analysis of cadmium concentration in the sampled foods. There have been seven NZTDS studies to date, including the first study in 1974/75, and the most recent one in 2009. We included results from the 2009 study, as data from a more recent study (currently underway) are not yet available.

Results

Cadmium in fertiliser
Across all weekly samples from the main manufacturing sites, the average cadmium concentration between January 2003 and July 2015 was 184 mg Cd/kg P (Figure 1). Ninety-five percent of the samples had cadmium concentrations less than 246 mg Cd/kg P, while five percent of the samples had concentrations less than 108 mg Cd/kg P. The monthly mean values fluctuated within this range, falling below 108 mg Cd/kg P in the last two months of the series (June and July 2015). The maximum monthly mean concentration over the period from 2003 to 2015 was 243.5 mg Cd/kg P.

Since 2003, there have been two individual samples declared as exceeding the voluntary limit of 280 mg Cd/kg P. These were slight exceedences at 285 and 299 mg Cd/kg P. Two additional exceedances were recorded (with concentrations of 282 and 293 mg Cd/kg P), but they were from samples mistakenly taken from rock phosphate prior to blending.

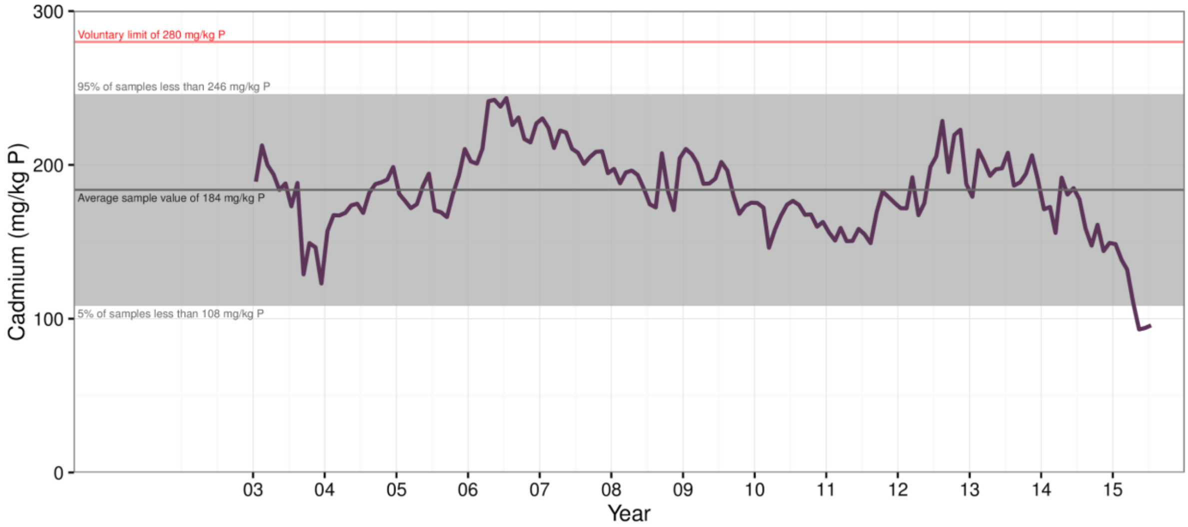


Figure 1. Cadmium concentration in fertiliser samples from the main manufacturing sites (based on data from Quality Consultants of New Zealand Limited). The line shows the monthly mean concentration, the straight line shows the mean value over the period, and the shading marks the 90th percentile interval of the sample data.

Cadmium in soil

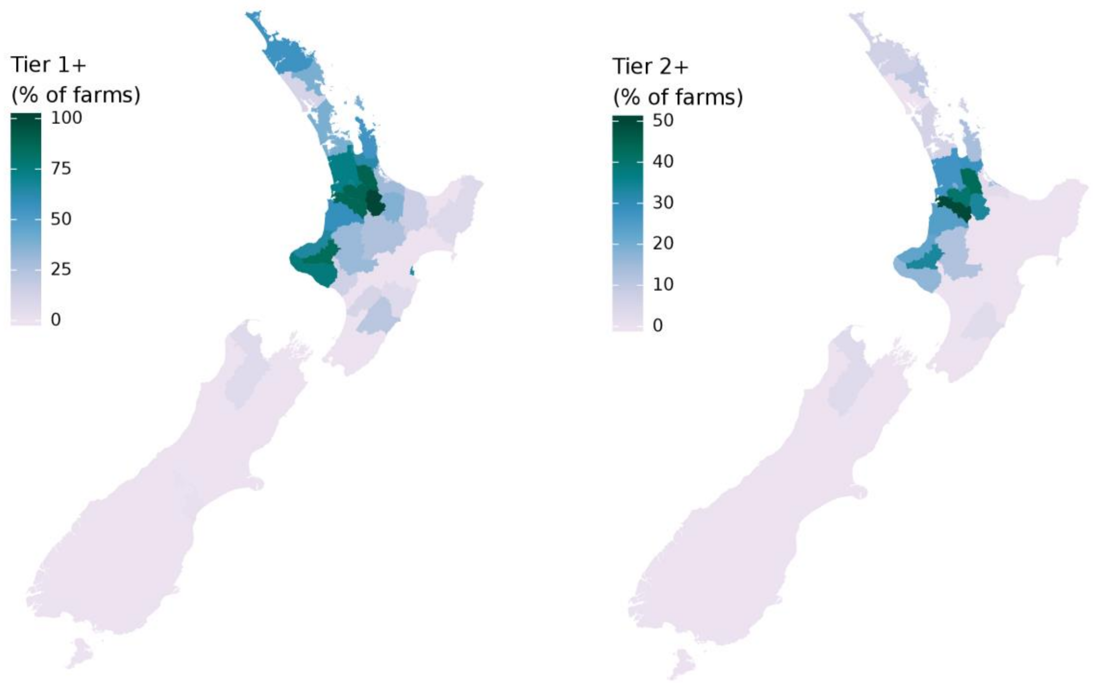
There were 8835 soil samples taken between 2006 and 2015. Of this total, 6840 samples were taken by the fertiliser industry, with the remainder being from regional councils and researchers. The mean soil concentration was 0.43 mg Cd/kg, and the highest recorded soil cadmium concentration was 3.05 mg Cd/kg. Across all samples, 95% had a soil cadmium concentration less than 1.16 mg Cd/kg. There were 29 individual samples (0.33% of all samples) that had a soil cadmium concentration at or above the TFMS Tier 4 threshold of 1.8 mg Cd/kg.

Of the industry samples, 3936 were associated with an identifiable farm. Of the 1980 identified farms that had been sampled for cadmium, 40.8% were only represented by a single sample, while the mean number of samples per farm was 1.99. There was considerable variability in the cadmium concentrations of individual farms. For example, there was one farm in Tasman District that had 19 samples taken. Of these samples, four had soil cadmium values that were greater than 1.8 mg Cd/kg, but seven samples from the same farm had concentrations of less than 0.3 mg Cd/kg. Across all the samples taken on this farm, the mean concentration was 0.93 mg Cd/kg. More generally, variability may be measured by the coefficient of variation (CV, defined as the ratio of the standard deviation to the mean value of the samples). The mean CV of the cadmium concentration of soil samples from the same farm was 0.29 (when restricted to the 99 farms that had 5 or more samples). When calculated for the 62 territorial authorities with five or more soil samples, the mean CV was 0.56. By this measure, variation in cadmium concentration within farms was around half the variation within territorial authorities.

Recent industry data (2012–2015) were used to compare mean cadmium concentrations on farms with the concentrations of the TFMS. Below a soil cadmium concentration of 0.6 mg Cd/kg, soil cadmium may be considered within the range of naturally occurring concentrations (corresponding to Tier 0 in the TFMS). In half of the territorial authorities for which data were available (32 of 62), there were no sampled farms whose mean concentration exceeded this value, and so all sampled farms were Tier 0 (Figure 2). In South Island, Tasman District had 6.25% of sampled farms in Tier 1 or above (2 sampled farms). Tasman District was the only South Island territorial authority that had any sampled farms with an average cadmium concentration above 0.6 mg Cd/kg. In North Island, there were five territorial authorities in the Taranaki and Waikato regions (South Waikato, Matamata-Piako, Waipa, Otorohanga and Stratford) that had over 80% of sampled farms in Tier 1 or over.

Farms in TFMS Tier 2 or over were defined by a mean soil cadmium concentration of 1.0 mg Cd/kg or higher. In 42 of the 62 sampled territorial authorities (68%), no farms were at Tier 2 or higher (Figure 2). Nine territorial authorities had 20% of the sampled farms at Tier 2 or higher, and Otorohanga had 49% of sampled farms with soil cadmium concentrations at Tier 2 or higher. The general pattern of elevated cadmium in the Taranaki and Waikato regions was seen in previous analyses (Taylor et al 2007, Cavanagh 2014).

Farms in TFMS Tier 3 or higher were defined by a mean soil cadmium concentrations of 1.4 mg Cd/kg or higher. Of the 62 territorial authorities that had sampled farms, 56 territorial authorities (90%) had no sampled farms with soil cadmium concentrations in Tier 3 or over. There were three territorial authorities (Matamata-Piako, Waipa and Waitomo) that had between 5% and 10% of sampled farms at Tier 3 or over, and one territorial authority (Otorohanga) had 16% of sampled farms with soil cadmium concentrations at Tier 3 or over (Figure 2).



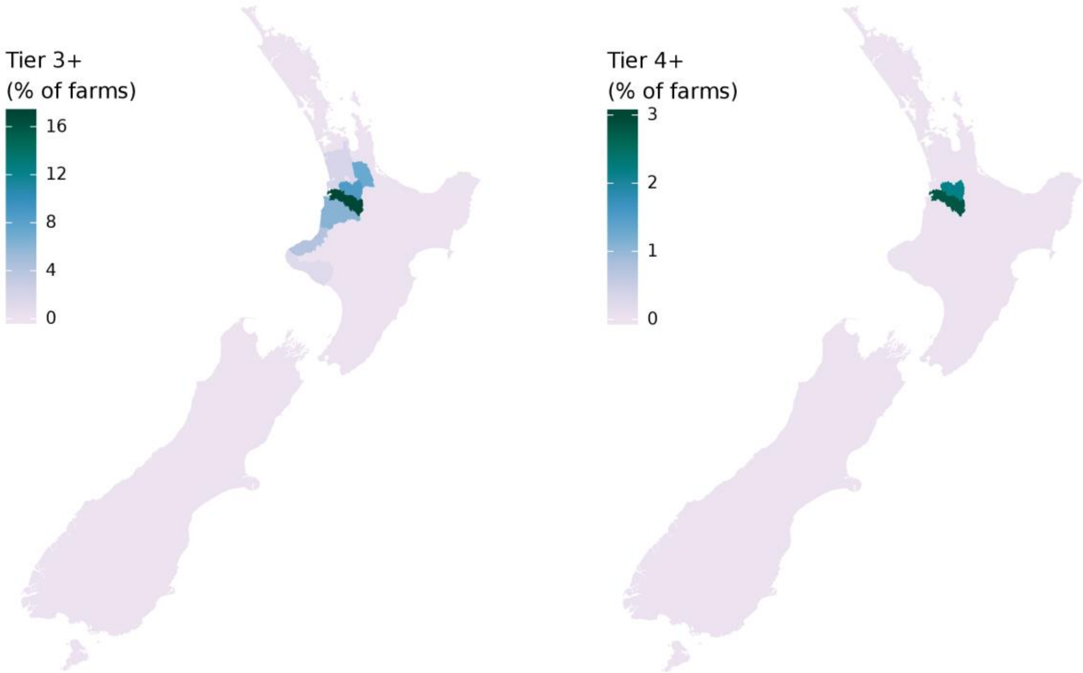


Figure 2. Percentage of sampled farms within each New Zealand territorial authority that had soil cadmium concentrations that were Tier 1 or above (soil cadmium 0.6 mg Cd/kg or higher); Tier 2 or above (1.0 mg Cd/kg or higher); Tier 3 or above (1.4 mg Cd/kg or higher); or Tier 4 (1.8 mg Cd/kg or higher) (following the Tiered Fertiliser Management System).

There were four sampled farms with a cadmium concentration over 1.8 mg Cd/kg (TFMS Tier 4). These properties were in two territorial authorities (Otorohanga and Waipa). Of these four farms, one farm had five samples taken, one farm had two samples, and two farms only had a single sample taken.

A key question is whether there is evidence of an increase in soil cadmium concentrations since 2006. To address this question, we assessed data from the Waikato region from agricultural and horticultural land use types (excluding a land use of background or other)(see summary of the individual sample data in Figure 3). With the exception of the non-industry data in 2015 (which were based on a small number of samples), the overall mean value was within the inter-quartile range in each year. Over this time period, and with this variability, there was no evidence of a change in cadmium concentration. The mean value of the non-industry data was lower than the mean value of the industry data. This finding shows that there is no evidence of under-reporting of cadmium concentrations in the industry data. Both these questions (comparison between industry and non-industry data, and change over time) would be better addressed in a statistical modelling framework that could account for variations in the number of samples by covariates such as soil type, land use category, and territorial authority.

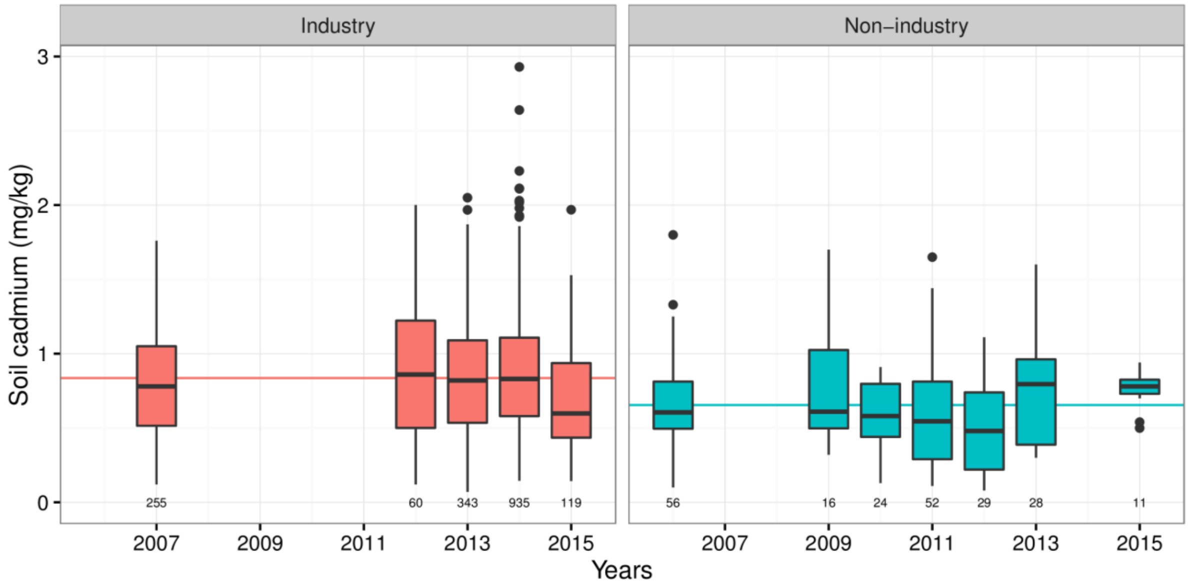


Figure 3. Sample cadmium values from the Waikato region, summarised by data source (Industry: Ballance and Ravensdown; Non-industry: regional council and researchers) and calendar year. The boxplots (Tukey 1977) show the median and interquartile ranges of the data, with points indicating sample values that are over 1.5 times the interquartile range of the median. Numbers below each box plot indicate the number of samples. Horizontal lines indicate the mean cadmium concentration of samples from each source.

Measurements of soil cadmium have been taken since the 1950s, as part of irrigation trials at Winchmore Research Station in Canterbury (McDowell 2012). These trials have maintained the same irrigation and fertiliser treatment for sixty years on sheep-grazed land in Canterbury. Measured and modelled time-series data of soil cadmium in phosphate-fertilised dryland and irrigated treatments (presented by McDowell 2012) show an increase in soil cadmium, peaking in 1992, with lower values since then (Figure 4). The cadmium mass-balance model (CadBal, Roberts and Longhurst 2005) shows either a slowing accumulation since the early 1990s (drylands treatment), or a decrease in soil cadmium (irrigated treatment). The difference between the dryland and the irrigated treatments is due both to higher production on the irrigated land (resulting in higher offtakes of cadmium), and to higher leaching (McDowell 2012).

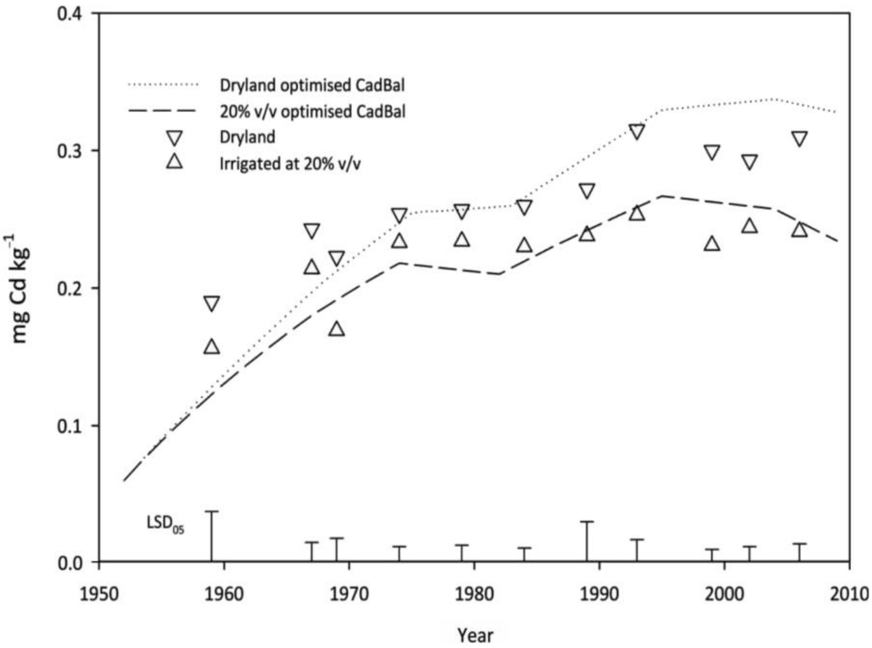


Figure 4. Change in soil cadmium concentrations over time in long-term irrigation trials at Winchmore Research Station in Canterbury (redrawn from McDowell 2012). Symbols indicate the mean sample value of soil cadmium from dryland and irrigated treatments (both treatments received 250 kg/ha of single superphosphate fertiliser annually); bars on the lower axis give the least significant difference (at a level of significance of $P < 0.05$) for comparison of the mean values between treatments; dotted and dashed lines are fits of a cadmium mass-balance model (CadBal, Roberts and Longhurst 2005) to the data.

Cadmium in food

The World Health Organisation has recommended that dietary cadmium intake is less than the Provisional Tolerable Monthly Intake (PTMI) of 25 µg/kg bodyweight/month. The 2009 total diet study measured cadmium concentration in 123 different foods, representing the most commonly consumed food items for the majority of New Zealanders. For different age and gender groups, a simulated diet was made from these foods, and the total dietary exposure was calculated. For all age and gender groups, the estimated cadmium in the diet was less than the PTMI (Figure 5). The highest cadmium value (as a percentage of the PTMI) was in the diets of toddlers and children (42.8% and 45.2%, respectively). For adult men and women (aged 25 years or over), the dietary exposure to cadmium was 26.8% and 21.6% of the PTMI, respectively.

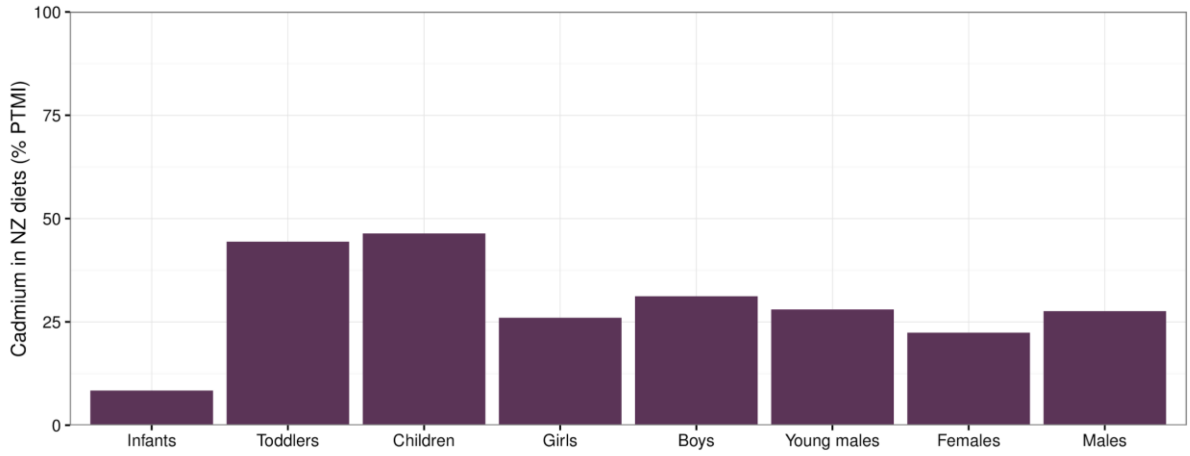


Figure 5. Cadmium in New Zealand diets, from the 2009 New Zealand Total Diet Study (Vannoort and Thomson 2009), as a percentage of the Provisional Tolerable Monthly Intake (PTMI). Dietary cadmium was estimated for the following groups: infants (6–12 months), toddlers (1–3 years), children (5–6 years), girls and boys (both 11–14 years), young males (19–24 years), and females and males (both 25 years and older).

Of the foods considered in the NZTDS, the foods that contributed most cadmium to the simulated diets were oysters, potatoes, and bread (Figure 6). Oysters accounted for 21.5% and 28.1% of the average dietary intake of adult women and men, respectively. Potatoes accounted for 23.5% and 25.1% of the average dietary intake of cadmium of adult women and men, respectively, whereas bread contributed 10.9% and 9.8% of the average dietary intake of cadmium of adult women and men, respectively. Carrot, mussels and trim milk were also included in the ten foods with the highest percentage of dietary cadmium.

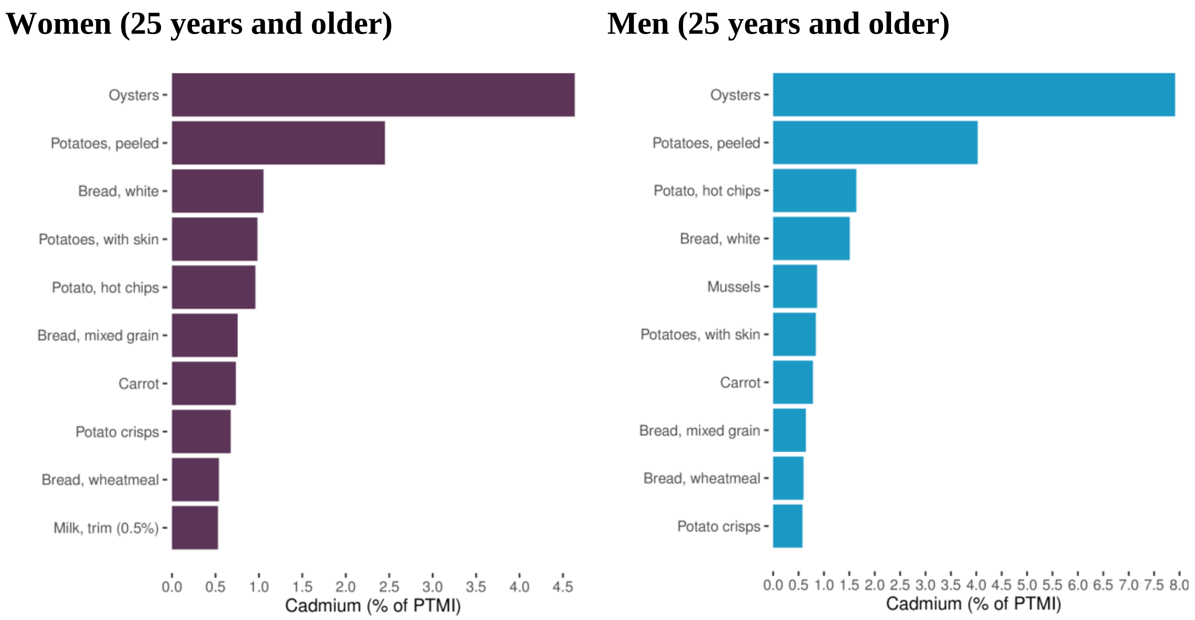


Figure 6. Ten foods that contributed the highest dietary cadmium, as a percentage of the Provisional Tolerable Monthly Intake (PTMI) for adult women and men (aged 25 years and older), from the 2009 New Zealand Total Diet Study (Vannoort and Thomson 2009).

Discussion

Cadmium in fertiliser

The monthly-averaged concentration of cadmium in phosphate fertiliser was consistently below the voluntary limits established by the fertiliser industry. There were some exceedances reported in individual samples. Since cadmium is a long-term cumulative contaminant, however, these slight exceedances are not of concern. The long-term sample average of cadmium in phosphate fertiliser was 184 mg Cd/kg P. This average is 66% of the voluntary limit of 280 mg Cd/kg P assumed for sulphuric acid derived products, such as superphosphate in developing the TFMS (Sneath 2015). Changes in the source of rock drive the variability of the cadmium concentration in the fertiliser (Cadmium Working Group 2008). In the last two available months of data, the monthly average sample concentration fell below 100 mg Cd/kg P for the first time.

Cadmium in soil

Soil cadmium from the industry data showed higher concentrations in districts within the Taranaki and Waikato regions, as has previously been found (e.g., Stafford et al 2014). This result is likely owing to the historical long-term application of fertiliser derived from Nauru rock phosphate. For most properties, concentrations were below the values at which site-specific investigation is required by the TFMS. In the Waikato region, there are four territorial authorities (Matamata-Piako, Waipa, Waitomo, and Otorohanga districts), where over 5% of the sampled farms were in Tier 3 of the TFMS. Active management of cadmium on these properties is required to ensure that there is no accumulation beyond the agreed soil cadmium limit of 1.8 mg Cd/kg (Tier 4). For some sampled farms (4 of 1980, or 0.37%), however, soil cadmium concentrations already exceeded this upper limit. On these farms no further accumulation of cadmium is permitted by the TFMS, without site-specific assessment being undertaken. There is currently no available reporting of the actions taken on these farms that ensure no further accumulation occurs. The TFMS specifies a five-year period at which all farms covered by the scheme (i.e., all farms applying at least 30 kg P/ha/yr of phosphate fertiliser) should test their soils for cadmium. As more farms are sampled, more farms may be found to be in the Tier 4 category. At the same time, it is possible that high values from individual farms are caused by outliers, and that further sampling will reduce the mean cadmium concentration on these properties.

The TFMS has requirements on the data that are collected with each sample. Because of confidentiality requirements (and because of requirements for consent from the farmer), location and farm-identifier information are not available with every sample. This omission reduces the value of the data. We recommend that the fertiliser industry works with farmers so that unique farm identifiers can be associated with every sample. Ideally, data for every sample would also include its precise location, as required by the TFMS. Improving the sample metadata will increase the long-term value of the dataset. We were only able to analyse the data by territorial authority. As it is likely that there is variation in soil cadmium concentration within districts, the lack of accurate location data prevented analysis of this variation.

In this paper, we report summaries of soil cadmium data. No statistical modelling has been carried out to account for variation in sample depth, land use, or soil type. We recommend that more detailed analysis of the soil cadmium dataset is undertaken. This analysis will allow quantification of factors associated with variation in soil cadmium, and will allow for a more thorough analysis of trends in soil cadmium concentrations in the Waikato region. A previous analysis of Regional Council data found no evidence of a trend (increasing or decreasing) in the cadmium concentration at repeatedly sampled sites (Cavanagh 2014); and we found no evidence of a change in soil cadmium concentration in the Waikato. Statistical modelling of soil cadmium would help quantify the range of trends that are consistent with the data. Long-term data from the irrigation trials at Winchmore Research Station suggest that cadmium accumulation at this Canterbury site has slowed since the early 1990s, with a model analysis showing a decrease in soil cadmium in the flood-irrigated land. McDowell (2012) concluded that, on flood-irrigated pastures, with application of phosphate fertiliser with current cadmium concentration, there is unlikely to be further accumulation of cadmium. It is not clear whether this same slowing would be found on intensively farmed land in the Waikato region that has different soil types and different irrigation.

Cadmium in food

The most recent NZTDS shows that cadmium concentrations were below the Provisional Monthly Tolerable Intake established by the World Health Organisation (2011). Variation in diet between individuals was not considered by the NZTDS. Oysters were the individual food that contributed most cadmium to the diet of adult New Zealanders, however there is considerable variation in consumption of oysters between individuals (with 94% of New Zealanders either never or rarely eating shellfish, Vannoort and Thomson 2009). Subject to the assumptions of the diet study, however, there is no evidence of risk to the health of New Zealanders from dietary cadmium.

The connections between cadmium inputs, soil cadmium, and cadmium concentrations in crops and produce are complex. Recent research on uptake of cadmium by vegetables and forage plants found marked differences between species and cultivars, and only weak relationships between plant tissue concentration and soil cadmium (e.g., Stafford et al 2016). Understanding the dynamics of cadmium in New Zealand's agricultural systems is an area of ongoing research.

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