Towards the development of an irrigation infrastructure based sampling strategy to rapidly evaluate the spatial distribution of Cd in rice-based agricultural systems

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Abstract

Cadmium (Cd) contamination of agricultural soils and crops is of considerable concern due to the effects of Cd on food security, livelihoods, environmental integrity, the sustainable use of soil resources and human health. The accurate identification and quantification of spatial Cd distribution and rice grain Cd contamination risk is an essential pre-requisite to the strategic implementation of appropriate management solutions aimed at protection of the food chain.

This research investigates the spatial distribution of soil Cd within three Field Groups comprising a total of 154 fields, in an irrigated rice-based agricultural system in Thailand that receives elevated levels of Cd via an irrigation system sourced from a Zn mineralized area. The results indicate that spatial soil Cd distribution is a function of a fields order in irrigation sequence as determined by proximity to primary outlets from in-field water courses and inter-field irrigation flows. For the Field Groups investigated, over 71.0% and 86.0% of total Field Group soil Cd loading was associated with the first two and first three fields in irrigation sequence, respectively. This suggests that in rice-based agricultural systems where the irrigation supply is both the primary Cd source and, mechanism of Cd distribution, an irrigation infrastructure-based field classification system should form the basis of any sampling strategy adopted to rapidly evaluate the spatial distribution of Cd and subsequently, rice grain Cd contamination risk. In addition, this has major implications for the development of a model to predict field specific rice grain Cd contamination risk and subsequently, the strategic targeting of appropriate management solutions.

Keywords: cadmium, irrigation infrastructure, rice, sampling strategy

Introduction

Over the last 40 years research undertaken primarily in irrigated rice-based agricultural systems receiving un-controlled discharge from non-ferrous mining, ore processing and/or smelting activities in Japan and China has, identified the irrefutable relationship between Cd contaminated rice and Cd-induced osteomalacia and renal dysfunction.

The long-term consumption of Cd contaminated rice has resulted in chronic or acute human Cd disease as manifested by Itai-Itai disease (Hagino, 1968; Yoshioka, 1970), a form of osteomalacia and/or proximal tubular renal dysfunction, respectively (Shimada *et al.,* 1977; Tohyama *et al.,* 1982; Kido *et. al.,* 1988 Cai *et al.,* 1990; Hochi *et al.,* 1995). Cadmium-induced renal dysfunction in individuals environmentally exposed to Cd is irreversible and progressive despite decreased exposure (Kido et. al., 1988; Nogawa and Kido, 1993). The effects of Cd on health are closely related to residence time in the polluted area (Nogawa and Ishizaka, 1979). In addition, several studies also suggest that Cd-induced renal dysfunction interferes with Vitamin D metabolism with, consequential reductions in Ca absorption resulting in osteopenia or osteoporosis particularly in multiparous women (Aoshima *et al.,* 1988; Kido *et al.,* 1990; Tsuritani *et al.,* 1992).

Considerable research has also established that levels of dietary Zn as well as Fe and to a lesser extent Ca are known to influence the absorption of Cd and its distribution in organs and tissues. (Evans *et al.,* 1970; Flanagan *et al.,* 1978; Koo *et al.,* 1978; Fox *et al.,* 1979; Kello *et al.,* 1979; Brzoska and Moniuszko-Jakoniuk, 1988; Berglund *et al.,* 1994; Vahter *et al.,* 1996; Reeves and Vanderpool, 1998; Reeves and Chaney, 2001).

Cadmium related health risks associated with the long-term consumption of Cd contaminated rice grain are further compounded by the fact that rice grain Fe, Zn and Ca contents are insufficient for human needs (Hallberg *et al.,* 1974; Hallberg *et al.,* 1977; Pedersen and Eggum, 1983). In addition, milling rice grain and the removal of the aleurone layer results in further Fe and Zn losses (Pedersen and Eggum, 1983; Zhang *et al.,* 1997) whilst grain Cd concentrations remain un-affected (Yoshikawa *et al.,* 1977).

Further, elevated levels of Cd, and other heavy metals and metalloids in agro-ecosystems have direct and indirect effects on food security and livelihoods by reducing yields and crop quality and hence on rural livelihoods, by reduced farm incomes. Direct affects on yield and yield quality are related primarily to element specific disruptions of plant metabolic processes (toxicity). Indirect affects are due to antagonism between heavy metals and essential macro and micronutrients in both uptake and metabolic pathways. Further, elevated levels of heavy metals in soils significantly reduce the sustainability of the soil resource and through significantly reducing soil bio-diversity. This impacts on biologically driven soil nutrient re-cycling processes and plant-soil biota symbiotic relationships.

In 1999, the Soil Chemistry Research Group (SCRG), Thai Department of Agriculture, undertook a preliminary investigation to determine the magnitude and spatial extent of Cd contamination in paddy soils receiving irrigation water sourced from a mineralized area containing extensive deposits of Zn-silicate and Zn-sulfate. *Aqua Regia* digested soil Cd concentrations were over 1600 times the Thai Cd Investigation Level (IL) of 0.15 mg Cd kg^{-1} (Pongsakul and Attajarusit 1999) and up to 83 times the EEC Maximum Permissible (MP) soil Cd value of 3.0 mg Cd kg^{-1} (EEC, 1986).

To put these results in context, in Toyama Prefecture, Japan, brown rice containing more than 1.0 mg Cd kg^{-1} was produced on soil with a Cd concentration of 0.67 mg Cd kg^{-1} (Iimura, 1981). In addition, Morishita and Anayama (1974) detected a rice grain Cd concentration of 3.57 mg Cd kg^{-1} in unpolished rice produced in soil with 4.2 mg Cd kg^{-1}. The Japanese MP rice grain Cd concentration for the safe lifetime consumption of rice is currently 0.3 mg Cd kg^{-1}. However, this is likely to be reduced to 0.2 mg Cd kg^{-1} (Personal Communication: Rufus Chaney, 2002). It is important to note that all rice grown within the study area is utilized from household and local consumption. This maximizes potential Cd-induced health risks to the local communities but ensures that rice with elevated levels of Cd does not enter the international market.

The rapid determination of spatial Cd distribution in rice-based agricultural systems receiving elevated levels of Cd is an essential pre-requisite to the strategic implementation of appropriate management solutions. The objective of this study is therefore to work towards the development an effective sampling strategy to evaluate the spatial distribution of elevated levels of soil Cd within irrigated rice-based systems.

Materials and Methods

Study Site

The rice-based agricultural system investigated in this study is within an isolated and geo-physically unique location in Thailand that receives irrigation via the Huai Mae Dtow, which is sourced from a mineralized area containing extensive Zn Silicate and Zn Sulfate deposits. A rice/soybean rotation with, occasional garlic and maize is the principle agricultural practice adopted within the study area. Rice is hand transplanted in late-July to early August and manually harvested in early-November. A high proportion of the harvested rice is retained for household consumption. This increases the potential health risk particularly if a high proportion of a particular farmers' field's produce rice with elevated levels of Cd. Soybean and/or garlic and maize are planted in late-December to early-January and harvested in late-March to early-April.

The irrigation practice adopted in the study area is primarily rotational irrigation whereby the required irrigation is applied at regular intervals. This may result in the field being without standing water for short periods between irrigations but ensures better equity among water users and effective utilization of rainfall. Irrigation is applied through inter-field irrigation flows from fields of higher to lower elevation in a cascade-type system. The Huai Mae Dtow is used to irrigate approximately 400-500 ha of paddy rice. To date only 30 ha (6%) has been surveyed of which, only 0.4 ha has been surveyed in detail. Soil Cd concentrations presented in this paper are in no way indicative of Thai background soil Cd concentrations (Zarcinas et al., 1999).

Through the use of aerial photographs in conjunction with field surveys and farmer interviews, three Field Groups (FG1-3) consisting of a total of 154 fields were selected for sampling. In addition, a detailed field-based investigation of the irrigation infrastructure to identify primary irrigation canals, in-field water courses, primary-outlets from in-field water courses and inter-field irrigation flows was undertaken.

Soil sampling and analysis

Field size for the 154 fields sampled, ranges from 2.33-144.6 m^2 with a mean field size of 28.4 m^2. In May 2000, as a function of field size, a randomly selected 5-15 point 0-20cm depth composite soil sample was collected from each field. To facilitate the determination of Effective Contamination Depth (E_{CD}) and hence 'Field Specific Cd Loading' soil samples were taken at 0-20, 20-30, 30-45, 45-60, 60-75, 75-90 and 90-105cm depth from five, four and six fields in FG1, FG2 and FG3, respectively. In addition, 10 'background', 10-point composite soil samples were taken at 0-20cm depth from fields in close proximity to the study area that do not receive irrigation sourced, from the Huay Mae Dtow. All soil samples were air-dried and ground to pass a <1mm sieve.

Soil samples were digested in *aqua regia* (3:1 $HCl:HNO_3$) using an open tube digestion method (McGrath and Cunliffe, 1985) and a Gerhardt KB-TR S/N-434508 block digester. The soil samples were digested in discrete batches over a 4-month period. To assess within-batch precision (Repeatability) and between-batch precision (Reproducibility), two reagent blanks, two replicates of an In-House Standard Reference Material (IH-SRM), and three duplicates from the previous analytical batch were included in each batch of analytical samples. In addition, analytical samples were analyzed in triplicate. Element concentrations were determined using a Perkin Elmer Analyst 3000 FAAS with Deuterium lamp background correction. Analytical accuracy was further assessed through the 'real time' comparison of IH-SRM results with, element specific control charts and the use of Continuous Verification Standards (CVS) at regular intervals.

Results and Discussion

Field Specific Cd loading (kg Cd ha^{-1}) was used in this study, to evaluate spatial Cd distribution. For the purpose of this initial study, the mean (n=200 C.V. = 15.66) Thai paddy soil bulk density value of 1365 kg m^3 (Motomura *et al.,* 1979) was used. Background soil Cd was determined as 0.507 mg Cd kg^{-1} (n=10 C.V. = 9.87).

Field Specific Cd loading (kg Cd ha^{-1}) =

$$\text{Soil Cd (mg kg}^{-1}\text{)} - \text{Background Soil Cd (mg kg-}^{1}\text{)} \times \frac{\text{Mass of Soil Contaminated (kg)}}{1000000}$$

Where:

$$\textit{Mass of Soil Contaminated} = [\text{Field Area (m}^2\text{)} \times E_{CD}\text{ (m)}] \times \text{Soil Bulk Density (kg m}^3\text{)}$$

For the purpose of this study, the determination of E_{CD} assumes no leaching losses and, that the sum of the 0-20, 20-30, 30-45, 45-60, 60-75, 75-90 and 90-105cm Cd concentrations represents 100% of the profile Cd loading. The soil sampling at depth results indicates that for the 15 soil cores taken, 88.47% (C.V = 11.57) of the total profile Cd loading is within the top 0-30cm of the soil profile (Figure 1). Similar results were observed by Iimura and Ito, (1978). The dense fibrous root system of rice plants is primarily composed of adventitious nodal roots that occur in and on the surface of the paddy soil and rapidly replace the temporary seminal roots. Chino and Baba, (1981) noted that Cd placed, within the root zone of subsurface soil layers was absorbed by the root developed in that layer but was not translocated to tops. In contrast, Cd placed in the surface layer was translocated efficiently. This suggests that adventitious roots within the oxidative surface layer are sufficiently active to transport Cd to tops. Consequently, on the basis of the soil sampling at depth results and, rice plant root distribution, for the purpose of this preliminary study, E_{CD} is taken as 30 cm.

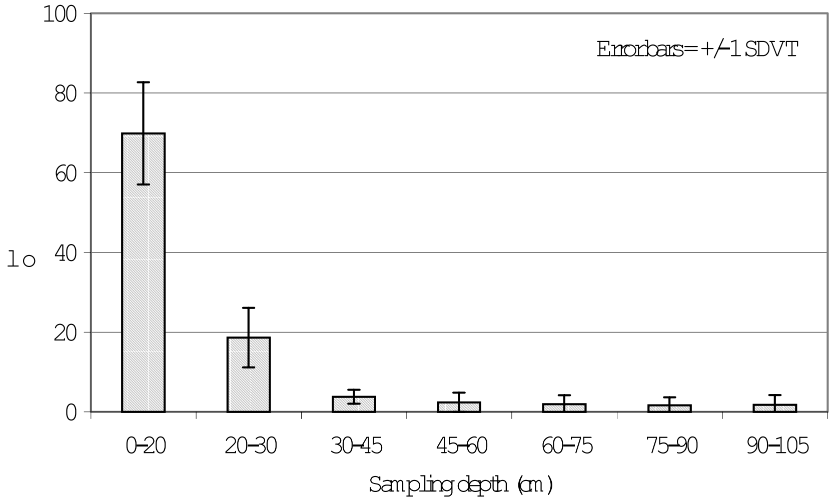

Figure 1 Cadmium distribution with depth as indicated by mean (n=15) percentage of total profile Cd loading.

The irrigation-based field classification system utilized in this study was developed on the basis of a fields' proximity to primary outlets from in-field water courses and inter-field irrigation flows (Figures 2a-c). This allows fields to be classified in terms of Field Order in Irrigation Sequence (Field Order^{IS}). Primary fields (1st Order) are those fields receiving irrigation directly from in-field irrigation channels. Secondary (2nd Order) fields may receive irrigation water from primary fields and tertiary (3rd order) fields receive irrigation directly from 2nd order fields. This classification sequence can be repeated until basal fields are encountered. Basal fields are the last fields in irrigation sequence from which excess irrigation water (if present) drains directly into sub-adjacent in-field drainage courses or the natural drainage system.

For Field Groups FG1, FG2 and FG3, field specific Cd concentrations ranged from 3.4-284.8, 3.7-183.2 and 3.6-240.7 mg Cd kg^{-1}, respectively (Figures 2a-c). This is for Field Group FG1, FG2 and FG3, up to 94, 61 and 80 times the EEC MP soil Cd concentration of 3.0 mg Cd kg^{-1}, respectively.

The Field Specific Cd loading results indicate that field specific Cd loading is dictated by a given fields position in irrigation sequence (Figures 2a-c and 3a-c). The primary fields of FG1, FG2 and FG3 account for over 47%, 56% and 45% of the FG1, FG2 and FG3 total Cd loading, respectively (Table 1). This in turn corresponds to 11.6%, 18.8% and 11.8% of the total areas of FG1, FG2 and FG3, respectively.

Further, over 71% and 86% of the FG1-3 Cd loading is associated with the first two and first three fields in irrigation sequence, respectively (Table 1). This has major implications for the design of strategic sampling strategies and the implementation of management solutions. However, it is also important to note that the minimum soil Cd concentrations for FG1, FG2, and FG3 are 3.448, 3.765 and 3.661 mg Cd kg^{-1}, respectively. As a function primarily of soil pH and redox, soils with Cd concentrations as low as 0.67 mg Cd kg^{-1} regularly produce rice with Cd concentrations exceeding 1.0 mg Cd kg^{-1} (Iimura, 1981). Any sampling strategy must therefore also take into account low order fields.

Figure 2a Field Group 3 (FG3)

Figure2a-c Field Specific Cd Loading (mg kg^{-1}) in relation to Field Order^{IS} as governed by primary outlets from in-field water courses and inter-field irrigation flows.

An effective sampling strategy cannot be established without farmer/community inputs. Ideally, pre-sampling community-based information gathering in the form of farmer interviews, community meetings and, questionnaires should be initiated with the full knowledge and preferably participation of all stakeholders.

In rice-based agricultural systems where the irrigation supply is both the primary Cd source and, mechanism of Cd distribution the acquisition and collation of pre-sampling information is essential to facilitate the classification of fields on the basis of Field Order^{IS} and hence design effective sampling programs. Essential pre-sampling irrigation related information includes; the total cultivated area receiving contaminated irrigation water; the identification of farmer specific and/or in-field water course specific Field Groups; Field Group specific irrigation schedules; irrigation duration and water availability. This information should be combined with the identification and detailed mapping of the irrigation infrastructure including primary irrigation canals, in-field water courses, primary outlets from in-field water courses and inter-field irrigation flows.

Figure 3b. Field Group 2 (FG 2)

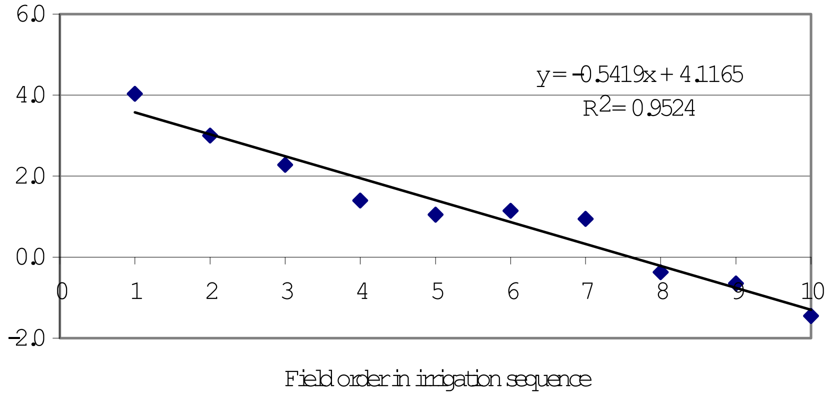

Figure 3c. Field Group 3 (FG 3)

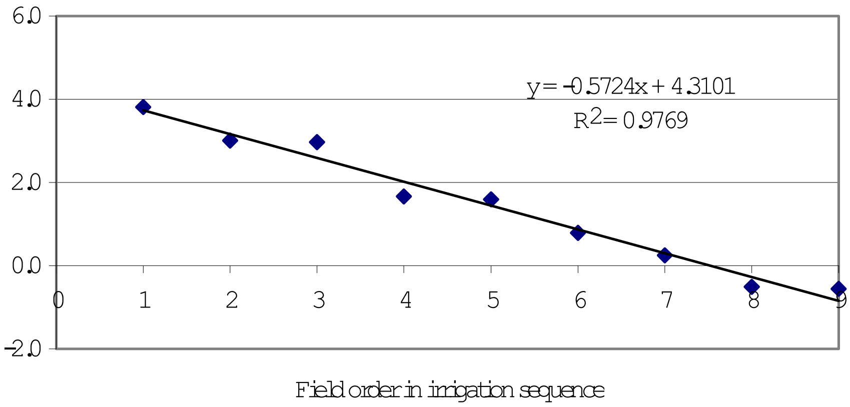

Figure3a-c The effect of field order in irrigation sequence on the spatial distribution of Cd as represented by LN % of total field group Cd loading.

Table 1 Effect of Field Order in Irrigation Sequence (Field Order^{IS}) on the spatial distribution of Cd.

	% of Total Field Group Cd loading			% of Total Field Group Area		
Field Order^{IS}	1st	1st + 2nd	1st + 2nd + 3rd	1st	1st + 2nd	1st + 2nd + 3rd
Field Group 1	47.54	74.14	87.46	11.63	22.33	35.70
Field Group 2	56.14	76.17	85.94	18.82	32.67	46.398
Field Group 3	45.36	65.67	85.12	11.85	21.59	38.81
Mean	49.68	71.99	86.17	14.10	25.53	40.30
STDEV	5.70	5.57	1.19	4.09	6.19	5.50
CV	11.47	7.73	1.38	29.00	24.26	13.65

In summary, an effective sampling strategy to evaluate spatial Cd distribution and rice grain Cd contamination risk in rice-based agricultural systems, where the irrigation supply is both the primary Cd source and, mechanism of Cd distribution should be based on the pre-sampling acquisition and collation of essential irrigation related information and the identification of farmer specific and/or in-field water course specific Field Groups. Subsequently, for each Field Group, fields should be classified, in terms of Field Order^{IS}. Strategic sampling of each Field Group, should focus on collecting soil and rice grain sampling from all 1st–3rd Order Fields and from a Field Order^{IS}-based transect running from 1st Order to Basal Order fields. This should effectively identify and quantify 'high' rice grain Cd contamination risk fields and quantify the risk associated with low irrigation order and basal order fields.

Conclusions

The Field Order^{IS} classification system adopted in this study is simplistic in that it does not take into account fields that receive irrigation water from adjacent fields of differing irrigation order, the Cd adsorption capacity of adjacent fields or the quantity and quality of flow derived from adjacent fields of differing field order. However, in rice based agricultural systems where irrigation is both the primary Cd source and, mechanism of Cd distribution the classification of fields in terms of Field Order^{IS} is an effective basis on which to form strategic sampling programs to evaluate the spatial Cd distribution and rice grain Cd contamination risk.

The geo-statistical GIS-based interpretation of spatial rice grain Cd concentrations, soil total and phyto-available Cd and, critical soil characteristics affecting soil Cd phyto-availability in conjunction with spatial irrigation information, principally, Field Order^{IS} would be an effective basis on which to develop a model to predict rice grain Cd contamination. The current International Water Management Institute (IWMI) and Thai Department of Agriculture collaborative project (2001-2003) aims to further develop an effective irrigation infrastructure based sampling protocol to evaluate the spatial distribution of soil Cd and rice grain Cd contamination risk in irrigated rice-based agricultural systems where irrigation is both the primary Cd source and, mechanism of Cd distribution.

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