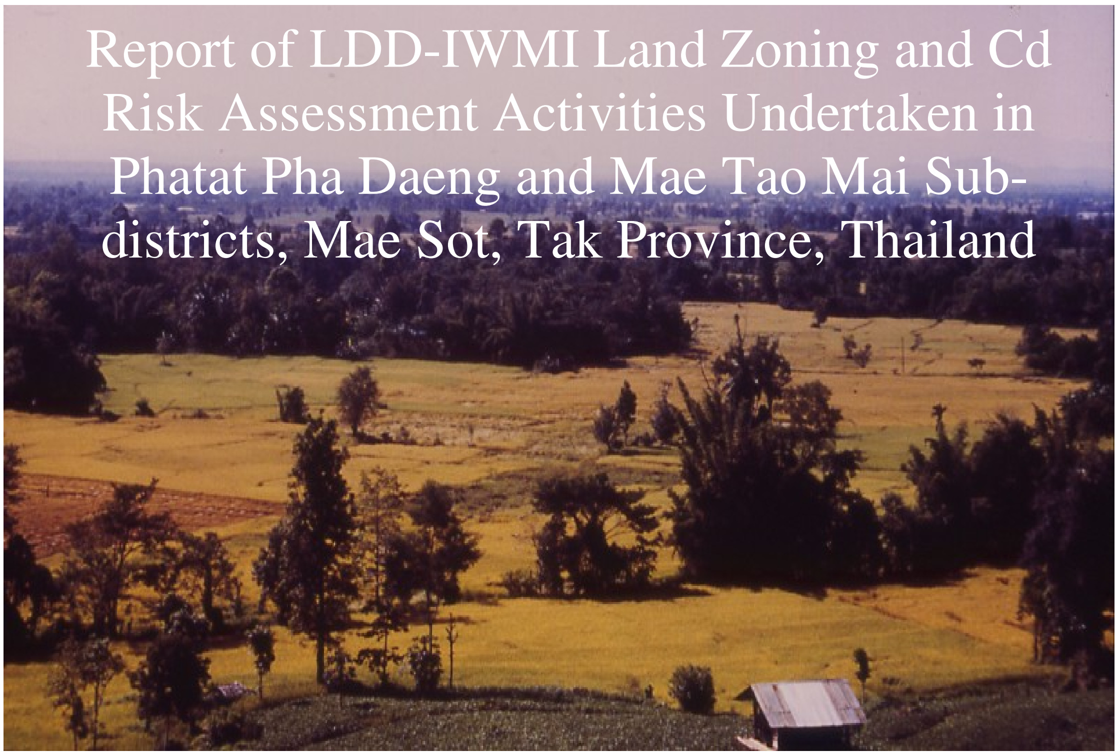
Report of LDD-IWMI Land Zoning and Cd Risk Assessment Activities Undertaken in Phatat Pha Daeng and Mae Tao Mai Sub-districts, Mae Sot, Tak Province, Thailand



Final Report
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EXECUTIVE SUMMARY

This summary report presents a consolidation of the collaborative research conducted by IWMI-DOA (2001-2003) and LDD-IWMI (2004-2005). In 2004-2005 LDD-IWMI collected 532 rice grain and 660 soil samples from pre-selected fields within the Phatat Pha Daeng and Mae Tao Mai sub-districts. This data set was combined with the 535 and 430 rice and soil samples collected from individual fields under the collaborative IWMI-DOA Project (2001-2003). Consequently, this report is based on the interpretation of soil and rice grain data from 1,090 and 1,067 individual fields within the Phatat Pha Daeng and Mae Tao Mai sub-districts, respectively. This represents a total of 44 Field Groups and is the most comprehensive and detailed data set of the Cd contaminated area to date. Utilization of the Irr-Cad model increases the number of fields effectively and accurately covered by the land zoning activities to 2,537. This corresponds to a total area of 88.76 ha or 554 Rai.

SUMMARY CONCLUSIONS

Internationally recognized Maximum Levels of Cd in Rice grain

- Internationally recognized Maximum Levels (ML) for contaminants in foods are established by the Joint FAO/WHO Food Standards Programme, Codex Alimentarius Commission (CAC). Specifically, MLs are established by the Codex Committee on Food Additives and Contaminants (CCFAC) and the Joint FAO/WHO Expert Committee on Food Additives (JECFA). At the 64th JECFA Meeting (JECFA Rome, 8-17 February 2005) polished rice was advanced to Step 5 at 0.4 mg Cd kg^{-1}. The 0.4 mg Cd kg^{-1} limit for rice is supported by recent epidemiological studies in Japan (Horiguchi et al., 2004); even higher levels may no longer cause adverse health effects because of improved nutrition of the Japanese population (Nakadaira and Nishi, 2003).
- The previous ML for Cd in rice grain of 0.2 mg Cd kg^{-1} was established at the 34th Session CCFAC (Rotterdam, The Netherlands during the 11-15th March 2002) proposed a *draft* provisional Maximum Level (ML).

Provisional Tolerable Weekly Intake (PTWI)

The 55th Joint FAO/WHO Expert Committee on Food Additives (JECFA) agreed to maintain the Provisional Tolerable Weekly Intake (PTWI) of Cd at 7µg Cd per kg Body Weight (BW) per week. This PTWI value is established on the basis of preventing potential Cd-induced detrimental health impacts via dietary Cd.

Recommended Maximum Levels of Cd in Thai Rice as a pre-cautionary measure to protect public health

- If 0.4 mg Cd kg^{-1} is adopted in Thailand as the acceptable limit for Cd in rice grain using the national average daily rice intake of 0.28 kg and the national mean body weight for men and women (40-49 yrs) of 58.71 and 59.81, WI values would be <u>13.35</u> and <u>13.11</u> µg Cd per kg BW, respectively. This <u>***exceeds***</u> the JECFA PTWI value for Cd of 7µg Cd per kg Body Weight (BW) per week.
- If 0.2 mg Cd kg^{-1} is adopted in Thailand as the acceptable limit for Cd in rice grain using the national average daily rice intake of 0.28 kg and the national mean body weight for men and women (40-49 yrs) of 58.71 and 59.81, WI values would be 6.68 and 6.55 µg Cd per kg BW, respectively. This is ***below*** the JECFA PTWI value for Cd of 7µg Cd per kg Body Weight (BW) per week.

- It is strongly recommend that as a pre-cautionary measure, and based on the level of rice consumption and average body weight in Mae Sot, Thailand that ***0.2 mg Cd kg^{-1}*** is taken as the ML for Cd in Thai rice.

Rice grain Cd concentrations in Phatat Pha Daeng and Mae Tao Mai sub-districts, Mae Sot, Thailand

- Rice grain Cd concentrations for the 1,067 fields sampled range from <0.01 – 7.75 mg Cd kg^{-1}. This is up to 38.75 times the recommended ML for Cd in Thai rice grain of 0.2 mg Cd kg^{-1}.
- Further, and of great concern with regards public health over 83.0% of the fields sampled produced rice grain with Cd concentrations exceeding the recommended ML for Cd in Thai rice grain.
- The results clearly indicate that **all** fields that receive irrigation from the Mae Tao Creek are at high risk of Cd contamination and that there is a 75-100% probability that these fields will produce rice grain with Cd concentrations significantly exceeding the recommended ML for Cd in Thai rice grain..

Soil Cd concentrations

- Soil total Cd concentrations for the 1,090 field's sampled range from 0.1 – 284 mg Cd kg^{-1} with 85.0% of the fields sampled having a total soil Cd concentration exceeding the European Union (EU) Maximum Permissible (MP) level of 3.0 mg Cd mg^{-1} for agricultural (sludge amended) soils.

Potential public health risks associated with villages receiving irrigation sourced from Mao Tao Creek

- The JECFA Provisional Tolerable Weekly Intake (PTWI) for Cd is 7µg Cd per kg Body Weight (BW) per week. This PTWI value is established on the basis of preventing negative impacts on human health via dietary Cd.
- As indicated by the estimated Weekly Intake (WI) values the rice grain Cd concentrations in the 1,067 fields sampled pose a significant threat to public health.
- Household rice grain screening indicates that for villages utilizing irrigation sourced from Mae Tao Creek, between 66-100% of household rice grain samples were associated with estimated WI values > 7µg Cd kg^{-1} BW.
- For women and men of 50 yrs in the 4 villages sampled, estimated mean WI of Cd from the consumption of rice alone ranged from 19.92 – 41.73 µg Cd kg^{-1} BW and 19.56 – 40.96 µg Cd kg^{-1} BW, respectively.

Potential public health risks associated with villages receiving irrigation sourced from Mao Ku Creek

- Of concern is the fact that in Mae Ku Noi and Mae Ku Nua villages, estimated mean Cd WI values are >14.0 and >18.0 µg Cd kg^{-1} BW, respectively.
- 65-82% of household rice grain samples in Mae Ku Noi and Mae Ku Nua villages were associated with estimated WI values > 7µg Cd kg^{-1} BW.

Irr-Cad Model

- In irrigated rice based agricultural systems receiving Cd contaminated sediment transported by irrigation water, *Irr-Cad* is an effective decision support tool to rapidly and cost effectively estimate the spatial distribution of soil Cd.
- Utilization of the Irr-Cad model resulted in 2,537 fields being effectively and accurately covered by the Land Zoning activities. This corresponds to a total area of 88.49 ha or 554 Rai.
- 96.86% of the 554 Rai currently covered by the *Irr-Cad* model has a total soil Cd > 3.0 mg Cd kg^{-1}.
- It is also strongly recommended that *Irr-Cad* is applied to all paddy rice areas of Mae Ku Creek catchment and all areas irrigated by Mae Tao Creek.

Probability-based risk assessment

- For all the soil Cd contamination classes evaluated ranging from <3.0 to >100 mg Cd kg^{-1} there is a 73.05 – 100% probability that rice fields **will** produce rice grain that is **unsafe** for human consumption (e.g rice grain Cd >0.2 mg Cd kg^{-1})

Predicting uptake of Cd to rice grain

- For 'air-dry soils' total and bio-available soil Cd **cannot** be used to predict uptake of Cd to rice grain.
- Initial IWMI-DOA research results indicate that a generalized multiple regression model incorporating 0.05N $CaCl_2$ extractable Cd and Zn in conjunction with soil pH of soil at 'Field Moisture Condition' collected at the grain-fill stage accounts for 92.5% of the variability in rice grain Cd.
- Further development of this generalized multiple regression model is being undertaken by LDD and IWMI.

Cd concentrations in soybean grown in Phatat Pha Daeng sub-district

- In addition, soybean Cd concentrations for the 113 fields sampled under the IWMI-DOA Project (2001-2003) ranged from 0.34 – 3.37 mg Cd kg^{-1}. 100% of the soybean samples contained Cd at values exceeding the CCFAC ML for Cd in soybean of 0.2 mg Cd kg^{-1} (Simmons et al., 2003).

RECOMMENDATIONS

- It is recommended that rice production and the production of agricultural products for human consumption are stopped in all areas that receive irrigation from Mae Tao Creek.
- In the absence of field sampling of soil and food crops, it is strongly recommended that economically viable and marketable non-food crops e.g. industrial crops are grown in the study area and that adequate training is provided to the farming communities to ensure their successful adoption.
- For the recommended non-food crops, structured research programs should be conducted to evaluate and quantify the route of Cd throughout the whole process from field to end product (including the disposal or re-use of industrial by-product)
- If upon the implementation of a set of 'validated' remediation options rice production and the production of other agricultural products for human consumption are allowed to continue it is strongly recommended that a long-term 'transparent' and externally evaluated 'monitoring and certification program' is conducted.
- It is also strongly recommended that *Irr-Cad* in association with both field and household rice grain sampling is applied to all paddy rice areas of Mae Ku Creek catchment and all areas irrigated by Mae Tao Creek.
- Research activities should continue to be undertaken to develop a robust 'trigger value' or model to predict uptake of Cd to rice grain.
- Additional potentially Cd contaminated sites in Thailand should be systematically investigated and effective management programs implemented to protect public and environmental health.

Protecting the integrity of Thai rice exports

The MLs established by CCFAC and JECFA are based on the 'safe' lifetime consumption of agricultural produce and the *free movement* of products in international trade. MLs set by the CCFAC are used internationally as criteria to establish *non-tariff trade barriers*. In addition, ISO 14000 is being sought by many food importers to guarantee that food and fiber are produced using environmentally sustainable practices. As a result of the Cd contamination in Mae Sot in June 2004 the US Food and Drug Administration expressed concerns over Thai Rice exports. In addition, in February 2005, Vietnam identified high levels of Cd in rice exported from Mae Sot.

It is of utmost importance to the integrity of Thai rice exports that representatives of Thai rice importers are unequivocally assured that rice from Mae Sot will not enter the export market. The Royal Thai Government can give no stronger assurance that Thai rice is safe than by prohibiting rice production in all areas irrigated by Mae Tao Creek.

Protecting public health

Cadmium induced renal dysfunction occurs following the prolonged consumption of Cd contaminated rice. The estimated WI values presented in this report indicate that populations consuming Cd contaminated rice in Mae Sot are potentially exposed to a lifetime of significantly elevated dietary Cd. Ikeda et al., (2003) demonstrate that a critical threshold level of Cd must accumulate in the kidney before the onset of irreversible renal dysfunction. By **prohibiting** the cultivation of rice and other crops for human consumption the Royal Thai Government will effectively prevent further accumulation of Cd in the kidneys of exposed populations in Mae Sot and thus protect the health of current and future generations.

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1. INTRODUCTION

This summary report presents a consolidation of the collaborative research conducted by IWMI-DOA (2001-2003) and LDD-IWMI (2004-2005). In 2004-2005 LDD-IWMI collected 532 rice grain and 660 soil samples from pre-selected fields within the Phatat Pha Daeng and Mae Tao Mai sub-districts. This data set was combined with the 535 and 430 rice and soil samples collected from individual fields under the collaborative IWMI-DOA Project (2001-2003). Consequently, this report is based on the interpretation of soil and rice grain data from 1,090 and 1,067 individual fields within the Phatat Pha Daeng and Mae Tao Mai sub-districts, respectively (Figures 1 and 2). This represents a total of 44 Field Groups and is the most comprehensive and detailed data set of the Cd contaminated area to date.

Based on the initial results presented in IWMI-DOA Report (Simmons et al., 2003) the focus of the 'Land Zoning' activities conducted by LDD-IWMI (2004-2005) has been within a 'high' risk area irrigated by Mae Tao Creek extending 3.5 km west from the village of Baan Pha Te to the Mae Sot-Umphang Road (Highway 1090).

1.1 Cadmium contaminated study area

The Cd-contaminated rice-based agricultural system investigated in this study is within Phatat Pha Daeng and Mae Tao Mai sub-districts, Mae Sot, Tak Province, Thailand and has been previously described by Simmons et al., (2003). A paddy rice (July-November) and soybean (December-May) rotation is the dominant agricultural practice adopted in the study area. Irrigation is sourced from Mae Tao Creek the upper stretches of which pass through an actively mined Zn-mineralized zone (Figures 1 and 2).

Soil total Cd concentrations in the study area ranged from 0.5 – 284 mg Cd kg^{-1} (Simmons et al., 2003). In comparison, the European Union (EU) Maximum Permissible (MP) total soil Cd and concentration for sludge amended soil utilized for agricultural purposes ranges from 1.0 - 3.0 mg Cd kg^{-1} as a function of soil pH (Directive 86/278/EEC). In addition, Simmons et al., (2003) observed rice grain Cd concentrations in the 463 fields sampled, ranging from <0.05 – 7.7 mg kg^{-1}.

Figure 1. Total soil Cd (mg kg^{-1}) in 1,090 fields of Phatat Pha Daeng and Mae Tao Mai sub-districts, Mae Sot, Tak Province, Thailand: Data derived from IWMI-DOA (2001-2003) and IWMI-LDD (2004-2005) collaborative research projects.

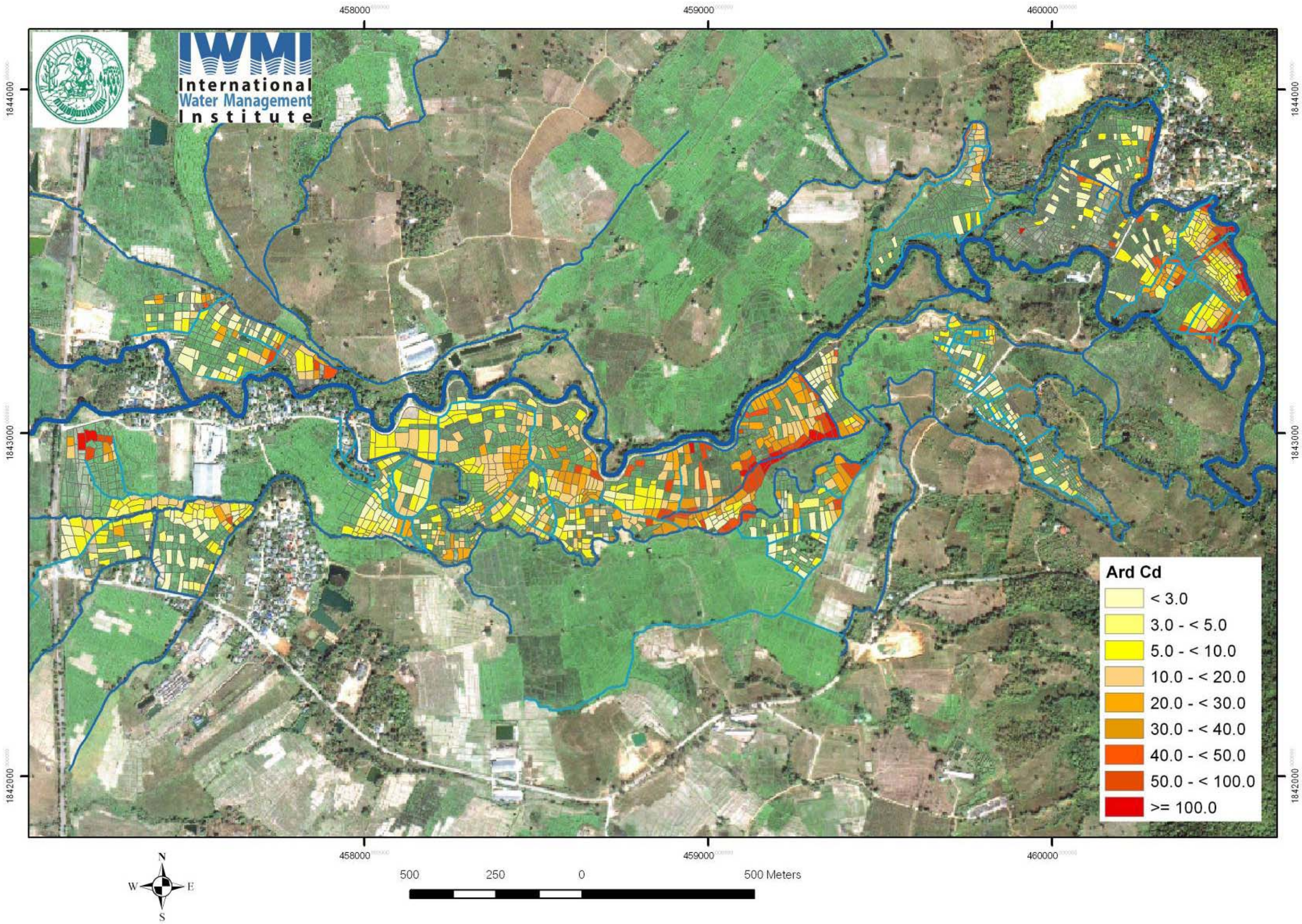
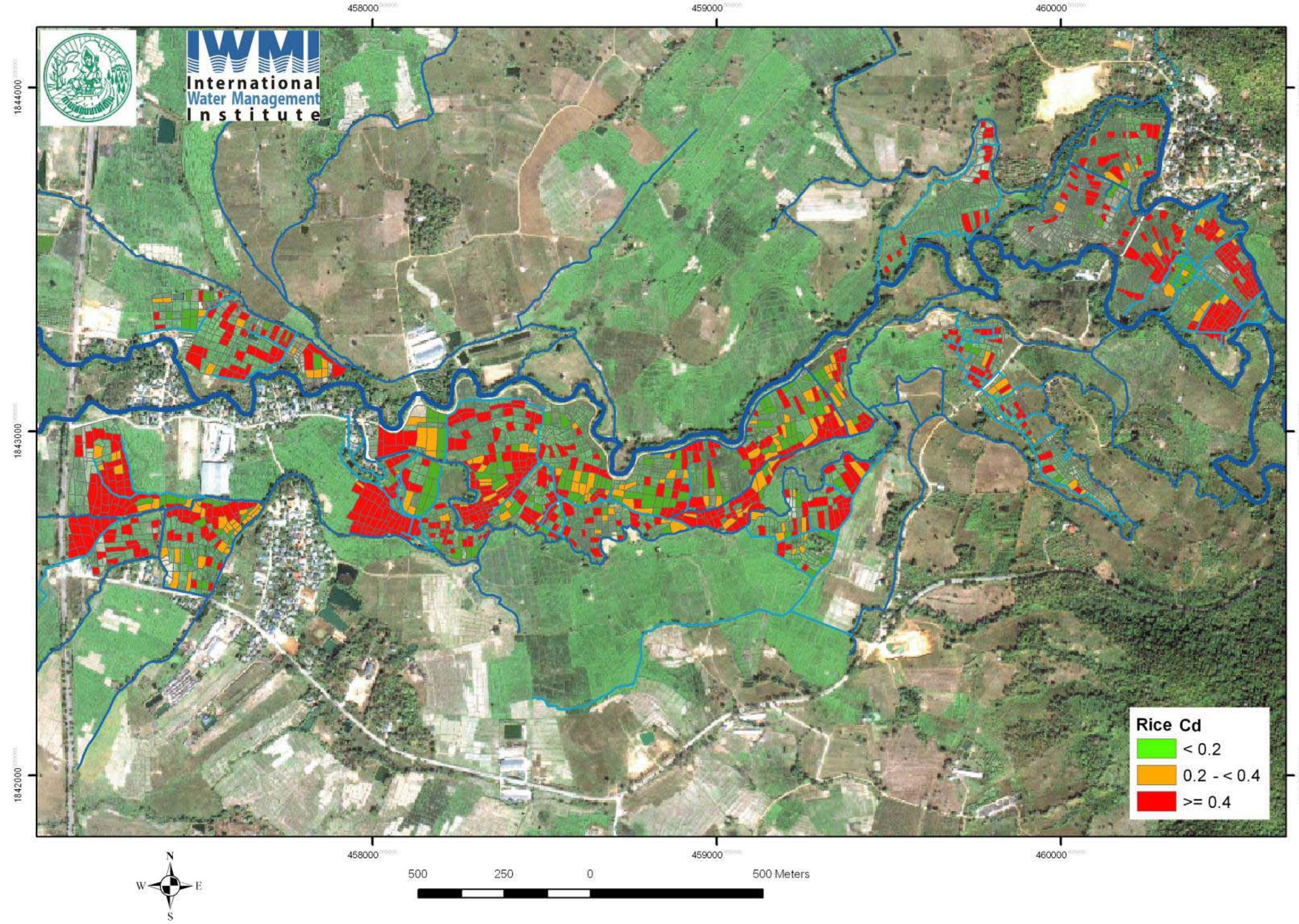


Figure 2. Rice grain Cd (mg kg^{-1}) in 1,067 fields of Phatat Pha Daeng and Mae Tao Mai sub-districts, Mae Sot, Tak Province, Thailand: Data derived from IWMI-DOA (2001-2003) and IWMI-LDD (2004-2005) collaborative research projects. (Note: Rice with Cd concentrations <0.2 mg Cd kg^{-1} are acceptable for human consumption).



1.2 Elevated levels of cadmium in the rice food chain and impacts on human health

Research undertaken over the last 40 years has identified the irrefutable relationship between the long-term consumption of cadmium (Cd) contaminated rice and human Cd disease (Shimada et al., 1977; Tohyama et al., 1982; Nogawa et al., 1983; Kido et al., 1988 Hochi et al., 1995). Reports of health effects of Cd in populations not occupationally exposed to Cd have centered on Japan (Watanabe et al., 1998; Kobayashi et al., 2002; Nogawa et al., 1983; Kido et. al., 1988; Nogawa and Kido, 1993; Kido *et al.,* 1990*;* Tsuritani *et al.,* 1992) and China (Cui et al., 2004; Jin et al., 2002; Wu et al., 2001; Jin et al., 1999; Cai et al., 1995; Cai et al., 1990; Nordberg, 2003) where rice-based agricultural systems are contaminated with Cd from the use of irrigation waters that receive natural runoff and/or un-controlled discharges from non-ferrous mines and smelters. This is further confirmed by studies undertaken on dietically exposed populations from non-rice growing areas, which did not identify elevated levels of renal dysfunction in the exposed populations (Baker *et al.,* 1977; Ewers *et al.,* 1985; McKenzie-Parnell and Eynon 1987; Strehlow and Barlthrop 1988; Sarasua *et al.,* 1995).

The long-term consumption of Cd contaminated rice has resulted in chronic and acute human Cd disease as manifested by Itai-Itai disease (Hagino, 1968; Yoshioka, 1970), a form of osteomalacia and proximal tubular renal dysfunction, respectively (Shimada et al., 1977; Tohyama et al., 1982; Nogawa et al., 1983; Kido et. al., 1988 Cai et al., 1990; Hochi et al., 1995). Cadmium-induced renal dysfunction in individuals dietarily exposed to Cd is irreversible and progressive despite decreased exposure (Kido et. al., 1988; Nogawa and Kido, 1993). Several studies have also suggested 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 (Kido et al., 1990; Tsuritani et al., 1992). The emerging paradigm of Cd risk assessment is therefore focused on communities nutritionally deficient in Zn, Fe and Ca consuming Cd contaminated rice.

1.3 Unique health 'risks' posed by elevated levels of Cd in rice grain

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 (Flanagan *et al.,* 1978; Koo *et al.,* 1978; Fox, *et al.,* 1979; Brzóska and Moniuszko-Jakoniuk, 1988*;* Reeves and Vanderpool, 1988; Berglund *et al.,* 1994*;* Reeves and Chaney, 2001). Cadmium related health risks associated with the long-term consumption of Cd contaminated rice grain are exacerbated by the fact that rice grain Fe, Zn and Ca contents are insufficient for human needs (Hallberg et al., 1977; Pedersen and Eggum 1983). In addition, milling rice grain 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.,* 1981). Further, Fe in milled rice has very low bio-availability (Welch and Graham, 1999). Cadmium related health risks associated with the long-term consumption of Cd contaminated rice grain result from several compounding factors. Firstly, rice grain Fe, Zn and Ca contents are insufficient for human needs (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., 1981). Further, rice grain accumulates higher Cd than Zn and Fe levels when compared to rice stem and leaf, thus resulting in high rice grain Cd:Zn and Cd:Fe ratios which significantly increases the risks to human health (Simmons et al., 2003; Chaney et al., 1996).

1.4 Internationally recognized Maximum Levels of Cd in rice grain

1.4.1 Maximum Level of Cd in Rice grain

Internationally recognized Maximum Levels (ML) for contaminants in foods are established by the Joint FAO/WHO Food Standards Programme, Codex Alimentarius Commission (CAC). Specifically, MLs are established by the Codex Committee on Food Additives and Contaminants (CCFAC) and the Joint FAO/WHO Expert Committee on Food Additives (JECFA). At the 64th JECFA Meeting (JECFA Rome, 8-17 February 2005) polished rice was advanced to Step 5 at 0.4 mg Cd kg^{-1}. The 0.4 mg Cd kg^{-1} limit for rice is supported by recent epidemiological studies in Japan and a significant decline in daily rice intake. (Horiguchi et al., 2004). Even higher levels may no longer cause adverse health effects because of improved nutrition of the Japanese population (Nakadaira and Nishi, 2003). The previous ML for Cd in rice grain of 0.2 mg Cd kg^{-1} was established at the 34th Session CCFAC (Rotterdam, The Netherlands during the 11-15th March 2002) proposed a *draft* provisional Maximum Level (ML).

1.4.2 Provisional Tolerable Weekly Intake (PTWI)

The 55th Joint FAO/WHO Expert Committee on Food Additives (JECFA) agreed to maintain the Provisional Tolerable Weekly Intake (PTWI) of Cd at 7µg Cd per kg Body Weight (BW) per week. This PTWI value is established on the basis of preventing potential Cd-induced detrimental health impacts via dietary Cd.

Recommended Maximum Levels of Cd in Thai Rice as a pre-cautionary measure to protect public health:

If the revised JECFA ML of 0.4 mg Cd kg^{-1} is adopted in Thailand as the acceptable limit for Cd in rice grain using the national mean daily rice intake of 0.28 kg and the mean national body weight for men and women (40-49 yrs) of 58.71 and 59.81, WI values would be 13.35 and 13.11 µg Cd per kg BW, respectively. This ***exceeds*** the JECFA PTWI value for Cd of 7µg Cd per kg Body Weight (BW) per week. In addition, this indicates that the revised JECFA ML for Cd in rice grain may not be applicable to all dietary exposed populations.

If the previously established JECFA ML of 0.2 mg Cd kg^{-1} is adopted in Thailand as the acceptable limit for Cd in rice grain using the national mean daily rice intake of 0.28 kg and the mean national body weight for men and women (40-49 yrs) of 58.71 and 59.81, WI values would be 6.68 and 6.55 µg Cd per kg BW, respectively. This is ***below*** the JECFA PTWI value for Cd of 7µg Cd per kg Body Weight (BW) per week.

It is strongly recommend that as a pre-cautionary measure, and based on the national mean daily rice intake of 0.28 kg and the mean national body weight for men and women (40-49 yrs) that ***0.2 mg Cd kg^{-1}*** is taken as the ML for Cd in Thai rice. All subsequent risk assessment undertaken in this report is based on a MP level of Cd in rice grain of ***0.2 mg Cd kg^{-1}***.

1.4.3 Public health risks in Phatat Pha Daeng and Mae Tao Mai sub-districts

In terms of potential public health risks in Phatat Pha Daeng and Mae Tao Mai sub-districts estimated Weekly Intake (WI) values for Cd ranged from 20 - 98 µg Cd kg BW. This is up to 14x higher that the JECFA, PTWI value of 7 µg Cd kg BW (Simmons et al., 2003). Cadmium levels in blood and urine samples collected from residents within Phatat Pha Daeng, sub-district indicate potential renal dysfunction in 8% of the population studied. This will be confirmed by further detailed studies (Dr Jaral Trinvuthipong Director General of Disease Control Department, Thai Ministry of Health, personal communication).

1.5 Factors affecting Cd mobility in paddy soils

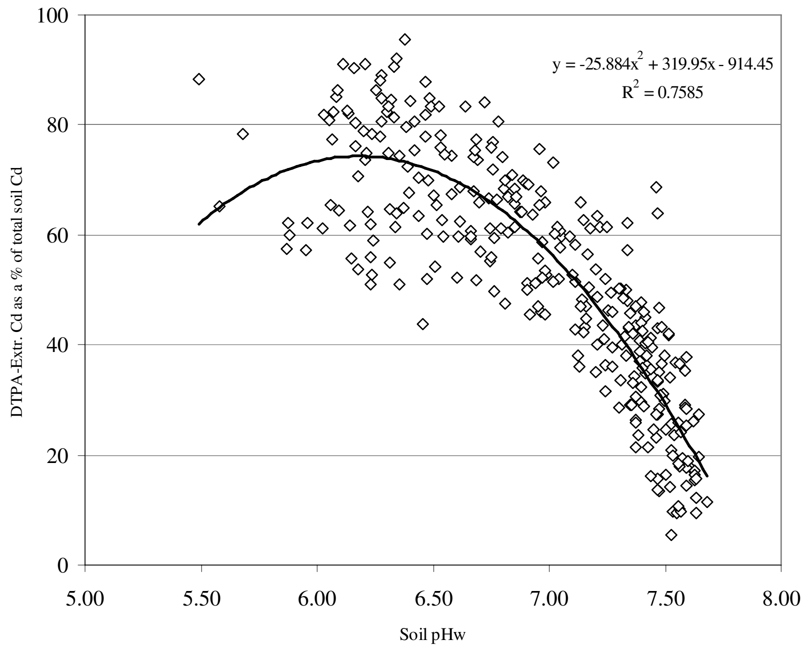
The phyto-availability of Cd in soils is a function primarily of the interactions between soil pH and redox condition (Babich and Stotsky 1978; Bingham et al., 1980; Page et al., 1981; Iimura et al., 1981; Chaney et al., 1996). In paddy soils, soil solution pH alters towards near neutral as the system moves from oxidizing to reducing conditions, which reduces Cd phyto-availability (Chaney et al., 1996). However, drainage of fields at the critical grainfill stage in order to optimize yields and facilitate ease of harvesting, decreases soil pH to the antecedent condition and increases Cd phyto-availablity to rice plants (Chaney et al., 1996). In addition, increased acidity upon drainage and oxidation also results in the dissolution of secondary Al precipitates and the release of any sorbed Cd. The increased acidity also leads to desorption of Cd from soil organic matter (Zachara et al., 1992). Conversely, oxidation results in the formation of Fe and Mn oxides and subsequent co-precipitation of Cd (Alloway, 1997). If reducing conditions reoccur, co-precipitated Cd becomes exchangeable and is sorbed onto surfaces of Al and organic matter.

In tropical highly weathered soils the adsorption of Cd^{2+} may also be a function of the pH dependant charge associated with the edge of clays, humus polymers and oxides (Zachara et al., 1992). Figure 3 clearly demonstrates the significant ($p<0.001$) relationship between soil pH_w (1:5) and bio-available soil Cd as expressed by DPTA-extractable Cd as a percentage of total soil Cd (Simmons et al., 2004). Further, in submerged paddy soils sulphate (SO_4^{2-}) ions may be reduced to sulphide (S^{2-}) resulting in the precipitation of the Cd and Zn sulphide minerals (Iimura et al., 1981; Chaney *et al.,* 1996). Drainage and oxidation of paddy soils prior to the grain fill stage to maximize rice grain yield and facilitate harvesting results in the rapid transformation of CdS and ZnS to Cd^{2+}, Zn^{2+} and SO_4^{2-}. Cadmium sulphide oxidizes more readily than ZnS (Iimura, 1981; Chaney et al., 1996) and the resultant Cd^{2+} is highly available for uptake. Iimura et al., (1981) observed un-polished rice grain Cd concentrations of 0.75 and 4.85 mg kg^{-1} for rice grown on submerged soil and soil drained after tillering.

Simmons et al., (2003) suggest a greater availability of Cd during the grain fill stage which coincides with oxic field conditions. Simmons et al., (2003) demonstrate that in soils significantly co-contaminated with Zn and Cd the rice plant irrespective of total or bio-available soil Zn concentrations, effectively controls rice grain Zn at a level that may reflect the metabolic/compositional requirements of rice grain. However, the rice plant is unable to control the translocation and accumulation of Cd to grain.

Finally, it has been shown that rice grain accumulates higher Cd than Zn and Fe levels when compared to rice stem and leaf, thus resulting in high rice grain Cd:Zn and Cd:Fe ratios which significantly increases the risks to human health (Simmons et al., 2003; Chaney et al., 1996). In summary, drainage, oxidation and potentially acidification of paddy soils prior to the critical grain fill stage, significantly increases Cd phyto-availability and risk of Cd accumulation in rice grain.

Figure 3. Relationship between soil pHw (1:5) and DTPA-extractable Cd as expressed by DPTA-extractable Cd as a percentage of total soil Cd.



1.6 *Irr-Cad* Model for rapid zoning of Cd contamination

The IWMI-DOA Project (2001-2003) developed and validated an Irrigation Infrastructure-based Cadmium Hazard Mapping model (*Irr-Cad*) to rapidly evaluate the spatial distribution of Cd (Simmons et al., 2004). *Irr-Cad* was developed as a decision support tool for rapid risk assessment in irrigated rice-based agricultural systems receiving contaminated suspended sediment transported in irrigation water. *Irr-Cad* provides a method of assessing the possible distribution of Cd associated with Cd contaminated surface irrigation. Simmons et al., (2003 and 2004) indicate that in agricultural systems receiving Cd contamination via suspended sediment, the determination of Field Order in Irrigation Sequence (Field Order^{IS}) is an essential pre-requisite to accurately assess Cd contamination risk (Annex 1: Table 1, Figures 2 and 3).

Primary fields (1st Order) are those fields receiving irrigation directly from in-field irrigation channels. Secondary (2nd Order) fields 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.

Irr-Cad utilizes the relationship between Field Order^{IS} and spatial Cd distribution (Table 1, Figures 2 and 3: Annex 1) to generate weighed coefficients ($Coeff_W$) that express the ratio between the mean total soil Cd in the 'Primary Fields' ($T\text{-}Cd_P$) and mean total soil Cd in all subsequent fields in the irrigation sequence. Mean total Field Order soil Cd in the respective Field Order e.g. Field Order 2, 3, 4 etc. is divided by the Mean total Field Order soil Cd in the Primary Field ($T\text{-}Cd_P$) (Table 2: Annex 1.) *Irr-cad* is a General Linear Regression Model (Genstat 5.0) incorporating $T\text{-}Cd_P$, $Coeff_W$ and Field Order^{IS} to predict the spatial distribution of soil Cd. This reflects the multiplicative relationship between the total Cd concentration in a given field and the fields' proximity to primary outlets from in-field irrigation channels as dictated by inter-field irrigation flows. Data from 8 randomly selected FGs consisting of 371 fields covering an area of 10.56 hectares was used to generate the Irr-Cad model.

Simmons et al., (2004) indicate that the *Irr-Cad* model accounts for 97.8% of the variance in mean Field Order total soil Cd (mg kg^{-1}) (Annex 1: Equations 1a and 1b and Figure 4).

1.7 Utilization of Irr-Cad in a Cadmium Contaminated Area: Mae Tao Watershed, Ampher Mae Sot, Tak Province, Thailand

The Land Development Department of the Royal Thai Government (LDD) and IWMI applied *Irr-Cad* to Cd Land Zoning activities in 'high risk' areas of Phatat Pha Daeng and Mae Tao Mai sub-districts, Mae Sot, Tak Province, Thailand. Twenty-five pre-selected areas comprising a total area of 75 hectares of irrigated rice (465 Rai) consisting of 30 ha adjacent to Baan Pha Te and 45 ha adjacent to Baan Mae Tao Mai were included in the study.

1.7.1 Irrigation Infrastructure mapping and field classification

Following initial training provided by IWMI, in July and August 2004 joint LDD-IWMI teams mapped approximately 75 hectares of irrigated rice (465 Rai) consisting of 30 ha adjacent to Baan Pha Te and 45 ha adjacent to Baan Mae Tao Mai. The detailed mapping of the irrigation infrastructure was undertaken to identify primary irrigation canals, in-field water courses, field boundaries, primary-outlets from in-field water courses and inter-field irrigation flows. Based on the irrigation maps fields' were classified in terms of Field Order^{IS} and a strategic sampling program developed. The irrigation infrastructure information was input to GIS (Arc-GIS Version 8.2) by LDD and IWMI staff.

1.7.2 Soil and rice grain sampling

In November 2004 rice grain samples were collected from 532 fields identified during the initial irrigation infrastructure mapping and field classification phase. Rice grain samples were collected at physiological maturity from 2 x 2 m sampling plots. For each plot, all rice panicles (cut approximately 5-10 cm from top) were removed and place in appropriately labeled paper bags. Grain samples were subsequently separated and oven dried at 65^{o}C for 48hrs prior to de-hulling and grinding to a fine powder. In addition, in November and December 2004 for each of the 2 x 2 m sampling plots soil samples were collected from 10-15 random points (0-20 cm depth).

Further, during 8-10th and 22-23rd of February 2005 an additional 72 and 56 composite soil samples were collected from primary fields (10-15 random points (0-20 cm Depth). All soil samples were air-died and ground prior to analysis. In summary, LDD-IWMI collected rice grain and concurrent soil samples from 532 individual fields. Further, an additional 128 ‘primary fields’ were sampled for soil. Therefore, a total of 532 rice samples and 660 soil samples were collected.

This data set was combined with the 535 and 430 rice and soil samples collected from individual fields under the collaborative IWMI-DOA Project (2001-2003). Consequently, the key recommendations of this report are based on the interpretation of soil and rice grain data from 1,090 and 1,067 individual fields within the Phatat Pha Daeng and Mae Tao Mai sub-districts, respectively (Figures 1 and 2). This represents the most comprehensive and detailed data set of the Cd contaminated area to date.

Total soil Cd in primary fields was input to the *Irr-Cad* model. Rice grain Cd was used as the most reliable indicator of Cd bioavailability and rice food chain contamination risk.

1.8 Analytical methods

Total soil Cd and Zn will be determined in *aqua regia* (3:1 $HCl:HNO_3$) using an open tube digestion method (McGrath and Cunliffe, 1985) and block digester. Plant samples will be digested in 2:1, $HNO_3:HClO_4$ using an open tube digestion technique following Zarcinas et al., (1983). Prior to digestion, plant samples were pre-digested overnight at ambient temperature ranging from 26-34°C. This was to avoid excessive reaction on heating. Soil pH_w will determined on a 1:5 soil:water (Rayment and Higginson, 1992). To assess within-batch and between-batch precision, two reagent blanks, two replicates of an In-House Standard Reference Material (IH-SRM), and two duplicates from the previous analytical batch were included in each batch of samples analyzed. Cadmium concentrations were determined using a Perkin Elmer Analyst 3000 Atomic Adsorption Spectrophotometer. 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. Statistical analysis was undertaken using GENSTAT 5 (Genstat Committee, 1993).

1.8.1 External proficiency testing and validation of internal quality control and In-House Standard Reference Materials

The rice grain, and soil IH-SRM samples were validated at the accredited CSIRO Land and Water Laboratory in Adelaide. The mean (n=200) IWMI-DOA In-House Rice Grain SRM Cd concentration is 1.105 mg Cd kg^{-1} +/- 0.101. Therefore, the control limits of +/- 2 Standard Deviations (Klesta and Bartz, 1996) range from 0.901 – 1.308 mg Cd kg^{-1}. The mean (n=3) CSIRO value for the IWMI-DOA In-House Rice

Grain SRM is 0.989 +/- 0.071 which, is within the control limits. Finally, the mean (n=250) IWMI-DOA In-House Soil SRM Cd concentration is 9.690 mg Cd kg^{-1} +/- 0.732. Therefore, the control limits of +/- 2 Standard Deviations range from 8.226 – 11.155 mg Cd kg^{-1}. The mean (n=3) CSIRO value for the IWMI-DOA In-House Soil SRM is 10.37 +/- 0.23 which, is within the control limits. This effectively verifies the accuracy of the analytical data produced by the IWMI-DOA and IWMI-LDD projects.

RESULTS AND DISCUSSION

2.1 Soil Cd Concentrations

Based on the consolidated IWMI-DOA (2001-2003) and LDD-IWMI (2004-2005) data sets soil total Cd concentrations for the 1090 fields sampled range from 0.1 – 284 mg Cd kg^{-1}. This is up to 1,893 times the Thai 'Investigation Value' established by Pongsakul and Attajarusit, (1999) and Zarcinas et al., (2004). Further, 85.0% of the fields sampled have total soil Cd concentrations exceeding the European Union (EU) Maximum Permissible (MP) total soil Cd concentration agricultural (sludge amended) soil of 3.0 mg Cd kg^{-1} (Directive 86/278/EEC) (Table 1 and Figure 4). Of grave concern is the fact there is an 82.69 % probability that fields with a total soil Cd concentration <3.0 mg kg^{-1} will produce rice unfit for human consumption (Table 5).

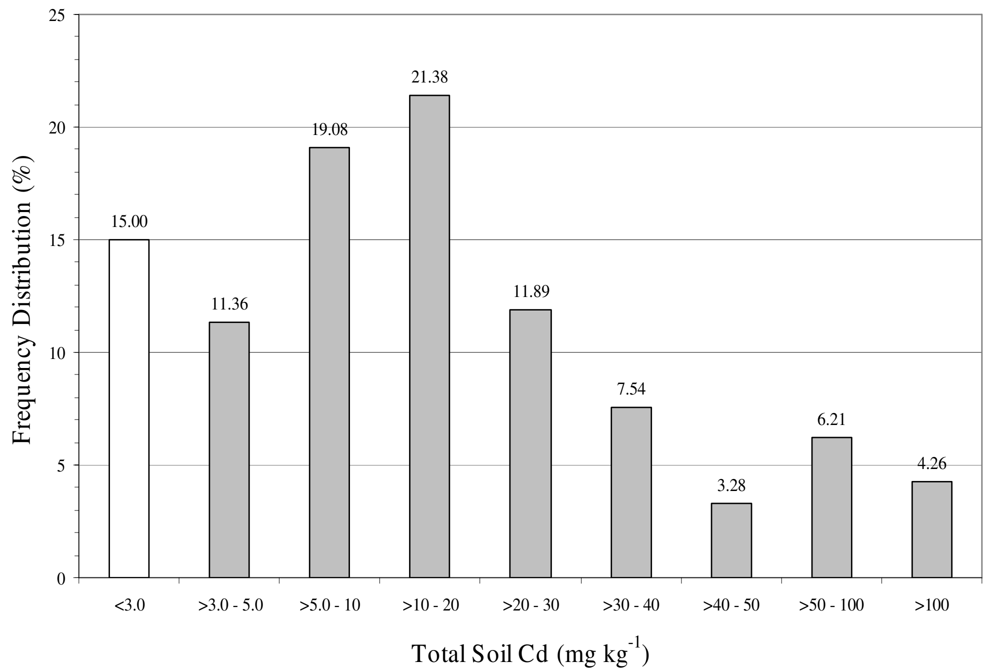
GIS-generated Field Group specific images of total soil Cd concentrations are given in Annex 2b. In addition, Field Group specific total soil Cd Frequency Distributions (%) are given in Annex 3b.

Table 1 Frequency distribution (n=1090) and summary statistics of total soil Cd in Phatat Pha Daeng and Mae Tao Mai sub-districts, Mae Sot, Tak Province, Thailand.

Total Soil Cd (mg kg^{-1})	Mean (±1 Standard Error)	Number of Fields	Frequency (%)
<3.0*	1.648 (±0.061)	168	15.00
>3.0 - <5.0	3.972 (±0.051)	129	11.36
>5.0 - <10	7.319 (±0.097)	226	19.08
> 10 - <20	14.43 (±0.154)	318	21.38
>20 - <30	24.36 (±0.242)	107	11.89
>30 - <40	35.3 (±0.418)	41	7.54
>40 - <50	45.81 (±0.811)	16	3.28
>50 - <100	71.57 (±2.001)	41	6.21
>100	170.0 (±6.659)	44	4.26
	Total	*1090*	*100*

*European Union (EU) Maximum Permissible (MP) total soil Cd concentration agricultural (sludge amended) soil of 3.0 mg Cd kg^{-1} (Directive 86/278/EEC). Values in parentheses equal ±1 Standard Error.

Figure 4. Frequency distribution (n=1090) of total soil Cd in Phatat Pha Daeng and Mae Tao Mai sub-districts, Mae Sot, Tak Province, Thailand.



2.2 Rice grain Cd concentrations

Based on the consolidated IWMI-DOA (2001-2003) and LDD-IWMI (2004-2005) data sets rice grain Cd concentrations for the 1067 fields sampled range from <0.01 – 7.75 mg Cd kg^{-1}. This is up to 38.75 times the CCFAC ML for Cd in rice grain of 0.2 mg Cd kg^{-1} (Report of the 34^{th} Session, CCFAC, 2002). Further, and of great concern with regards public health 83.01% of the fields sampled produced rice grain with Cd concentrations exceeding the CCFAC Maximum Level (ML) for Cd in rice grain (Figure 5 and Table 2).

GIS-generated Field Group specific images of rice grain Cd concentrations are given in Annex 2a. In addition, Field Group specific rice grain Cd Frequency Distributions (%) are given in Annex 3a.

Figure 5. Frequency distribution (n=1067) of rice grain Cd in 'high risk' areas of Phatat Pha Daeng and Mae Tao Mai sub-districts, Mae Sot, Tak Province, Thailand.

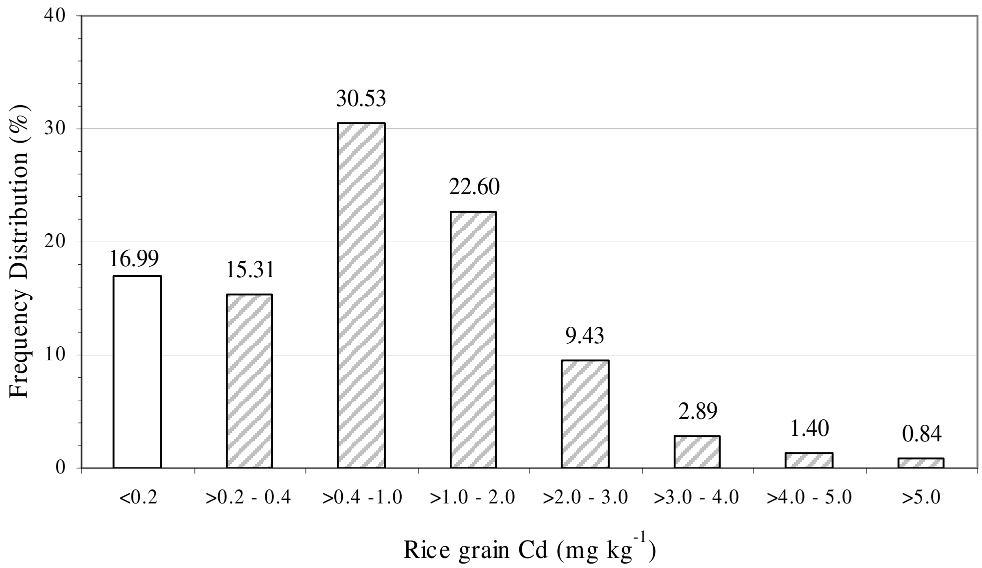


Table 2. Frequency distribution (n=1067) and summary statistics of rice grain Cd in 'high risk' areas of Phatat Pha Daeng and Mae Tao Mai sub-districts, Mae Sot, Tak Province, Thailand.

Rice grain Cd (mg kg^{-1})	Mean (±1 Standard Error)	Number of Fields	Frequency (%)
<0.2*	0.091 (±0.005)	185	16.99
>0.2 - <0.4	0.297 (±0.004)	162	15.13
>0.4 - <1.0	0.672 (±0.009)	324	30.53
>1.0 - <2.0	1.409 (±0.017)	241	22.59
>2.0 - <3.0	2.378 (±0.028)	100	9.43
>3.0 - <4.0	3.303 (±0.049)	31	2.89
>4.0 - <5.0	4.37 (±0.052)	15	1.40
>5.0	5.717 (±0.217)	9	0.84
	Total	882	100

*Codex Committee on Food Additives and Contaminants (CCFAC) Maximum Permissible Level for Cd in rice grain = 0.2 mg Cd kg^{-1} (Report of the 34^{th} Session, CCFAC, 2002). Values in parentheses equal ±1 Standard Error.

A detailed breakdown of soil and rice grain Cd and Zn and soil pH (1:5 water) is given in Table 3. The results confirm the findings of Simmons et al., (2003) in that irrespective of total (or bio-available: data not shown) soil Zn, the rice plant effectively controls the uptake of Zn to rice grain. No reciprocal control was observed for Cd uptake to grain.

Table 3. Summary Statistics of soil and rice grain Cd and Zn concentrations (mg kg^{-1}) and soil pH for the 44 Field Groups covered by the IWMI-DOA (2001-2003) and LDD-IWMI (2004-2005) data sets.

Field Group	Soil Cd (mg kg^{-1})	Soil Zn (mg kg^{-1})	Rice Grain Cd (mg kg^{-1})	Grain Zn (mg kg^{-1})	Soil pH (1:5 Water)
BFG-2-3	3.4 – 284 **56.48** (±77.62)	197 – 8036 **2178** (±2343.18)	0.01 – 4.4 **1.76** (±0.95)	0.01 – 25.9 **19.27** (±4.13)	6.16 – 8.25 **7.45** (±0.68)
BFG-4-4a	3.8 – 183 **45.48** (±46.75)	450 – 7266 **2492** (±1876)	0.01 – 4.4 **1.57** (±0.98)	16.6 – 22.9 **20.18** (±1.31)	6.01 – 7.56 **6.52** (±0.48)
BFG-5	3.7 – 240 **42.8** (±54.16)	301 – 7505 **1900** (±1683.16)	0.26 – 2 **1.01** (±0.47)	14.86 – 19.78 **16.85** (±1.88)	6.27 – 8.08 **7.3** (±0.56)
BFG-6	4.6 – 61 **32.10** (±14.51)	599 – 2385 **1386** (±464.50)	0.01 – 0.49 **0.12** (±0.15)	16.94 – 20.84 **18.14** (±1.05)	6.71 – 7.91 **7.68** (±0.27)
BFG-8	0.152 - 90.9 **17.83** (±23.67)	75.7 – 3152 **837** (±856)	6.01 – 3.09 1.15 (±1.08)	14.97 – 21.04 **18.16** (±1.60)	5.5 – 8 **7.12** (±0.76)
BFG-9	0.293 – 35 **7.93** (±8.83)	66.0 – 1041 **317** (±283.52)	0.199 – 2.560 **0.691** (±0.634)	14.85 – 23.90 **18.75** (±2.08)	6.6 – 8.1 **7.72** (±0.39)
BFG-10	0.302 – 124 **18.49** (±24.7)	93.1 – 3584 **788** (±801.80)	0.01 – 4.57 **1.31** (±1.08)	8.69 – 19.39 **14.58** (±2.80)	5.3 – 8 **7.02** (±0.77)
BFG-11	0.55 – 46.1 **11.64** (±13.67)	62.08 – 1630 **502** (±409.28)	0.311 – 2.70 **0.97** (±0.51)	11.63 – 20.17 **15.29** (±2.20)	5.1 – 8.1 **6.33** (±0.86)
BFG-12	0.63 – 48.3 **12.52** (±11.46)	89.5 – 2279 **611** (±459.32)	0.42 – 5.65 **1.23** (±1.08)	8.5 – 20.86 **14.83** (±2.22)	5.9 – 8 **7.31** (±0.68)
BFG-13a	1.10 – 3.90 **2.23** (±0.91)	103 – 294 **187** (±70.09)	0.53 – 1.34 **0.84** (±0.28)	12.57 – 19.14 **15.62** (±1.91)	6.4 – 7.6 **6.92** (±0.35)
BFG-13b	1.16 – 9.86 **6.00** (±4.20)	132 – 688 **420** (±244)	0.41 – 1.59 **0.97** (±0.64)	15.32 – 18.70 **16.70** (±1.42)	6.9 – 7.7 **7.32** (±0.35)
BFG-13	1.61 – 56.5 **12.95** (±13.01)	169 – 1289 **60**8 (±339.28)	0.17 – 4.08 **1.09** (±1.12)	16.01 – 21.15 **17.99** (±1.48)	6.5 – 8.2 **7.62** (±0.42)
CFG-1	0.97 – 80.3 **15.76** (±21.68)	136 – 2734 **785** (±760.59)	0.11 – 10.16 **1.40** (±1.94)	10.52 – 18.58 **15.35** (±1.88)	6.1 – 7.8 **7.02** (±0.58)
CFG-2	14.80 – 94.3 **41.68** (±27.56)	972 – 3062 **184**8 (±798.29)	0.17 – 2.16 **0.73** (±0.62)	13.51 – 17.48 **15.97** (±1.25)	7.2 – 8.1 **7.76** (±0.28)
CFG-3	0.18 – 10.64 **3.25** (±3.32)	68.7 – 489 **196** (±140.05)	0.01 – 0.55 **0.21** (±0.20)	10.78 – 18.42 **15.97** (±2.21)	5.9 – 7.7 **6.57** (±0.56)
DFG-2	0.46 – 49.8 **10.52** (±12.24)	100 – 2108 **655** (±583.61)	0.08 – 3 **0.87** (±0.89)	18.61 24.56 **21.22** (±1.57)	6.28 – 7.35 **6.84** (±0.34)
DFG-3	10.82 – 218 **78.84** (±66.06)	652 – 7919 **3024** (±2194.55)	0.01 – 7.75 **1.22** (±1.57)	16.59 – 25.37 **19.64** (±2.06)	7.15 – 7.68 **7.51** (±0.11)
DFG-4a	1.61 – 177 **41.07** (±41.73)	227 – 5214 **1927** (±1390.98)	0.14 – 5.12 **1.49** (±1.38)	0.01 – 23.75 **19.16** (±3.68)	6.3 – 7.63 **7.20** (±0.39)
DFG-5	2.90 – 65.7 **16.93** (±18.15)	303 – 3489 **1077** (±955.21)	6.01 – 2.09 **0.49** (±0.66)	17.04 – 21.48 **19.86** (±1.29)	6.25 – 7.56 **7.14** (±0.45)
DFG-6	4.20 – 39.2 **20.12** (±10.17)	20 – 2090 **1010** (±484.74)	0.13 – 3.98 **0.59** (±0.86)	15.84 – 23.48 **19.21** (±1.75)	6.16 – 7.5 **7.14** (±0.35)
DFG-7	3.43 – 35.8 **14.67** (±9.13)	302 – 2106 **858** (±453.18)	0.09 – 5.70 **1.22** (±1.17)	17.76 – 25.74 **20.01** (±1.49)	5.49 – 7.48 **6.83** (±0.41)

Table 3. Continued					
DFG-8	2.21 – 24.8 **7.85** (±6.33)	212 – 1270 **441** (±255.73)	0.35 – 4.29 **1.13** (±0.68)	17.35 – 23.74 **20.83** (±1.47)	5.55 – 7.42 **6.46** (±0.40)
DFG-9	1.55 – 38.3 **10.78** (±8.75)	210 – 1395 **612** (±358.83)	0.14 – 1.02 **0.52** (±0.26)	12378 – 19.18 **15.50** (±1.51)	6.6 – 8.1 **7.64** (±0.46)
DFG-9a	1.83 – 76.5 **25.78** (±20.61)	203 – 3070 **1423** (±861.82)	0.01 – 2.86 **1.13** (±0.92)	14.44 – 18.73 **16.36** (±1.71)	6.6 – 8.1 **7.60** (±0.44)
DFG-10	11.48 – 119 **41.79** (±28.88)	355 – 4629 **1603** (±1028.77)	0.01 – 5.95 **1.66** (±2.11)	13.61 – 22.25 **16.49** (±2.48)	7.5 – 7.9 **7.76** (±0.11)
DFG -10a	3.03 – 50.6 **18.45** (±14.26)	235 – 1985 **757** (±498.30)	1.01 – 4.46 **0.57** (±1.01)	13.88 – 17.93 **15.58** (±1.03)	6.2 – 7.9 **7.56** (±0.49)
DFG-11	3.15 – 67.3 **24.71** (±16.62)	193 – 2971 **1086** (±735.54)	0.07 – 2.22 **0.86** (±0.66)	13.14 – 18.18 **15.60** (±1.47)	7.3 – 8 **7.73** (±0.19)
DFG-11a	2.65 – 24.7 **12.06** (±5.78)	175 – 1197 **604** (±252.40)	0.14 – 3.00 **0.88** (±0.69)	12.54 – 18.57 **15.63** (±1.72)	6.4 – 8.1 **7.56** (±0.38)
DFG-12	10.42 – 94.6 **31.67** (±16.98)	382 – 3027 **1402** (±676.27)	0.01 – 2.04 **0.33** (±0.46)	13.73 – 17.22 **15.00** (±0.94)	6.8 – 8 **7.58** (±0.39)
DFG-13	5.89 – 14.50 **8.71** (±2.96)	337 – 735 **499** (±134.79)	0.01 – 3.25 **0.80** (±0.98)	11.57 – 17.49 **14.11** (±1.78)	6.5 – 7.9 **7.5** (±0.39)
DFG-14	2.42 – 17.7 **9.26** (±5.93)	204 – 789 **498** (±217.47)	0.01 – 0.56 **0.17** (±0.21)	13.38 – 18.47 **15.01** (±1.42)	6.6 – 7.6 **7.14** (±0.33)
DFG-15	1.58 – 15.80 **5.88** (±4.09)	166 – 799 **357** (±185.19)	0.19 – 1.18 **0.69** (±0.30)	15.15 – 17.12 **16.37** (±0.53)	5.7 – 7.5 **6.60** (±0.49)
DFG-16	2.56 – 32.06 **10.56** (±8.47)	223 – 1498 **613** (±375.24)	0.01 – 1.90 **0.92** (±0.50)	14.91 – 18 **16.28** (±0.95)	6.1 – 7.7 **7.01** (±0.51)
DFG-17	7.74 – 39.0 **19.71** (±9.81)	425 – 1807 **985** (±397.92)	0.01 – 1.80 **0.64** (±0.68)	13.04 – 16.48 **14.85** (±1.15)	5.8 – 7.7 **7.25** (±0.52)
DFG-18	2.25 – 38.56 **15.10** (±10.41)	172 – 1794 **800** (±474.75)	0.01 – 2.22 **0.72** (±0.56)	11.02 – 18.6 **14.16** (±1.54)	6.0 – 7.8 **7.14** (±0.42)
EFG-1	1.8 – 53.3 **10.35** (±11.11)	177 – 1566 **505** (±325.74)	0.11 – 2.6 **0.59** (±0.57)	16.62 – 23.61 **19.46** (±1.44)	5.58 – 7.47 **6.59** (±0.53)
EFG-2	3.78 – 18.56 **9.16** (±4.31)	253 – 875 **511** (±179.61)	0.09 – 3.67 **1.62** (±1.08)	19.27 – 27.20 **22.44** (±1.73)	6.28 – 7.5 **6.98** (±0.42)
EFG-3	1.22 – 12.8 **5.32** (±3.87)	133 – 648 **336** (±171.38)	1.08 – 3.77 **2.13** (±0.66)	20.15 – 26.19 **23.64** (±1.51)	6.04 – 7.2 **6.37** (±0.33)
EFG-4	0.59 – 21.26 **5.40** (±5.28)	72.1 – 584 **249** (±154.67)	0.01 – 1.83 **0.51** (±0.46)	13.20 – 17 **15.09** (±1.09)	5.9 – 7.9 **6.7** (±0.53)
EFG-5	2.02 – 20.3 **6.74** (±4.87)	154 – 822 **343** (±188.60)	0.67 – 2.38 **1.25** (±0.42)	10.04 – 20.66 **16.42** (±2.86)	6.0 – 7.5 **6.59** (±0.52)
EFG-6	5.28 – 67.4 **25.33** (±19.46)	272 – 2088 **1127** (±654.04)	0.12 – 0.55 **0.36** (±0.13)	12.2 – 19.18 **14.87** (±2.12)	7.0 – 7.8 **7.54** (±0.25)
EFG-7	0.76 – 68.9 **12.03** (±16.39)	89.6 – 2410 **536** (±583.60)	0.14 – 2.07 **0.80** (±0.49)	9.60 – 21.44 **14.76** (±2.44)	5.2 – 7.9 **7.06** (±0.57)
EFG-8	0.83 – 42.1 **13.58** (±13.24)	101 – 1592 **561** (±427.61)	0.01 – 1.23 **0.35** (±0.44)	13.54 – 18.47 **15.84** (±1.31)	6.3 – 8.1 **7.25** (±0.56)
EFG-10	12.58 – 195 **62.21** (±60.86)	764 – 6085 **2418** (±1932.76)	0.21 – 4.73 **1.58** (±1.50)	15.63 – 19.52 **17.49** (±1.25)	5.9 – 7.4 **6.75** (±0.54)

Note: Values in bold represent the arithmetic mean. Values in parentheses equal **±**1 Standard Error.

2.3 *Irr-Cad* model results

A total of 1090 fields were sampled by the IWMI-DOA (2001-2003) and LDD-IWMI (2004-2005) Projects. Utilization of the Irr-Cad model increases the number of fields effectively and accurately covered by the Land Zoning activities to 2,537. This corresponds to a total area of 88.76 ha or 554 Rai of which 165.5 Rai was covered by IWMI-DOA (2001-2003) and 387 Rai was covered by LDD-IWMI (2004-2005) (Figure 7).

Table 4 Percentage and estimated area (ha and Rai) of fields covered by the *Irr-Cad* model (n=2,537) occupied by each Cd classification class.

Total Soil Cd (mg kg^{-1})	Area (ha)	Area (Rai)	Frequency (%)
<3.0*	7.72	48.25	3.14
>3.0 - <5.0	12.73	79.59	13.64
>5.0 - <10	24.72	154.52	33.06
> 10 - <20	21.66	135.40	29.65
>20 - <30	10.83	67.66	11.23
>30 - <40	3.28	20.47	1.94
>40 - <50	2.75	17.17	3.49
>50 - <100	3.26	20.37	2.36
>100	1.54	9.64	1.50
	88.76	*554.7*	*100*
Note: As indicated in Figure 3 approximately 26.5 Rai of land still requires further validation of Field Order^{IS}			

*European Union (EU) Maximum Permissible (MP) total soil Cd concentration agricultural (sludge amended) soil of 3.0 mg Cd kg^{-1} (Directive 86/278/EEC).

The results in Table 4 indicate that 66.81% of the 554 Rai currently covered by the Irr-Cad model has a total soil Cd of > 3.0 and < 20 mg kg^{-1} (Table 4 and Figure 6). The results also indicate that only 135.3 Rai or 24.5% of the area currently covered by Irr-Cad has a total soil Cd concentration >20 mg Cd kg^{-1}. GIS-generated Field Group specific Irr-Cad Predicted Mean Field Order Total Cd (PMFOT Cd) concentrations are given in Annex 2c.

Figure 6. Frequency distribution of percentage of area covered by the *Irr-Cad* model occupied by each Cd contamination classification class.

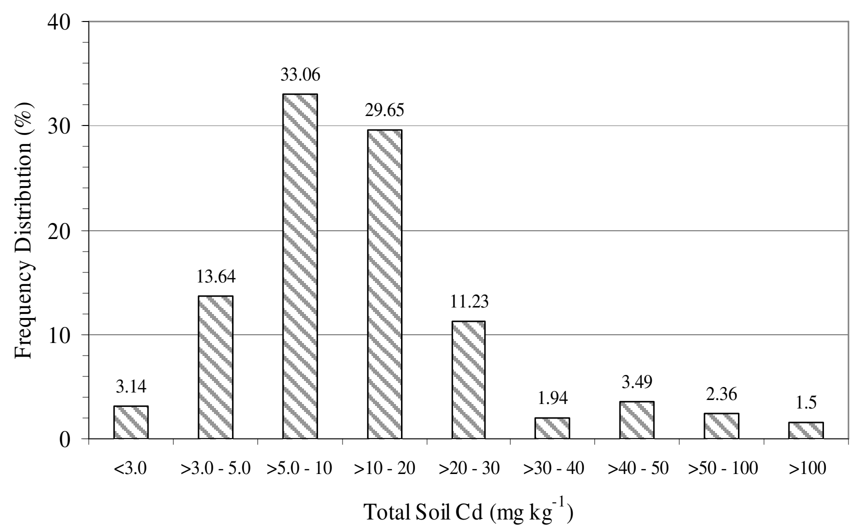
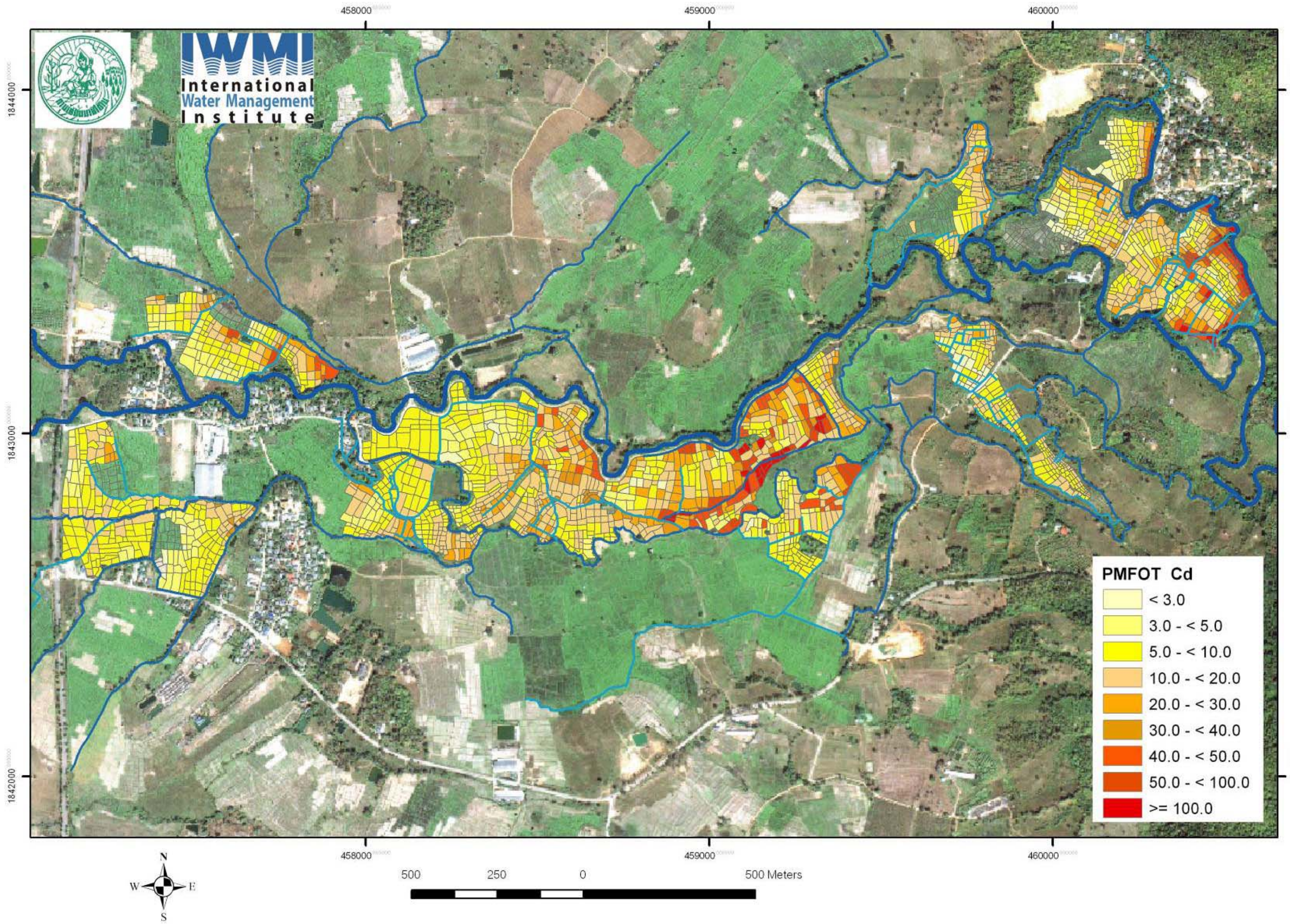


Figure 7. *Irr-Cad* Predicted Mean Field Order Total (PMFOT Cd) Soil Cd (mg kg^{-1}) in 2,537fields of Phatat Pha Daeng and Mae Tao Mai sub-districts, Mae Sot, Tak Province, Thailand.



2.4 Probability-based risk assessment

Table 5 below indicates that for all the soil Cd contamination classes evaluated ranging from <3.0 to >100 mg Cd mg^{-1} (Table 1) there is a 73.05 – 100% probability that rice fields **will** produce rice grain that is **unsafe** for human consumption. The risk assessment methodology is based on the probability of a given field producing rice grain with a Cd concentration exceeding the CCFAC Maximum Level (ML) for Cd in rice grain of 0.2 mg Cd kg^{-1}.

Table 5. Probability based risk assessment of fields in each soil Cd contamination class producing rice grain 'unsafe' for human consumption.

Soil Cd (mg kg^{-1})	% of fields producing rice grain safe for human consumption (Cd <0.2 mg kg^{-1})*	% of fields producing rice grain unsafe for human consumption (Cd >0.2 mg kg^{-1})
<3.0	17.31	**82.69**
>3.0 - <5.0	18.35	**81.65**
>5.0 - <10	11.77	**88.23**
> 10 - <20	26.95	**73.05**
>20 - <30	12.20	**87.80**
>30 - <40	18.52	**81.48**
>40 - <50	0	**100**
>50 - <100	5	**95.0**
>100	0	**100**

A more detailed breakdown of the rice grain Cd concentrations >0.2 mg kg^{-1} indicates that rice grain Cd is not simply 'marginally' elevated above the CCFAC Standard but that for the 1067 fields sampled, over 50% produce rice grain with Cd concentrations ranging from >0.4 -<2.0 mg Cg kg^{-1}. Further, 14.59% of the fields sampled produce rice grain with Cd concentrations ranging from >2.0 (Tables 6 and Figure 5).

Table 6. Frequency distribution (%) of rice grain Cd considered unsafe for human consumption (Cd >0.2 mg kg^{-1}) in relation to soil Cd contamination classes.

		Frequency distribution (%) of rice grain Cd considered unsafe for human consumption (Cd >0.2 mg kg^{-1})						
Soil Cd (mg kg^{-1})	% of fields producing rice grain unsafe for human consumption**	>0.2 to <0.4	>0.4 to <1.0	>1.0 to <2.0	>2.0 to <3.0	>3.0 to <4.0	>4.0 to <5.0	>5.0
<3.0	**82.69**	17.95	40.38	18.59	5.13	0.64	-	-
>3.0 - <5.0	**81.65**	11.93	34.86	28.44	4.59	1.83	-	-
>5.0 - <10	**88.23**	14.29	34.39	25.40	8.46	3.18	1.58	1.05
> 10 - <20	**73.05**	13.28	28.91	16.80	9.38	2.34	1.17	1.17
>20 - <30	**87.80**	18.29	28.05	19.51	13.41	2.44	4.88	1.22
>30 - <40	**81.48**	14.81	11.11	33.33	22.2	-	-	-
>40 - <50	**100**	25.00	37.50	25.00	12.50	-	-	-
>50 - <100	**95.00**	20.00	40.00	20.00	5.00	-	5.00	5.00
>100	**100**	7.14	7.14	10.71	35.71	21.43	10.71	7.14
	Mean Frequency Distribution	*16.13* (±1.78)	*29.43* (±4.16)	*22.06* (±2.24)	*12.97* (±3.38)	*6.25* (±3.80)	*4.72* (±1.71)	*3.17* (±1.27)

*Codex Committee on Food Additives and Contaminants (CCFAC) Maximum Permissible Level for Cd in rice grain = 0.2 mg Cd kg^{-1} (Report of the 34th Session, CCFAC, 2002). Values in parentheses equal ±1 Standard Error. ** Values taken from Table n.

2.5 Public health risk-based risk assessment

Potential public health risk is determined through the estimation of Weekly Intake (WI) values based on the mean rice grain Cd concentration for each soil Cd contamination class in comparison with the Joint FAO/WHO Expert Committee on Food Additives (JECFA) Provisional Tolerable Weekly Intake (PTWI) for Cd of 7µg Cd per kg Body Weight (BW) (Table 7).

$$\textbf{WI} = \frac{\text{Weekly Cd intake } \mu g\ kg^{-1}}{\text{Body Weight (BW) kg}}$$

Weekly Cd intake µg kg^{-1} = (Daily rice intake (kg) x 7) x rice grain Cd concentration (µg Cd kg^{-1})

The results indicate that estimated WI values for Cd based on rice grain intake alone significantly exceed the JECFA PTWI value of 7µg Cd per kg BW (Table 7). Estimated mean WI values for females and males of 50 yrs from rice intake alone range from 24.94 – 93.04 and 24.48 – 91.33 µg Cd kg^{-1} BW. This is up to over 13 times the JECFA recommended PTWI value and poses a significant risk to public health.

In addition, January 2005 an initial rapid screening of household rice grain samples was undertaken by LDD. Household grain samples were collected from 465 households in four villages within Mae Tao Creek catchment as compared with samples collected from three villages irrigating paddy rice with water sourced from the Mae Ku Creek and Pong Creek. It is important to note that the Mae Ku Creek also originates from the Zn-mineralized area. The results of the household rice grain screening indicate that for villages utilizing irrigation sourced from Mae Tao Creek, between 66-100% of household rice grain samples were associated with estimated WI values > 7µg Cd kg^{-1} BW. For women and men of 50 yrs in the 4 villages sampled, estimated mean WI of Cd from the consumption of rice alone ranged from 19.92 – 41.73 µg Cd kg^{-1} BW and 19.56 – 40.96 µg Cd kg^{-1} BW, respectively (Table 8).

In comparison although 29.82% of rice grain samples collected from Khang Phiban were associated with estimated WI values > 7µg Cd kg^{-1} BW. Notably, the mean (n=57) estimated WI value of 5.18 and 5.08 µg Cd kg^{-1} BW for female and male residents, is within acceptable levels (Table 8). Of concern is the fact that in Mae Ku Noi and Mae Ku Nua, estimated mean Cd WI values are >14.0 and >18.0 µg Cd kg^{-1} BW, respectively.

Cadmium levels in urine samples collected from 6000 residents within Phatat Pha Daeng, sub-district indicate potential renal dysfunction in 12% of the resident population as based on the critical urine Cd threshold established by Ikeda et al., (2003) of 10-12 µg Cd g $creatinine^{-1}$ (Personal Communication: Dr. Chantana Padungtod, Bureau of Occupational & Environmental Disease, Department of Disease Control, Ministry of Public Health). It is essential that further detailed dietary and epidemiological studies are conducted to clarify health impacts in the resident population.

Table 7. Estimated Weekly Intake (WI) values of Cd (μg kg BW) based on the range and mean rice grain Cd for each soil Cd contamination class. Data derived from 1,067 rice fields sampled by IWMI-DOA (2001-2003) and LDD-IWMI (2004-2005).

Body Weight (kg)*		58.71	59.81
Daily rice intake (kg)**		0.280	0.280
Soil Cd (mg kg^{-1})	Rice grain Cd (mg kg^{-1})	WI Female (50 yrs)	WI Male (50 yrs)
<3.0	0.01 – 3.09 ***0.747*** (±0.050)	0.3 – 103 ***24.94***	0.3 – 101 ***24.48***
>3.0 - 5.0	0.01 – 3.77 ***0.831*** (±0.067)	0.3 – 126 ***27.74***	0.3 – 124 ***27.23***
>5.0 - 10	0.01 – 5.65 ***1.068*** (±0.074)	0.3 – 189 ***35.65***	0.3 – 185 ***35.00***
> 10 - 20	0.01– 5.95 ***0.906*** (±0.064)	0.3 - 199 ***40.66***	0.3 - 195 ***39.91***
>20 - 30	0.01 – 5.70 ***1.218*** (±0.134)	0.3 - 190 ***42.73***	0.3 - 187 ***41.95***
>30 - 40	0.01 – 2.64 ***1.280*** (±0.168)	0.3 – 88 ***32.68***	0.3 – 87 ***32.08***
>40 - 50	0.286 – 2.07 ***0.979*** (±0.215)	9.3 – 69 ***32.68***	9.2 – 68 ***32.08***
>50 - 100	0.149 – 5.06 ***1.20*** (±0.296)	5.0 - 169 ***40.06***	4.9 - 166 ***39.32***
>100	0.379 – 7.75 ***2.787*** (±0.290)	12.76 - 259 ***93.04***	12.5 - 254 ***91.33***

* National Food and Nutrition Status Survey Report (No.4), 1995, Department of Health, Ministry of Public Health. ** National Nutrition Plan Sub-committee, National Nutrition Committee, 1998.

Table 8. Estimated Weekly Intake (WI) values of Cd (μg kg BW) based on household rice grain samples (2004 Harvest) from villages within Huai Mae Tao catchment as compared with villages irrigating paddy rice with water sourced from the Huai Mae Ku [(a)] and Huai Pong [(b)] .

			Female (50 yrs)	Male (50 yrs)		
Body Weight (kg)*			58.71	59.81	Female (50 yrs)	Male (50 yrs)
Daily rice intake (kg)**			0.280	0.280		
Village	No. of Samples	Rice grain Cd (mg kg^{-1})	Estimated WI (μg Cd kg BW)		% of household rice grain samples associated with estimated WI values > 7μg Cd per kg Body Weight (BW)	
Khang Phiban [(b)]	57	*ND – 1.11* **0.155** (±0.028)	*0.33 – 37.0* **5.18** (±0.930)	*0.32 – 36.3* **5.08** (±0.919)	**29.82%**	**29.82%**
Pha Te	38	*0.2 – 2.80* **1.25** (±0.116)	*6.67 – 93.46* **41.73** (±3.874)	*6.55 – 91.75* **40.96** (±3.802)	**97.36%**	**97.36%**
Mae Tao Mai	65	*0.06 – 2.42* **0.596** (±0.058)	*2.00 – 80.79* **19.92** (±1.962)	*1.96 – 79.30* **19.56** (±1.926)	**90.30%**	**89.23%**
Mae Tao San Pae	36	*ND – 3.91* **0.736** (±0.150)	*0.03-130.53* **24.59** (±5.032)	*0.03-128.13* **24.14** (±4.940)	**66.66%**	**66.66%**
Dong Chai	26	*ND – 1.87* **0.667** (±0.111)	*0.03-62.42* **22.29** (±3.707)	*0.03-61.28* **21.88** (±3.639)	**76.92%**	**73.07%**
Mae Ku Noi [(a)]	86	*ND – 2.06* **0.444** (±0.043)	*0.03-68.77* **14.84** (±1.466)	*0.03-67.5* **14.57** (±1.439)	**68.60%**	**65.11%**
Mae Ku Nua [(a)]	157	*ND – 1.97* **0.551** (±0.030)	*0.03-65.76* **18.40** (±1.005)	*0.03-64.55* **18.06** (±0.986)	**82.16%**	**80.89%**

*National Food and Nutrition Status Survey Report (No.4), 1995, Department of Health, Ministry of Public Health. ** National Nutrition Plan Sub-committee, National Nutrition Committee, 1998. Note: Mean values for rice grain Cd (mg kg^{-1}) and estimated WI of Cd (μg Cd kg BW^{-1}) are in bold. The value in parentheses represents ±1 Standard Error. The range in rice grain Cd (mg kg^{-1}) and estimated WI of Cd (μg Cd kg BW^{-1}) is italicized. Shaded cells represent those villages within the Huai Mae Tao catchment.

2.6 Soil pH and rice grain Cd

The results also indicate that for the rice crop, mitigating soil pH as a means of reducing rice grain Cd uptake may not be a viable option. Table 9 represents for each soil Cd contamination class, a comparison of the soil pH range (air-dry 1:5 water) for fields producing rice grain that is considered safe or unsafe for human consumption.

Table 9. Comparison of the soil pH range (air-dry 1:5 water) for fields producing rice grain that is safe or unsafe for human consumption in relation to soil Cd contamination classes.

Soil Cd (mg kg^{-1})	**(A)** pH of fields producing rice grain safe for human consumption (Cd <0.2)*	**(B)** pH of fields producing rice grain unsafe for human consumption (Cd <0.2)
<3.0	*range 5.87 – 7.8* ^{a}mean 6.73 (±0.089)	*range 5.2 – 7.9* ^{a}mean 6.60 (±0.055)
>3.0 - <5.0	*range 5.85 – 7.9* ^{a}mean 6.67 (±0.104)	*range 5.49 – 8.1* ^{a}mean 6.63 (±0.059)
>5.0 - <10	*range 6.3 – 7.9* ^{a}mean 7.26 (±0.089)	*range 5.6 – 7.9* ^{b}mean 6.93 (±0.070)
> 10 - <20	*range 6.7 – 7.9* ^{a}mean 7.45 (±0.034)	*range 5.8 – 8.13* ^{a}mean 7.34 (±0.034)
>20 - <30	*range 7.43 – 7.9* ^{a}mean 7.64 (±0.051)	*range 5.6 – 8.07* ^{b}mean 7.31 (±0.049)
>30 - <40	*range 7.45 – 7.53* ^{a}mean 7.48 (±0.017)	*range 6.85 – 8.25* ^{a}mean 7.43 (±0.078)
>40 - <50	(**no** fields produce rice safe for human consumption)	*range 7.30 – 8.08* mean 7.50 (±0.039)
>50 - <100	*7.57*	*range 7.30 – 8.08* mean 7.50 (±0.089)
>100	(**no** fields produce rice safe for human consumption)	*range 7.37 – 8.08* mean 7.54 (±0.037)

*Codex Committee on Food Additives and Contaminants (CCFAC) Maximum Permissible Level for Cd in rice grain = 0.2 mg Cd kg^{-1} (Report of the 34th Session, CCFAC, 2002). Between columns A and B mean values not followed by a common letter are significantly different at $p<0.05$ (two-tailed) as determined by t-Test (Two Sample Assuming Equal Variances). Values in parentheses equal ±1 Standard Error.

The results demonstrate that with the exception of the soil Cd >5 - <10 mg kg^{-1} and >20 - <30 mg kg^{-1} Cd classes there is no significant difference in soil pH between fields that produce either rice that is safe or unsafe for human consumption. This may be due to the influence of soil moisture/redox conditions on soil pH at the critical grain fill stage.

In paddy soils, soil solution pH alters towards near neutral as the system moves from oxidizing to reducing conditions, which reduces Cd phyto-availability (Chaney et al., 1996). However, drainage of fields at the critical grainfill stage in order to optimize yields and facilitate ease of harvesting, decreases soil pH to the antecedent condition and increases Cd phyto-availablity to rice plants (Chaney et al., 1996). In the study area field observations from 2000-2005 demonstrate that irrigation management at the grainfill stage is highly variable. At grainfill, fields range from having standing water to having severe dessication cracks. This in part explains why fields with equivalent soil pH and total soil Cd concentrations can produce rice with Cd concentrations below or significantly exceeding the CCFAC MP level. However, it should be reiterated that even with the observed variations in field moisture status at grainfill **83.0%** of the 1,067 fields sampled produced rice grain with Cd concentrations exceeding the CCFAC MP level (Figure 5 and Table 2).

2.7 Correlations between soil and rice grain Cd: Is it possible to predict the uptake of Cd to Rice Grain?

The results of research conducted by IWMI and partners, indicates that for 'air-dry soil samples, there is no correlation between total or bio-available soil Cd and rice grain Cd (Figures 8a-c). Consequently, these **cannot** be used to predict uptake of Cd to rice grain.

Figure 8a. Non-significant relationship between rice grain Cd and 0.005M DTPA-extractable soil Cd (mg kg^{-1}).

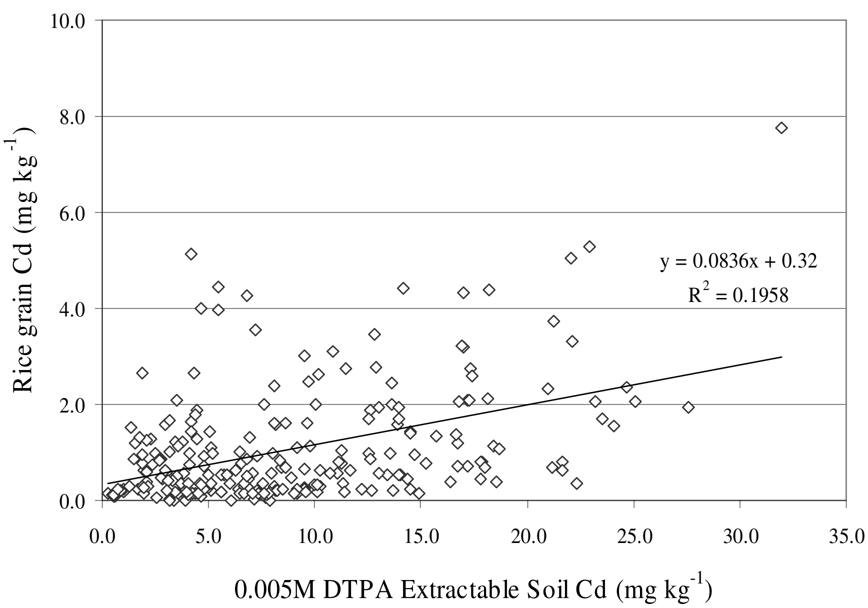


Figure 8b. Non-significant relationship between rice grain Cd and 0.01M $CaCl_2$-extractable soil Cd (mg kg^{-1}).

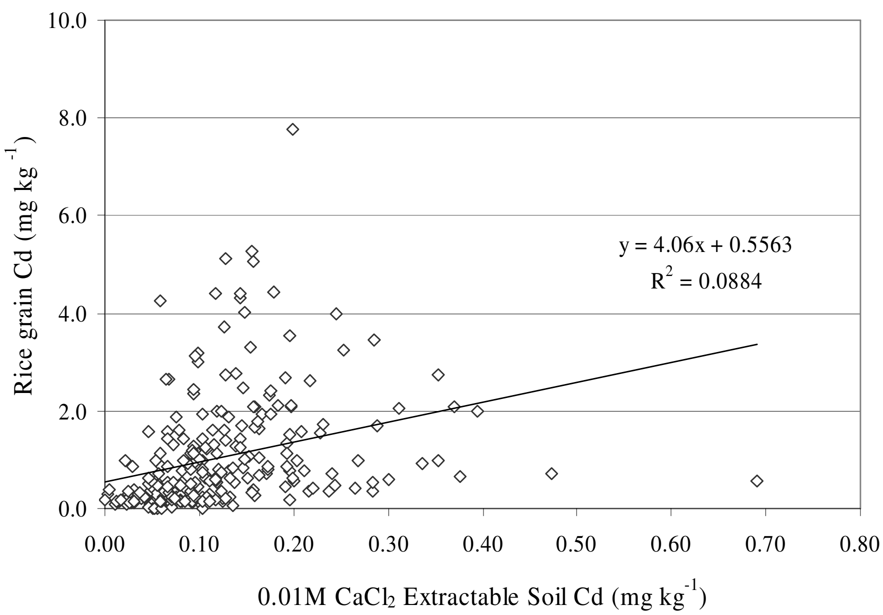
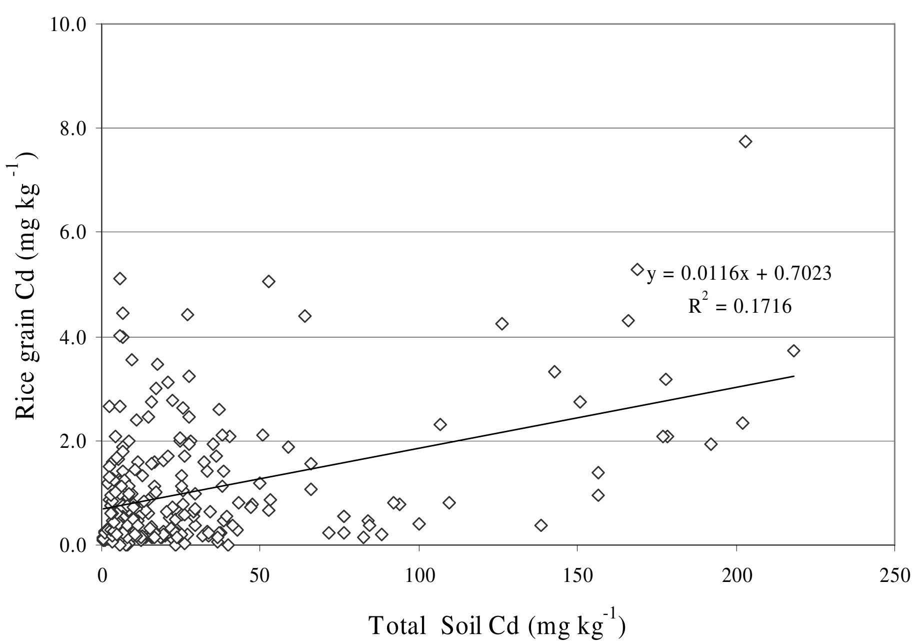


Figure 8c. Non-significant relationship between rice grain Cd and total soil Cd (mg kg^{-1}).



Consequently, in 2003 IWMI and the Thai Department of Agriculture undertook a series of field trials in conjunction with structured laboratory analyses to develop a multiple regression model utilizing critical parameters controlling Cd mobility in order to predict Cd uptake to rice grain. Soil pH, as a major factor controlling the solubility of Cd in soils was a key component of the model. Bulk soil samples were taken from selected Cd/Zn co-contaminated soils in Phatat Pha Daeng sub-district. Soil total Cd and Zn concentrations for the fields studied ranged from 2.4 – 168 and 254 – 6030 mg kg^{-1} respectively. Consequently, in this Zn dominated system 'bio-available' Zn was included as a variable influencing the interactions between Cd and Zn in soil-plant uptake pathways. Two regression models were investigated namely, a stepwise linear regression model and a generalized multiplicative multiple regression model (Simmons et al., 2005).

2.7.1 Methods

Cadmium uptake to rice grain occurs during the critical grain fill stage. Consequently, in November 2003 composite soil samples were collected at grainfill from 19 pre-selected fields with, concurrent grain samples collected at maturity. For subsequent analysis, soil samples were separated into two equal portions. Portion A was subjected to conventional air-drying and sample preparation procedures. Portion B was maintained at Field Condition (FC) and stored at <4ºC until extractions were undertaken. Two extraction methods commonly adopted as indicators of Cd and Zn 'bioavailability' were evaluated during the course of the study. $CaCl_2$-extractable Cd and Zn were determined by extracting soil portions A and B for 4 h in 0.01 M $CaCl_2$ 0.05M $CaCl_2$ and 0.1M $CaCl_2$ at a soil:extractant ratio of 1:5. In addition, soil portions A and B were extracted in 1M NH_4NO_3 for 2 h at a soil:extractant ratio of 1:2.5. Total Zn and Cd in soil and rice grain samples were determined in *aqua regia* (3:1 $HCl:HNO_3$) and 2:1, $HNO_3:HClO_4$, respectively. Soil pH_w was measured on a 1:5 soil:water suspension.

2.7.2 Results and discussion

The results demonstrate the comparative effectiveness of the $CaCl_2$-extraction method to predict Cd uptake by rice grain as compared to 1M NH_4NO_3 for soils at FC. Further, the $CaCl_2$ extractions results for soils at FC indicate that the generalized multiple regression model is more effective in predicting rice grain Cd uptake than a standard step wise approach (Table 10). This may in part be attributed to the fact that the generalized multiple regression model effectively takes into account the multiplicative nature of the interactions between soil pH, and exchangeable Zn and Cd in the plant uptake pathway. In addition, the results indicate that the generalized multiple regression model incorporating 0.05N $CaCl_2$ extractable Cd and Zn in conjunction with soil pH accounts for 92.5% of the variability in rice grain Cd (Table 10). In comparison, air-dried soil samples subjected to conventional preparation procedures resulted in no significant relationships, regardless of extractant, between the aforementioned soil variables and Cd uptake by rice grain (Table 10). Intuitively, this is to be expected, as the air-dry sample does not reflect the complex redox/pH interactions associated with the flooded soils at grainfill. Further, this demonstrates the importance of the timing of sample collection and post sampling preparation procedures when predicting soil crop interactions.

The results further confirm that soil pH at field condition is a dominant factor controlling Cd 'bioavailability' in paddy soils. In addition, the results indicate the critical role of bioavailable soil Zn in the uptake of Cd to rice grain.

Table 10. Regression relationships between $CaCl_2$-extractable Cd and Zn, NH_4NO_3-extractable Cd and Zn and, soil pHw (1:5) to predict Cd uptake in rice grain.

Response	Predictors	R-sq
	0.01M $CaCl_2$-Extr. Cd + pH	
Grain Cd	-18.14 + 12.69 0.01M $CaCl_2$ Cd + 2.45 pH	0.357
	-6.1– 52.3 0.01M $CaCl_2$ Cd + 0.56 pH + 10.60 0.01M $CaCl_2$ Cd*pH	0.373
	0.01M $CaCl_2$-Extr. Cd + pH + 0.01M $CaCl_2$-Extr. Zn	
Grain Cd	-18.55 + 10.4 0.01M $CaCl_2$ Cd + 2.54 pH + 0.113 0.01M $CaCl_2$ Zn	0.316
	63.7 – 441 0.01M $CaCl_2$ Cd – 8.59 pH – 11.0 0.01M $CaCl_2$ Zn + 59.4 0.01M $CaCl_2$ Cd*pH – 165.7 0.01M $CaCl_2$ Cd*0.01M $CaCl_2$ Zn + 0.32 pH*0.01M $CaCl_2$ Zn + 34.20 0.01M $CaCl_2$ Cd*pH*0.01M $CaCl_2$ Zn	0.832
	0.05M $CaCl_2$-Extr. Cd + pH	
Grain Cd	-17.28 + 2.226 0.05M $CaCl_2$ Cd + 2.492 pH	0.591
	-3.69 – 13.93 0.05M $CaCl_2$ Cd + 0.527 pH + 2.536 0.05M $CaCl_2$ Cd*pH	0.832
	0.05M $CaCl_2$-Extr. Cd + pH + 0.05M $CaCl_2$-Extr. Zn	
Grain Cd	-6.45+ 6.08 0.05M $CaCl_2$ Cd + 0.971pH – 0.306 0.05M $CaCl_2$ Zn	0.777
	2.05 – 72.0 0.05M $CaCl_2$ Cd - 0.213 pH + 3.00 0.05M $CaCl_2$ Zn + 10.36 0.05M $CaCl_2$ Cd*pH + 0.003 0.05M $CaCl_2$ Cd*0.05M $CaCl_2$ Zn – 0.440 0.05M$CaCl_2$ Zn*pH + 0.022 0.05M $CaCl_2$ Cd*0.05M $CaCl_2$ Zn*pH	0.925
	0.1M CaCl2-Extr. Cd + pH	
Grain Cd	-14.13+ 1.394 0.1M $CaCl_2$ Cd + 2.045 pH	0.592
	-0.88– 7.85 0.1M $CaCl_2$ Cd + 0.134 pH + 1.418 0.1M $CaCl_2$ Cd*pH	0.809
	0.1M CaCl2-Extr. Cd + pH + 0.1M CaCl2-Extr. Zn	
Grain Cd	-13.02 + 1.675 0.1M $CaCl_2$ Cd + 1.898 pH -0.0346 0.1M $CaCl_2$ Zn	0.574
	-0.76 – 20.47 0.1M $CaCl_2$ Cd + 0.18 pH + 0.652 0.1M $CaCl_2$ Zn + 2.94 0.1M $CaCl_2$ Cd*pH – 0.069 0.1M $CaCl_2$ Cd*0.1M $CaCl_2$ Zn – 0.097 pH*0.1M $CaCl_2$ Zn + 0.0255 0.1M $CaCl_2$ Zn*pH*0.1M $CaCl_2$ Cd	0.862
	1M NH_4NO_3-Extr. Cd + pH	
Grain Cd	-14.69 + 11.22 1M NH_4NO_3 Cd + 1.947 pH	0.507
	_-1.65 - 34.9 1M NH_4NO_3 Cd + 0.05 pH + 6.87 1M NH_4NO_3 Cd * pH_	0.538
	1M NH_4NO_3-Extr. Cd + pH + 1M NH_4NO_3-Extr. Zn	
Grain Cd	-15.24 + 10.19 1M NH_4NO_3 Cd + 2.039 pH + 0.038 1M NH_4NO_3 Zn	0.476
	_24.9 – 260 1M NH_4NO_3 Cd – 3.33 pH + 12.1 1M NH_4NO_3 Zn + 35.4 1M NH_4NO_3 Cd*pH – 25.7 1M NH_4NO_3 Cd*1M NH_4NO_3 Zn – 1.68 pH*1M NH_4NO_3 Zn + 3.97 1M NH_4NO_3 Cd*pH*1M NH_4NO_3 Zn_	0.753

N.B. General multiplicative multiple regression model is italicized.

Further validation of the generalized multiple regression model to predict uptake of Cd to rice grain is currently being undertaken by LDD and IWMI. The results will be finalized in early 2006.

3. CONCLUSIONS

Rice grain Cd concentrations in Phatat Pha Daeng and Mae Tao Mai sub-districts, Mae Sot, Thailand

- Rice grain Cd concentrations for the 1,067 fields sampled range from <0.01 – 7.75 mg Cd kg^{-1}. This is up to 38.75 times the recommended ML for Cd in Thai rice grain of 0.2 mg Cd kg^{-1}.
- Further, and of great concern with regards public health over 83.0% of the fields sampled produced rice grain with Cd concentrations exceeding the recommended ML for Cd in Thai rice grain.
- The results clearly indicate that **<u>all</u>** fields that receive irrigation from the Mae Tao Creek are at high risk of Cd contamination and that there is a 75-100% probability that these fields will produce rice grain with Cd concentrations significantly exceeding the recommended ML for Cd in Thai rice grain..

Soil Cd concentrations

- Soil total Cd concentrations for the 1,090 field's sampled range from 0.1 – 284 mg Cd kg^{-1} with 85.0% of the fields sampled having a total soil Cd concentration exceeding the European Union (EU) Maximum Permissible (MP) level of 3.0 mg Cd mg^{-1} for agricultural (sludge amended) soils.

Potential public health risks associated with villages receiving irrigation sourced from Mao Tao Creek

- The JECFA Provisional Tolerable Weekly Intake (PTWI) for Cd is 7µg Cd per kg Body Weight (BW) per week. This PTWI value is established on the basis of preventing negative impacts on human health via dietary Cd.
- As indicated by the estimated Weekly Intake (WI) values the rice grain Cd concentrations in the 1,067 fields sampled pose a significant threat to public health.
- Household rice grain screening indicates that for villages utilizing irrigation sourced from Mae Tao Creek, between 66-100% of household rice grain samples were associated with estimated WI values > 7µg Cd kg^{-1} BW.
- For women and men of 50 yrs in the 4 villages sampled, estimated mean WI of Cd from the consumption of rice alone ranged from 19.92 – 41.73 µg Cd kg^{-1} BW and 19.56 – 40.96 µg Cd kg^{-1} BW, respectively.

Potential public health risks associated with villages receiving irrigation sourced from Mao Ku Creek

- Of concern is the fact that in Mae Ku Noi and Mae Ku Nua villages, estimated mean Cd WI values are >14.0 and >18.0 µg Cd kg^{-1} BW, respectively.
- 65-82% of household rice grain samples in Mae Ku Noi and Mae Ku Nua villages were associated with estimated WI values > 7µg Cd kg^{-1} BW.

Irr-Cad Model

- In irrigated rice based agricultural systems receiving Cd contaminated sediment v irrigation water, *Irr-Cad* is an effective decision support tool to rapidly and cost effectively estimate the spatial distribution of soil Cd.
- Utilization of the Irr-Cad model resulted in 2,537 fields being accurately covered by the Land Zoning activities corresponding to a total area of 88.49 ha or 554 Rai.
- 96.86% of the 554 Rai covered by *Irr-Cad* has a total soil Cd > 3.0 mg Cd kg^{-1}.
- It is also strongly recommended that *Irr-Cad* is applied to all paddy rice areas of Mae Ku Creek catchment and all areas irrigated by Mae Tao Creek.

Probability-based risk assessment

- For all the soil Cd contamination classes evaluated ranging from <3.0 to >100 mg Cd kg^{-1} there is a 73.05 – 100% probability that rice fields **will** produce rice grain that is **unsafe** for human consumption (e.g rice grain Cd >0.2 mg Cd kg^{-1})

Predicting uptake of Cd to rice grain

- For ‘air-dry soils’ total and bio-available soil Cd **cannot** be used to predict uptake of Cd to rice grain.
- Initial IWMI-DOA research results indicate that a generalized multiple regression model incorporating 0.05N $CaCl_2$ extractable Cd and Zn in conjunction with soil pH of soil at ‘Field Moisture Condition’ collected at the grain-fill stage accounts for 92.5% of the variability in rice grain Cd.
- Further development of this generalized multiple regression model is being undertaken by LDD and IWMI.

Cd concentrations in soybean grown in Phatat Pha Daeng sub-district

- In addition, soybean Cd concentrations for the 113 fields sampled under the IWMI-DOA Project (2001-2003) ranged from 0.34 – 3.37 mg Cd kg^{-1}. 100% of the soybean samples contained Cd at values exceeding the CCFAC ML for Cd in soybean of 0.2 mg Cd kg^{-1} (Simmons et al., 2003).

4. RECOMMENDATIONS

- It is recommended that rice production and the production of agricultural products for human consumption are stopped in all areas that receive irrigation from Mae Tao Creek.
- In the absence of field sampling of soil and food crops, it is strongly recommended that economically viable and marketable non-food crops e.g. industrial crops are grown in the study area and that adequate training is provided to the farming communities to ensure their successful adoption.
- For the recommended non-food crops, structured research programs should be conducted to evaluate and quantify the route of Cd throughout the whole process from field to end product (including the disposal or re-use of industrial by-product)
- If upon the implementation of a set of ‘validated’ remediation options rice production and the production of other agricultural products for human consumption are allowed to continue it is strongly recommended that a long-term ‘transparent’ and externally evaluated ‘monitoring and certification program’ is conducted.

- It is also strongly recommended that *Irr-Cad* in association with both field and household rice grain sampling is applied to all paddy rice areas of Mae Ku Creek catchment and all areas irrigated by Mae Tao Creek.
- Research activities should continue to be undertaken to develop a robust 'trigger value' or model to predict uptake of Cd to rice grain.
- Additional potentially Cd contaminated sites in Thailand should be systematically investigated and effective management programs implemented to protect public and environmental health.

4.1 Protecting the integrity of Thai rice exports

The MLs established by CCFAC and JECFA are based on the 'safe' lifetime consumption of agricultural produce and the *free movement* of products in international trade. MLs set by the CCFAC are used internationally as criteria to establish *non-tariff trade barriers*. In addition, ISO 14000 is being sought by many food importers to guarantee that food and fiber are produced using environmentally sustainable practices. As a result of the Cd contamination in Mae Sot in June 2004 the US Food and Drug Administration expressed concerns over Thai Rice exports. In addition, in February 2005, Vietnam identified high levels of Cd in rice exported from Mae Sot. It is of utmost importance to the integrity of Thai rice exports that representatives of Thai rice importers are unequivocally assured that rice from Mae Sot will not enter the export market. The Royal Thai Government can give no stronger assurance that Thai rice is safe than by prohibiting rice production in all areas irrigated by Mae Tao Creek.

4.2 Protecting public health

Cadmium induced renal dysfunction occurs following the prolonged consumption of Cd contaminated rice. The estimated WI values presented in this report indicate that populations consuming Cd contaminated rice in Mae Sot are potentially exposed to a lifetime of significantly elevated dietary Cd. Ikeda et al., (2003) demonstrate that a critical threshold level of Cd must accumulate in the kidney before the onset of irreversible renal dysfunction. By **prohibiting** the cultivation of rice and other crops for human consumption the Royal Thai Government will effectively prevent further accumulation of Cd in the kidneys of exposed populations in Mae Sot and thus protect the health of current and future generations.

5. ACKNOWLEDGEMENTS

The authors would like to thank all the Land Development Department and the Department of Agriculture staff whom over the last 5 years, were involved in the collaborative research activities summarized in this report. Particular mention should go to Dr. Pichit Pongsakul for his continuous support and inputs from 2001-2004. In addition, mention must be made to the laboratory technicians of both LDD and DOA for their high quality analyses and dedicated work ethic.

ANNEX 1

Irr-Cad Model for the rapid and cost effective zoning of soil Cd contamination

The IWMI-DOA Project (2001-2003) developed and validated an Irrigation Infrastructure-based Cadmium Hazard Mapping model (*Irr-Cad*) to rapidly evaluate the spatial distribution of Cd (Simmons et al., 2004). *Irr-Cad* was developed as a decision support tool for rapid risk assessment in irrigated rice-based agricultural systems receiving contaminated suspended sediment transported in irrigation water. *Irr-Cad* does not predict absolute values of mean Field Order soil Cd but provides a method of assessing the possible distribution of Cd associated with Cd contaminated surface irrigation.

Simmons et al., (2003 and 2004) indicate that in agricultural systems receiving Cd contamination via suspended sediment, the determination of Field Order in Irrigation Sequence (Field Order^{IS}) is an essential pre-requisite to accurately assess Cd contamination risk (Table A1.1, Figures A1.1 and A1.2). Primary fields (1st Order) are those fields receiving irrigation directly from in-field irrigation channels. Secondary (2nd Order) fields 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.

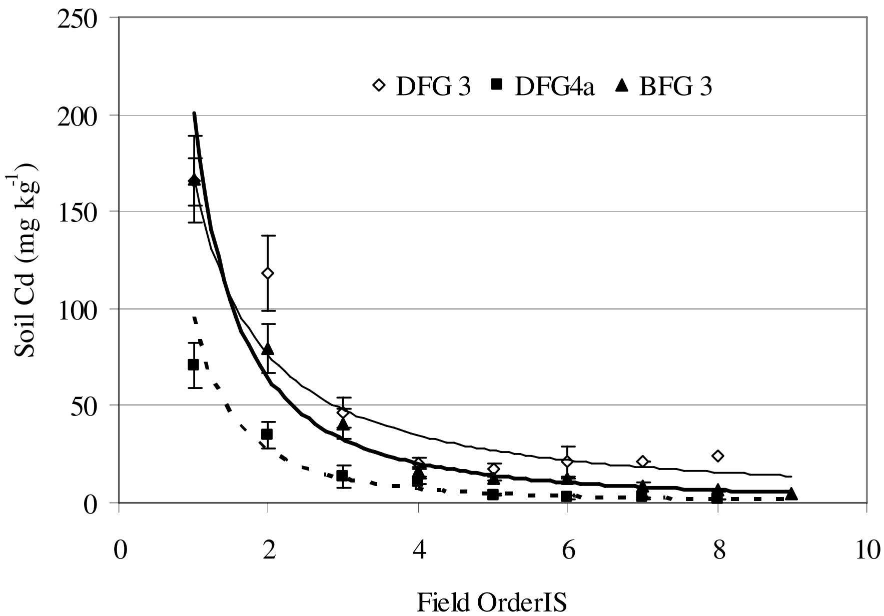
Table A1.1. Regressions relationships between mean total soil Cd concentration (mg kg^{-1}) for each Field Order in relation to Field Order^{IS}.

Field Group	n	Equation	R^2
BFG 2/3	9	$y = 256.68x^{-1.9485}$	0.9787**
BFG 4/4a	7	$y = 129.47x^{-1.6387}$	0.9614**
BFG 5	9	$y = 205.05x^{-1.7162}$	0.9711**
DFG 2	5	$y = 29.746x^{-2.285}$	0.9774**
DFG 4a	8	$y = 151.14x^{-2.0843}$	0.957**
DFG 5	7	$y = 61.047x^{-1.4715}$	0.9874**
DFG 6	4	$y = 37.727x^{-1.1837}$	0.9159**
DFG 7	7	$y = 28.685x^{-0.8627}$	0.9388**
D FG 8	7	$y = 19.645x^{-0.9202}$	0.976**
E FG 3	5	$y = 13.069x^{-1.195}$	0.9576**

Note. For each FG 'n' represents the number of Field Orders^{IS}. Significant p<0.05 * p<0.001** (Genstat 5.0).

Irr-Cad utilizes the relationship between Field Order^{IS} and spatial Cd distribution (Table A1.1, Figures A1.1 and A1.2) to generate weighed coefficients ($Coeff_W$) that express the ratio between the mean total soil Cd in the 'Primary Fields' ($T\text{-}Cd_P$) and mean total soil Cd in all subsequent fields in the irrigation sequence. Mean total Field Order soil Cd in the respective Field Order e.g. Field Order 2, 3, 4 etc. is divided by the Mean total Field Order soil Cd in the Primary Field ($T\text{-}Cd_P$) (Table A1.2)

Figure A1.1. Relationship between mean total soil Cd concentration (mg kg^{-1}) for selected Field Groups (FGs) for each Field Order in relation to Field $Order^{IS}$.



Note: DFG4a: $y = 96.076x^{-1.8442}$ $R^2 = 0.9674$; BFG3: $y = 200.86x^{-1.6489}$ $R^2 = 0.9758$; DFG3: $y = 167.17x^{1.1334}$ $R^2 = 0.8336$.

Table A1.2. Weighed coefficients ($Coeff_W$) for Cd in relation to Field $Order^{IS}$

Field $Order^{IS}$	$Coeff_W$ for Cd
1	1
2	0.492
3	0.356
4	0.229
5	0.175
6	0.114
7	0.090
8	0.097
9	0.171

Values represent the mean (n=8) $Coeff_W$ derived from 8 Field Groups within Tambon Phatat Padaeng and Tambon Mae Tao Mai.

Irr-cad is a General Linear Regression Model (Genstat 5.0) incorporating $T\text{-}Cd_P$, $Coeff_W$ and Field $Order^{IS}$ to predict the spatial distribution of soil Cd. This reflects the multiplicative relationship between the total Cd concentration in a given field and the fields' proximity to primary outlets from in-field irrigation channels as dictated by inter-field irrigation flows. Data from 8 randomly selected FGs consisting of 371 fields covering an area of 10.56 hectares was used to generate the *Irr-Cad* model. Simmons et al., (2004) indicate that the *Irr-Cad* model accounts for 97.8% of the variance in mean Field Order soil Cd (mg kg^{-1}) as expressed by Equations 1a and 1b.

Equation 1a

Response variate (y): Mean Field Order total soil Cd (mg kg^{-1})

Fitted Terms: Constant + $T\text{-}Cd_P$ + Field $Order^{IS}$ + $Coeff_W$ + $T\text{-}Cd_P$ x Field $Order^{IS}$ + $T\text{-}Cd_P$ x $Coeff_W$ + Field $Order^{IS}$ x $Coeff_W$ + $T\text{-}Cd_P$ x Field $Order^{IS}$ x $Coeff_W$

Equation 1b

$y = 1.02 + (-0.0853 \text{ x } T\text{-}Cd_P) + (-0.294 \text{ x Field } Order^{IS}) + (-10.83 \text{ x } Coeff_W) + (0.01651 \text{ x } (T\text{-}Cd_P \text{ x Field } Order^{IS})) + (1.3103 \text{ x } (T\text{-}Cd_P \text{ x } Coeff_W)) + (9.29 \text{ x } (\text{Field } Order^{IS} \text{ x } Coeff_W)) + (-0.2242 \text{ x } (T\text{-}Cd_P \text{ x Field } Order^{IS} \text{ x } Coeff_W))$

A similar $Coeff_W$ was generated for Zn and a General Linear Regression Model (Genstat 5.0) incorporating $T\text{-}Zn_P$, $Coeff_W$ and Field $Order^{IS}$ developed to predict the spatial distribution of soil Zn. The results indicate that the *Irr-Cad* model also accounts for 97.3% of the variance in mean Field Order soil Zn (mg kg^{-1}). The data from the remaining two randomly selected FGs consisting of 92 fields were used to validate the Irr-Cad model (Figures 4). The validation results indicate that the Irr-Cad model, predicted mean Field Order total soil Cd, was significantly ($p<0.001$) correlated (R^2 = 0.916) with the observed mean Field Order total soil Cd values (Figure A1.3). A similar highly significant ($p<0.001$) result was observed for mean Field Order total soil Zn with an R^2 value of 0.917.

The use of 'Primary Fields' as the basis for *Irr-Cad* is also an important practical consideration due to their inherent ease of identification and role in the classification of fields in terms of Field $Order^{IS}$. In addition, the use of 'Primary Fields' only, facilitates rapid and strategic sampling over large areas and limits the number of analytical samples to manageable levels.

Figure A1.2. Field Group BFG2 adjacent to Baan Pha Te, Mae Sot, Tak Province: Spatial distribution of Cd (mg kg^{-1}) in relation to primary outlets from in-field irrigation channels and inter-field irrigation flows.

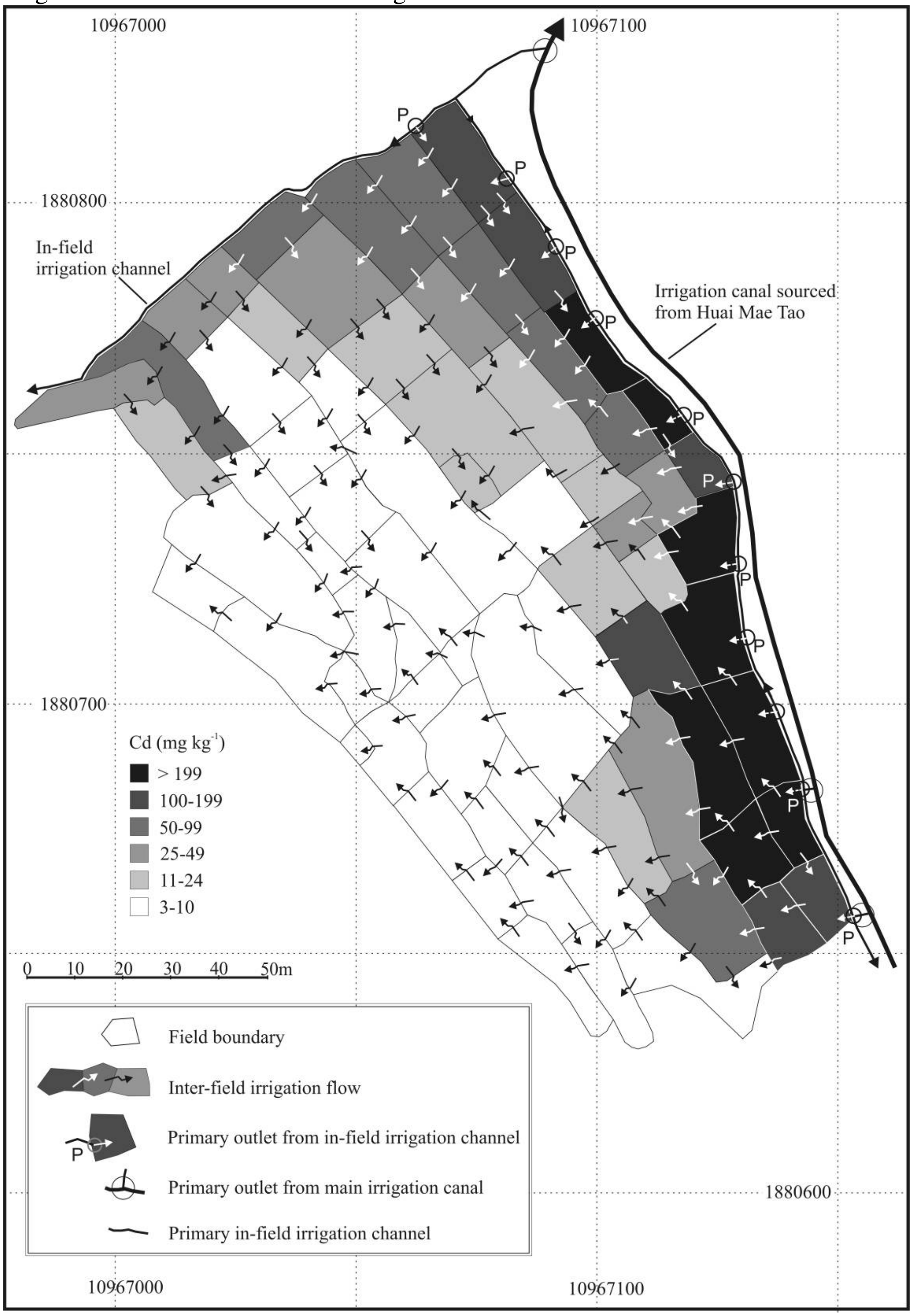
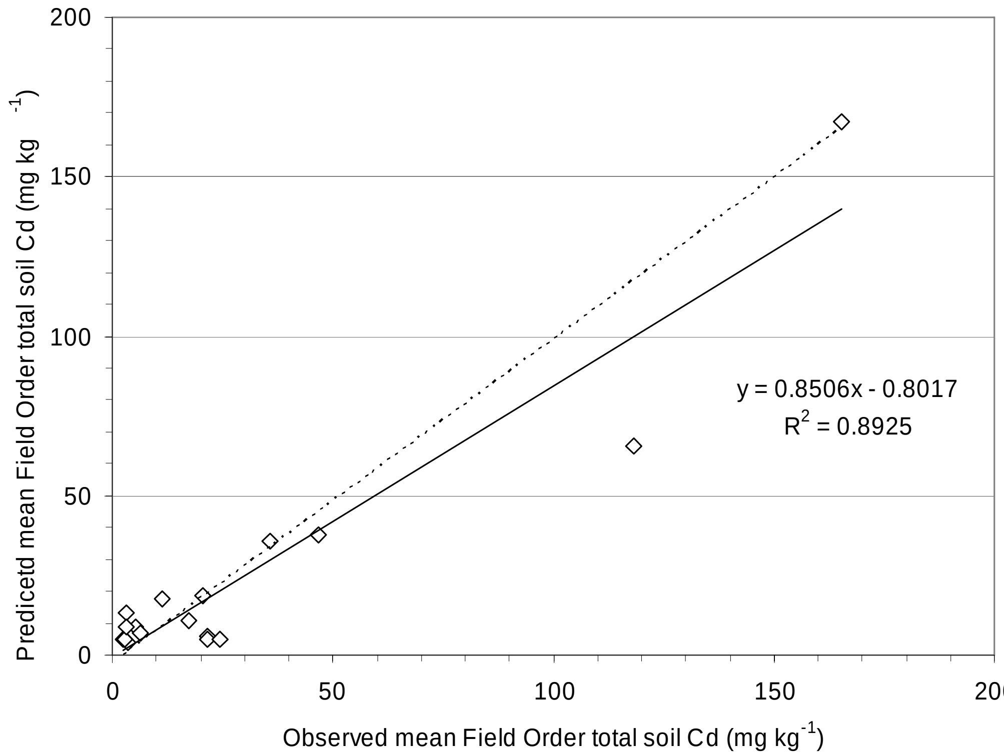


Figure A1.3. *Irr-Cad* predicted mean Field Order total soil Cd (mg kg^{-1}) vs observed mean Field Order total soil Cd (mg kg^{-1}).



Note: Dashed line indicates a 1:1 relationship

ANNEX 2b (A2b)

Field Group Specific *Aqua Regia* Digested total soil Cd

The following legend is for *Aqua Regia* Digested total soil Cd (ARD Cd). Values are in mg kg^{-1}.

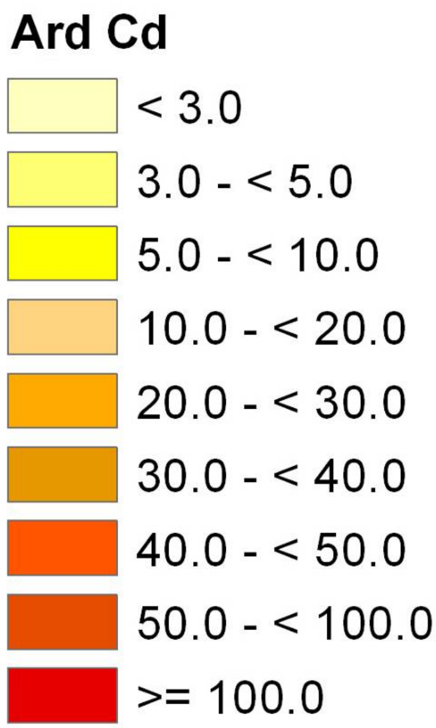


Figure A2b.1. *Aqua Regia* Digested total soil Cd (ARD Cd): Field Groups BFG2, BFG3, BFG4, BFG4a, BFG5, BFG6 and BFG11.

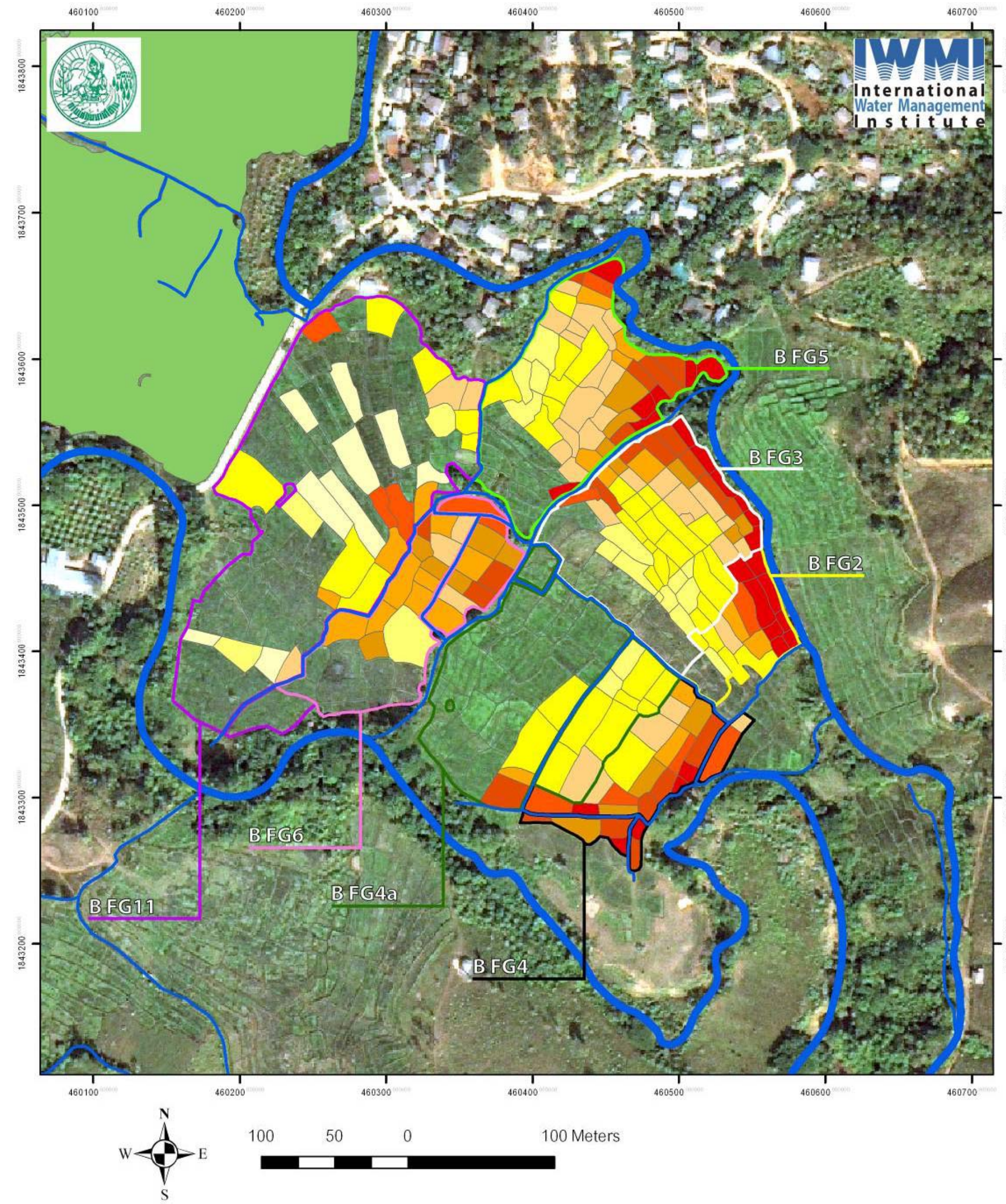


Figure A2b.2. *Aqua Regia* Digested total soil Cd (ARD Cd): Field Groups BFG8 and BFG10.

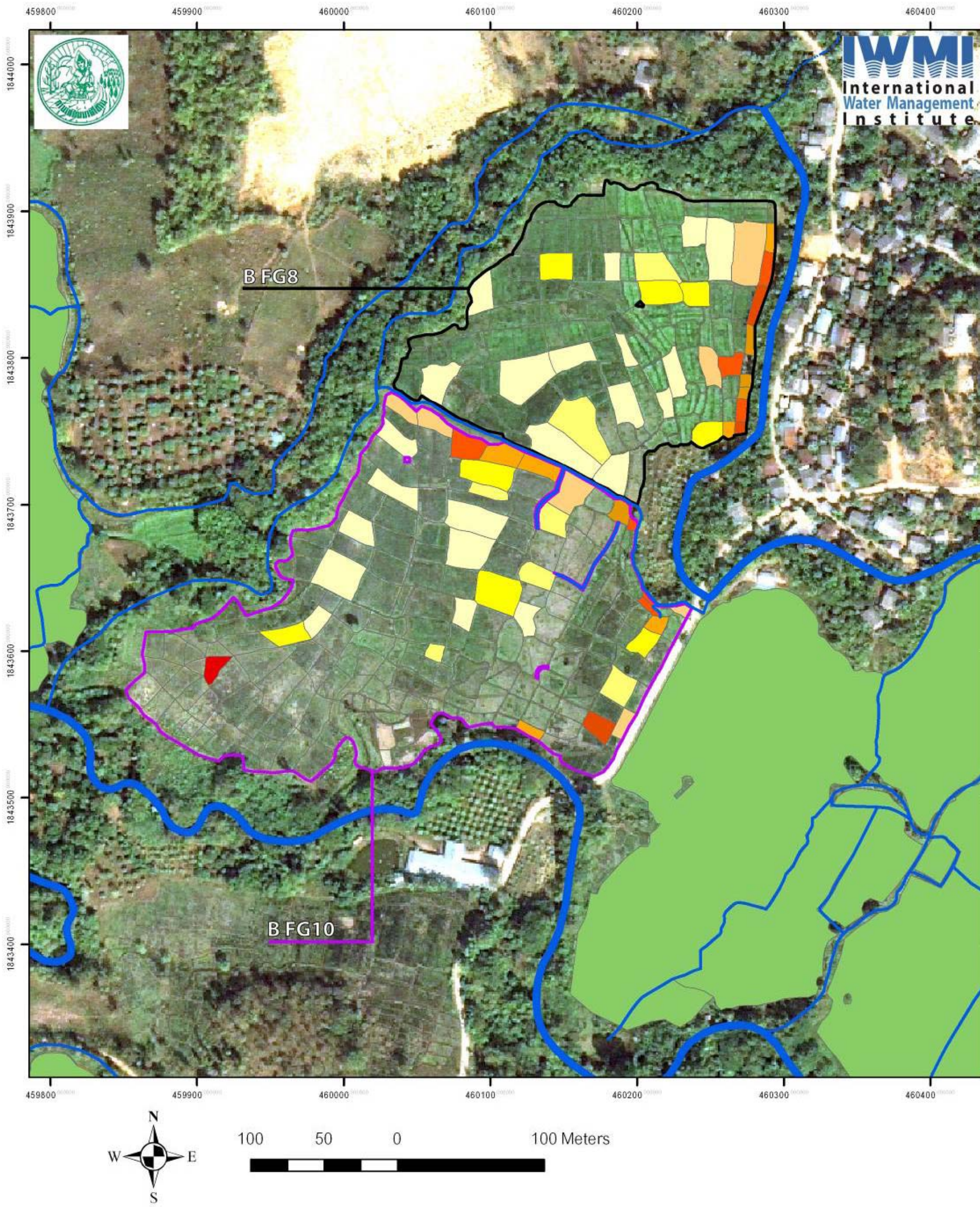


Figure A2b.3. *Aqua Regia* Digested total soil Cd (ARD Cd): Field Group BFG12.

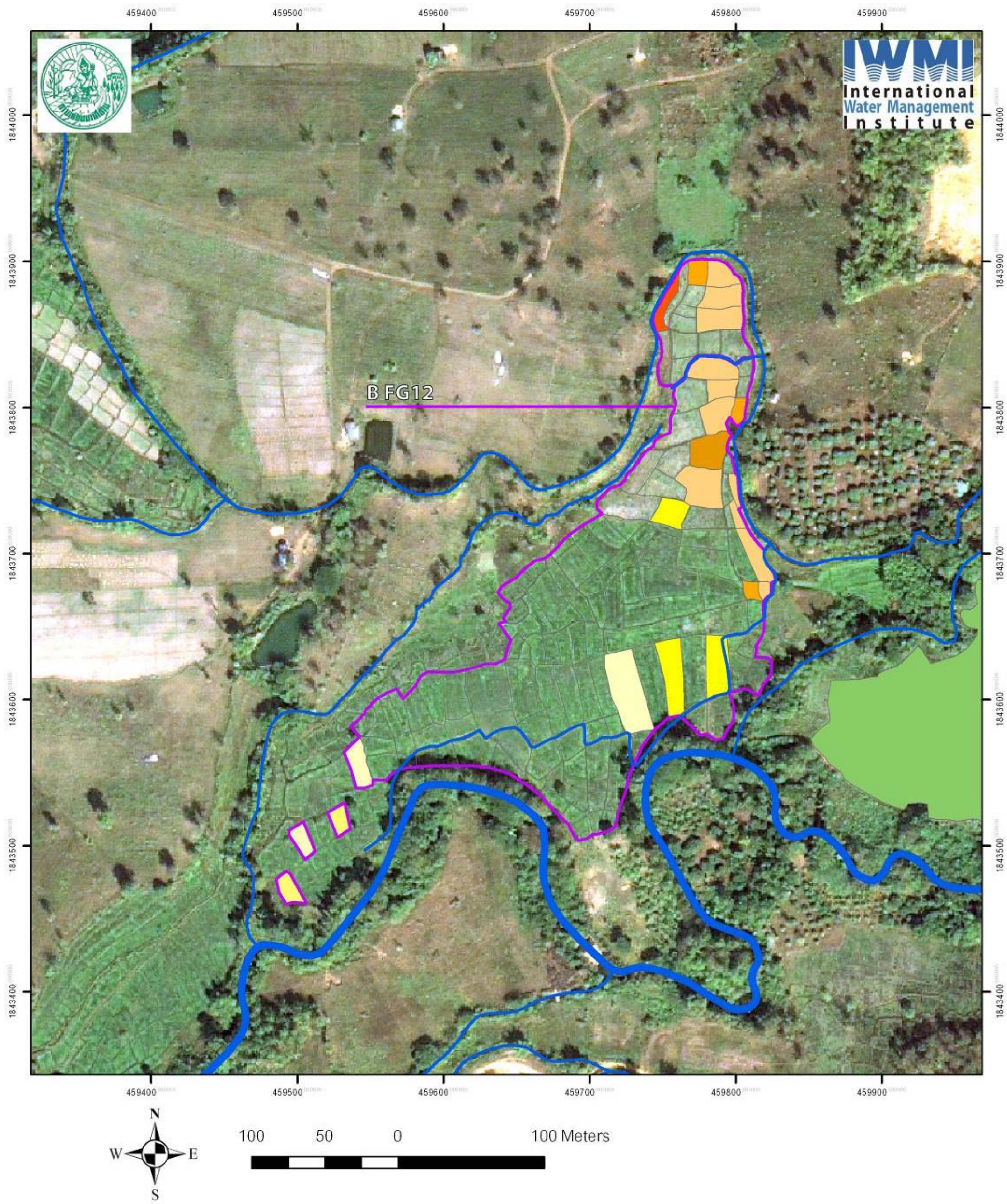


Figure A2b.4. *Aqua Regia* Digested total soil Cd (ARD Cd): Field Groups BFG9, BFG13, BFG13a and BFG13b.

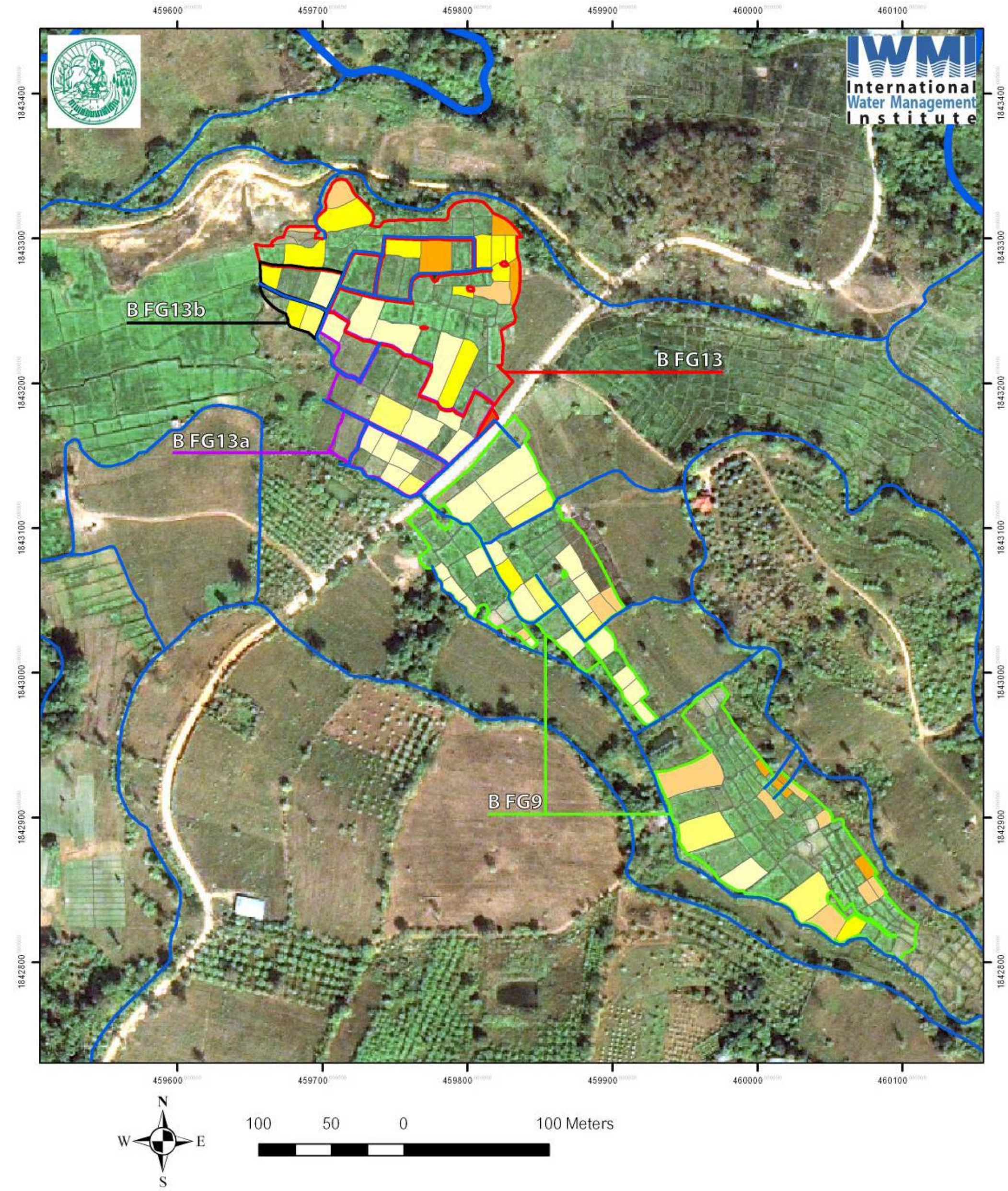


Figure A2b.5. *Aqua Regia* Digested total soil Cd (ARD Cd): Field Groups DFG2, DFG3, DFG4a, DFG10, DFG12 CFG1, CFG2 and CFG3.

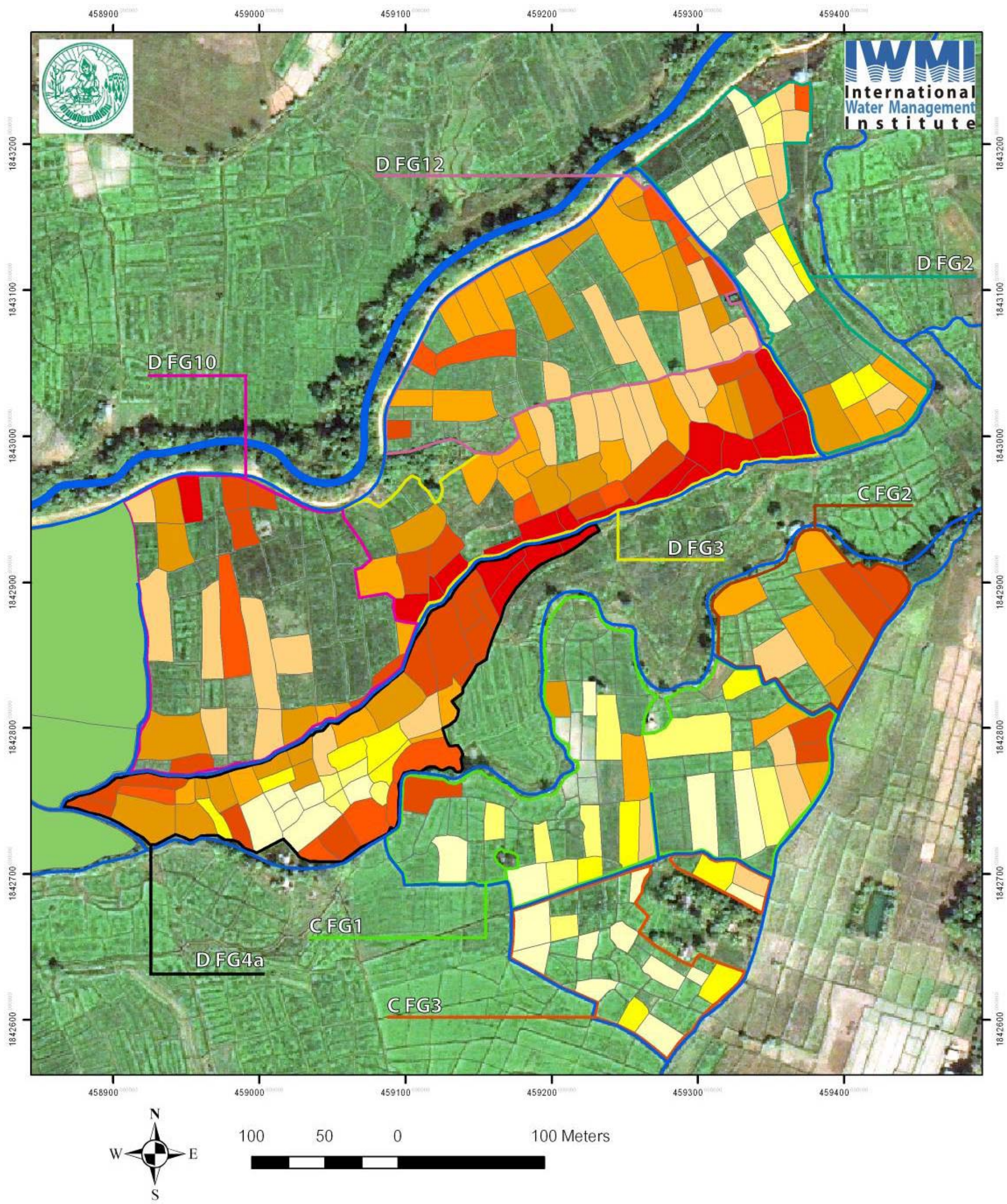


Figure A2b.6. *Aqua Regia* Digested total soil Cd (ARD Cd): Field Groups DFG5, DFG6, DFG9, DFG9a, DFG10a, DFG11 and DFG18.

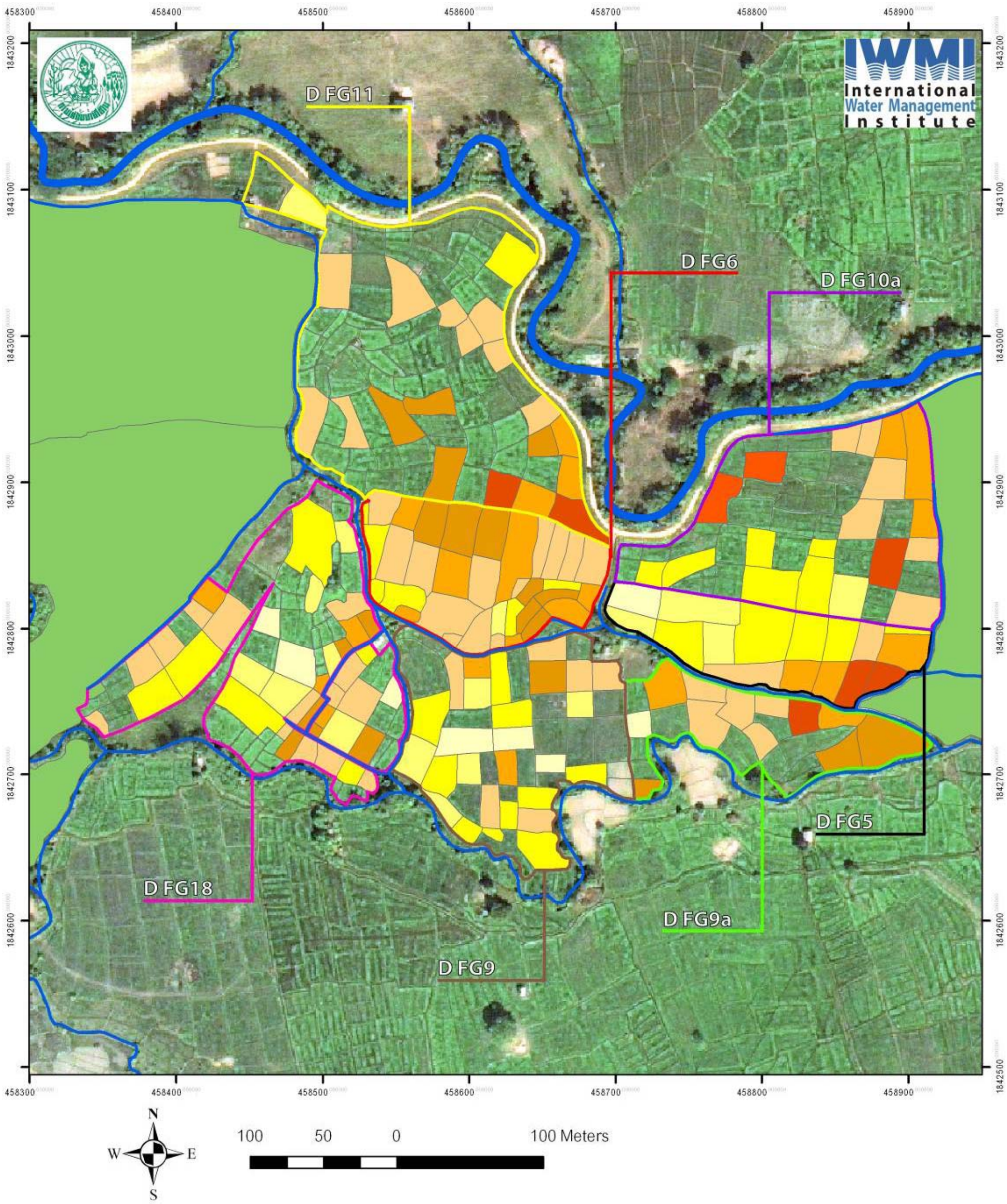


Figure A2b.7. *Aqua Regia* Digested total soil Cd (ARD Cd): Field Groups DFG7, DFG8, DFG11a, DFG13, DFG14, DFG15, DFG16 and DFG17.

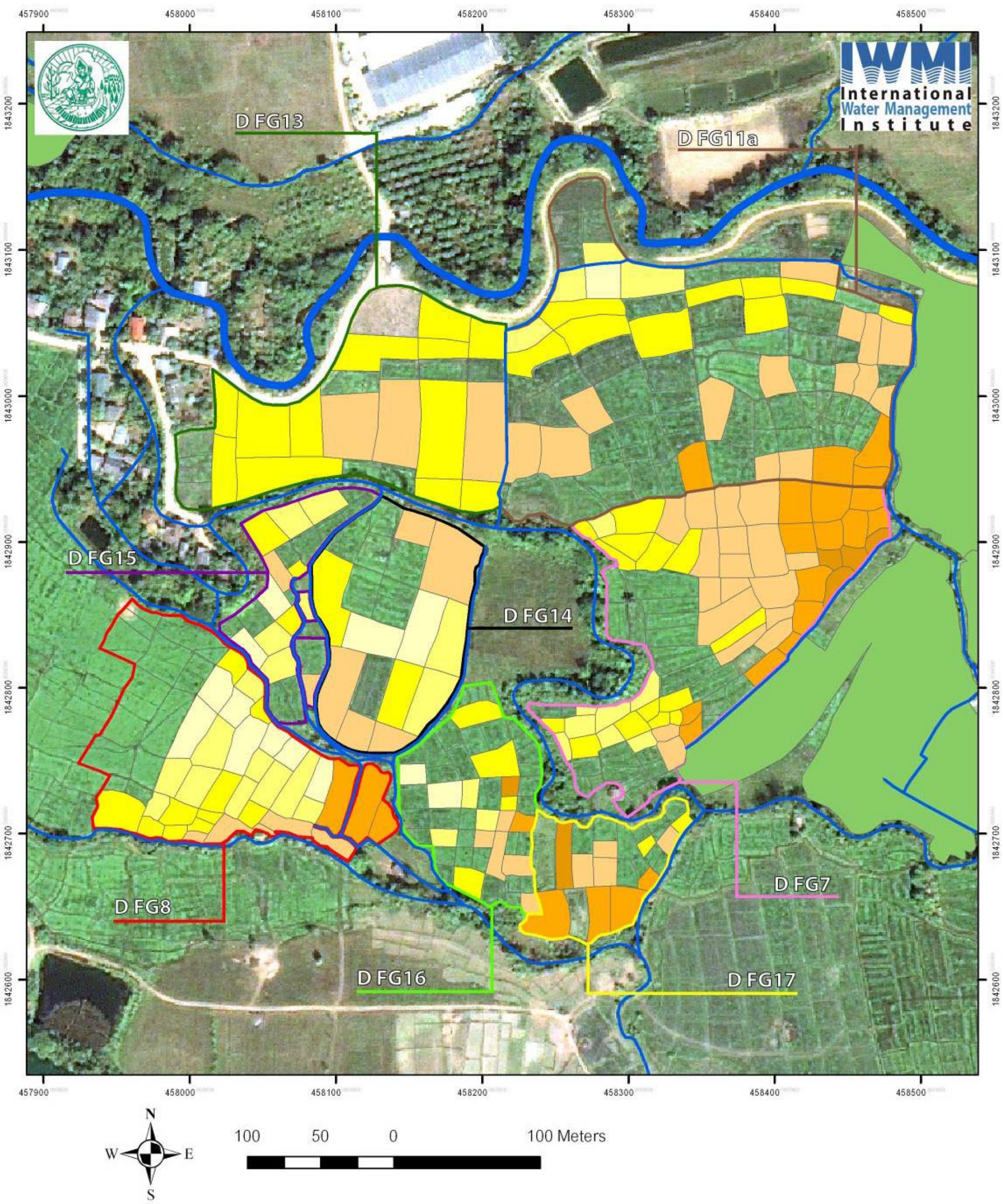


Figure A2b.8. *Aqua Regia* Digested total soil Cd (ARD Cd): Field Groups EFG1, EFG2, EFG3, EFG4a, EFG4, EFG5 and EFG10.

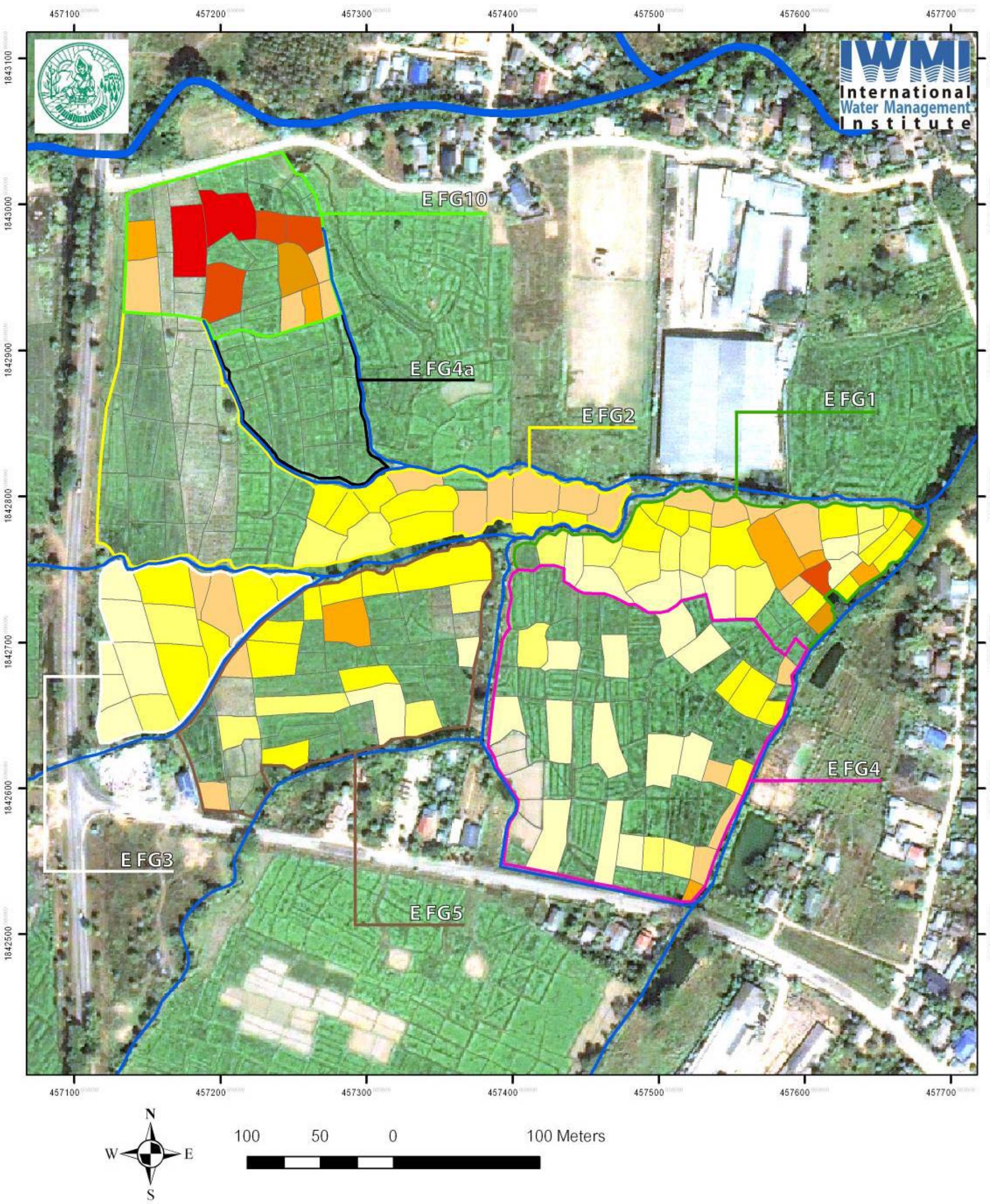
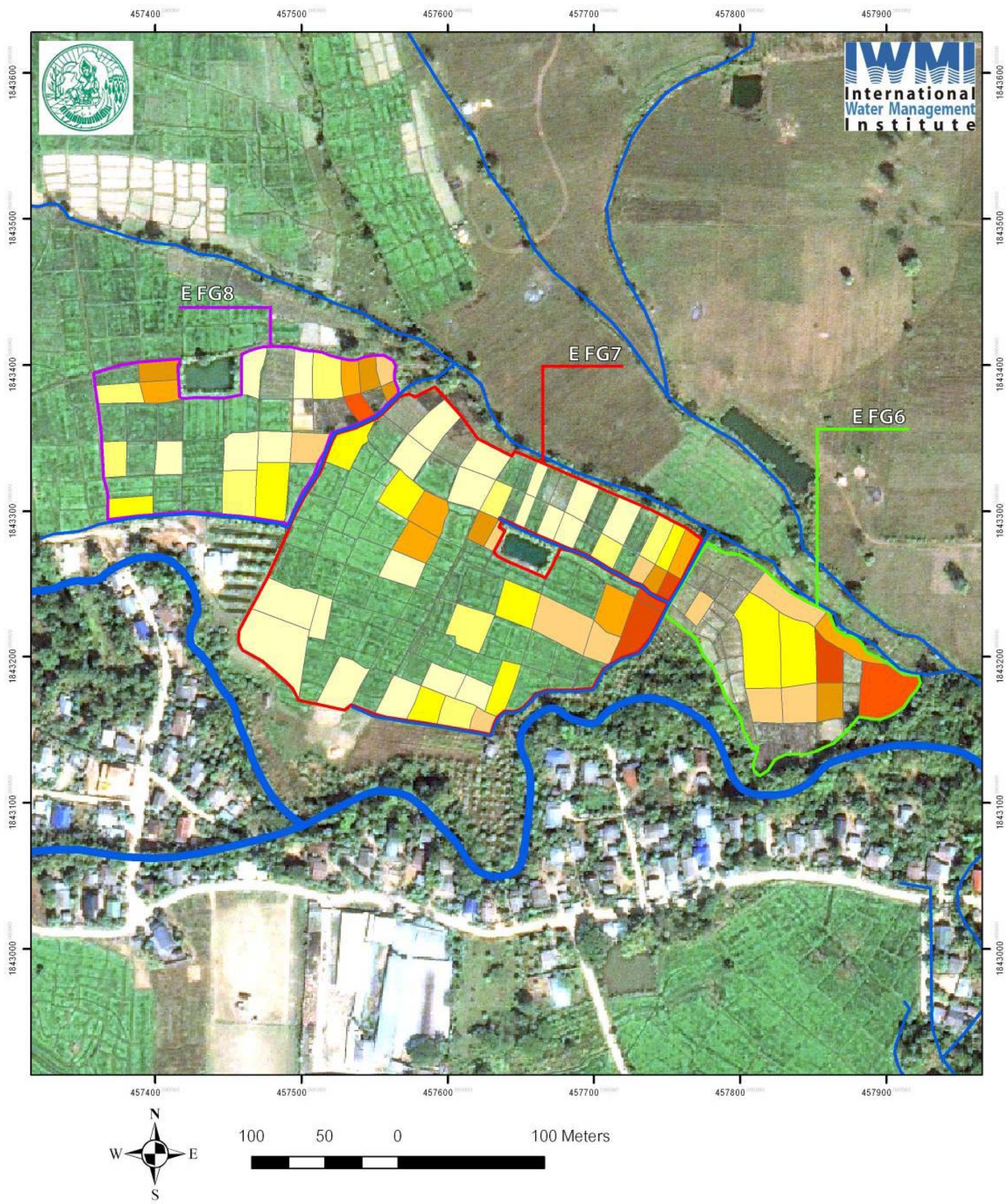


Figure A2b.9. *Aqua Regia* Digested total soil Cd (ARD Cd): Field Groups EFG6, EFG7 and EFG8.



ANNEX 2c (A2c)

Field Group Specific *Irr-Cad* predicted soil Cd

The following legend is for *Irr-Cad* Predicted Mean Field Order Total Cd (PMFOT Cd). Values are in mg kg^{-1}.

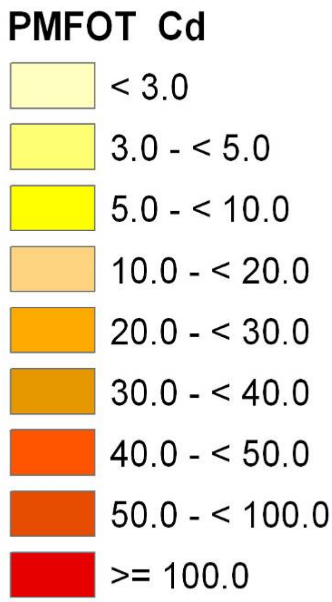


Figure A2c.1. *Irr-Cad* Predicted Mean Field Order Total soil Cd (PMFOT Cd): Field Groups BFG2, BFG3, BFG4, BFG4a, BFG5, BFG6 and BFG11.

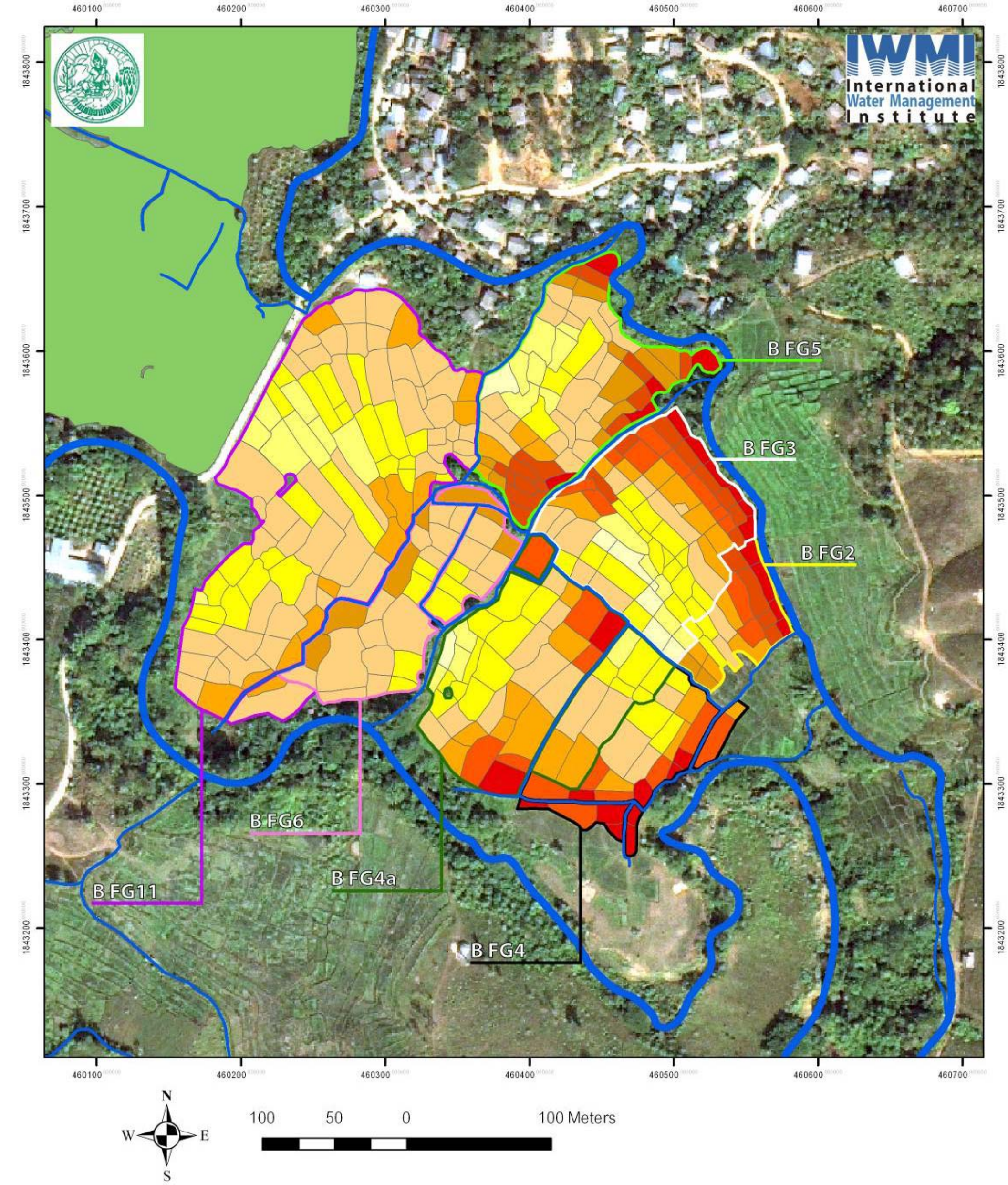


Figure A2c.2. *Irr-Cad* Predicted Mean Field Order Total soil Cd (PMFOT Cd): Field Groups BFG8 and BFG10.

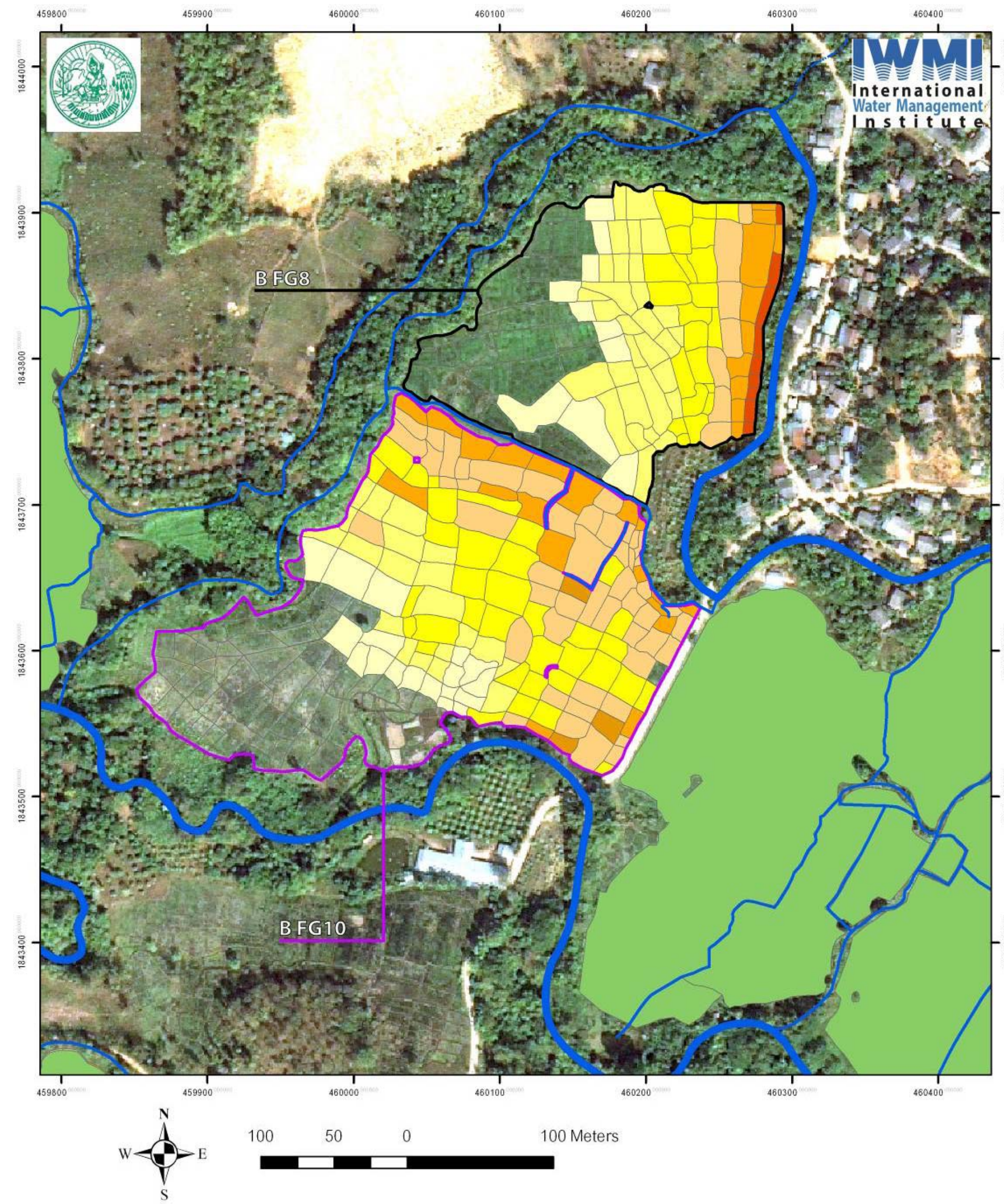


Figure A2c.3. *Irr-Cad* Predicted Mean Field Order Total soil Cd (PMFOT Cd): Field Group BFG12.

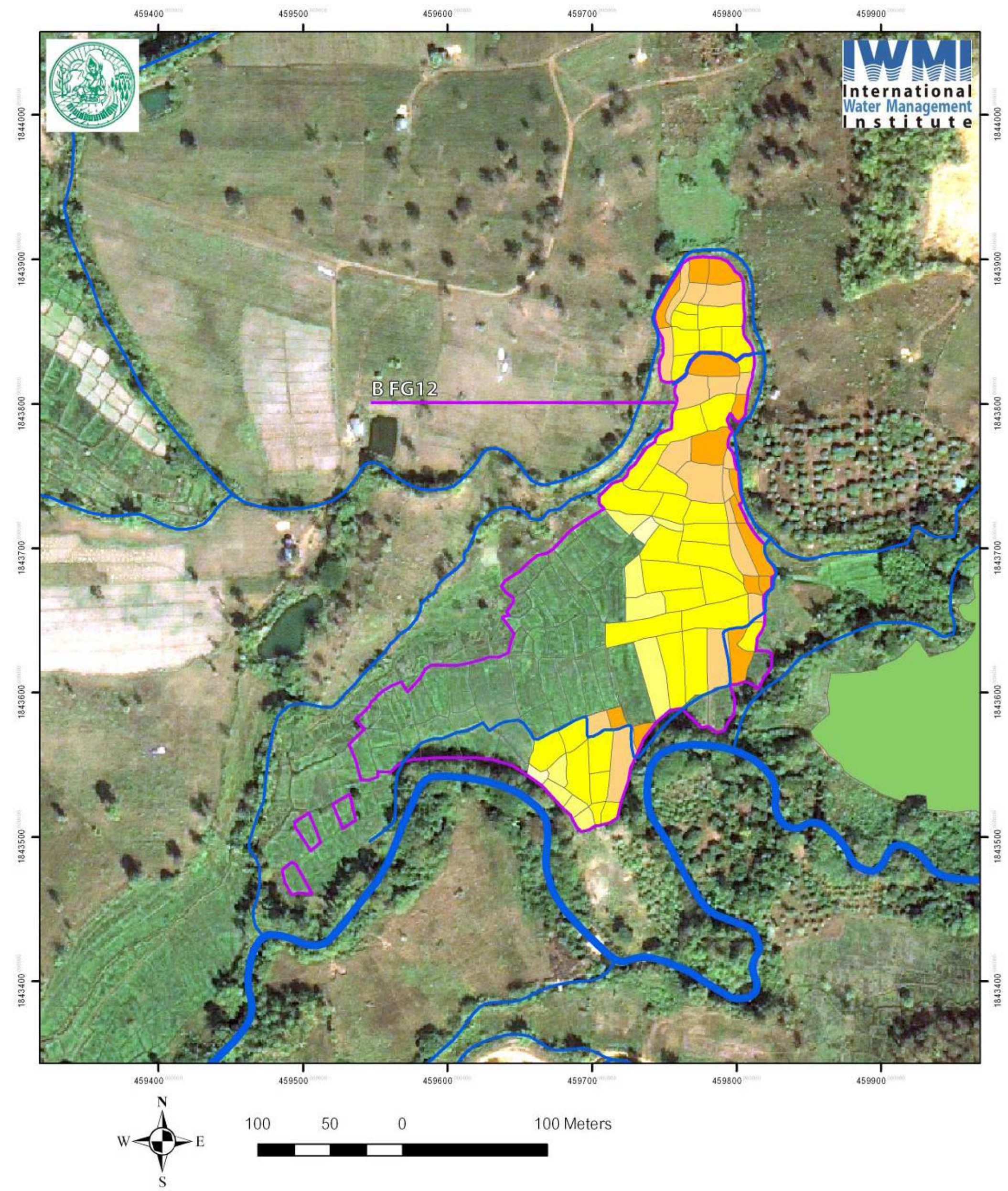


Figure A2c.4. *Irr-Cad* Predicted Mean Field Order Total soil Cd (PMFOT Cd): Field Groups BFG9, BFG13, BFG13a and BFG13b.

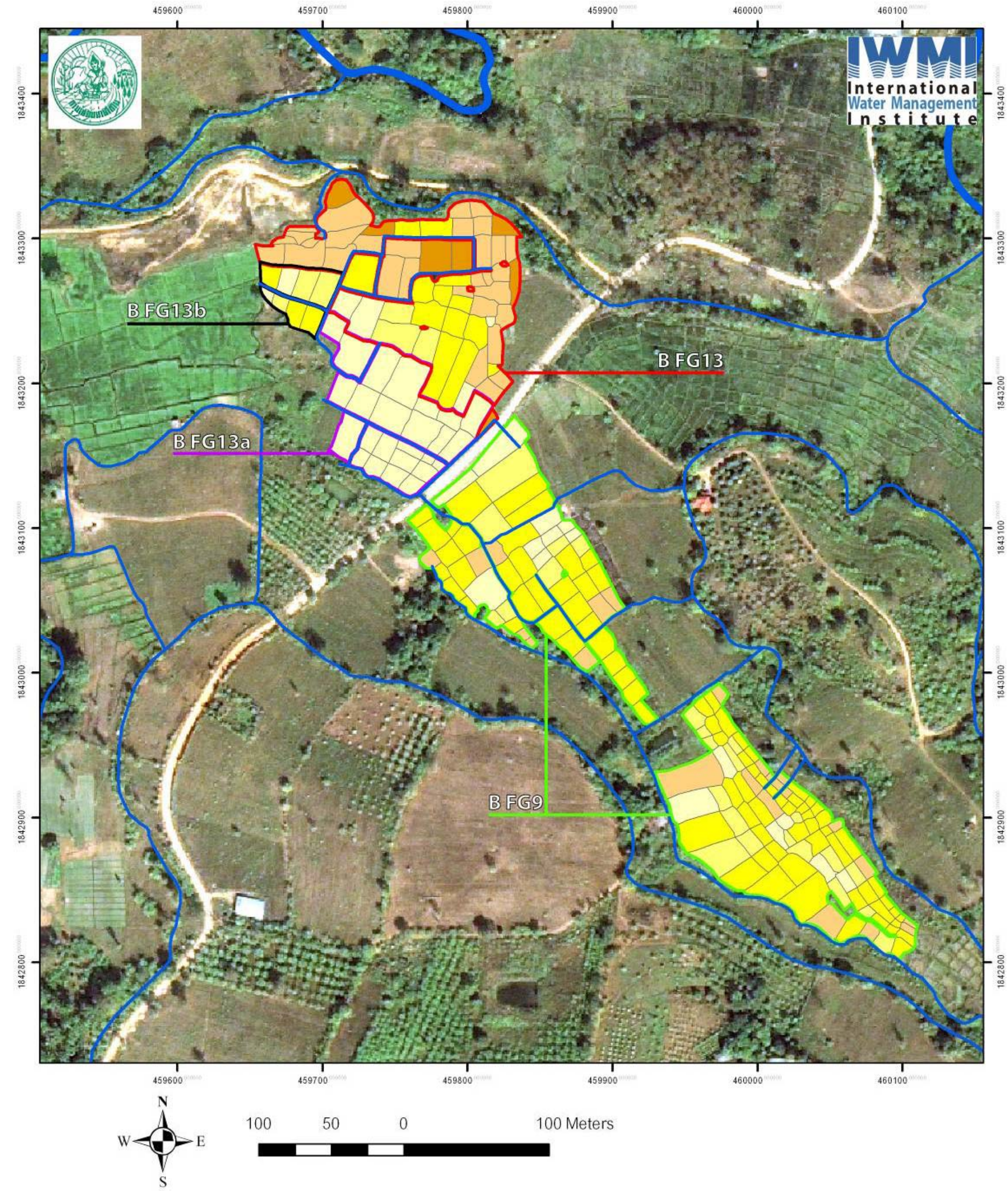


Figure A2c.5. *Irr-Cad* Predicted Mean Field Order Total soil Cd (PMFOT Cd): Field Groups DFG2, DFG3, DFG4a, DFG10, DFG12 CFG1, CFG2 and CFG3.

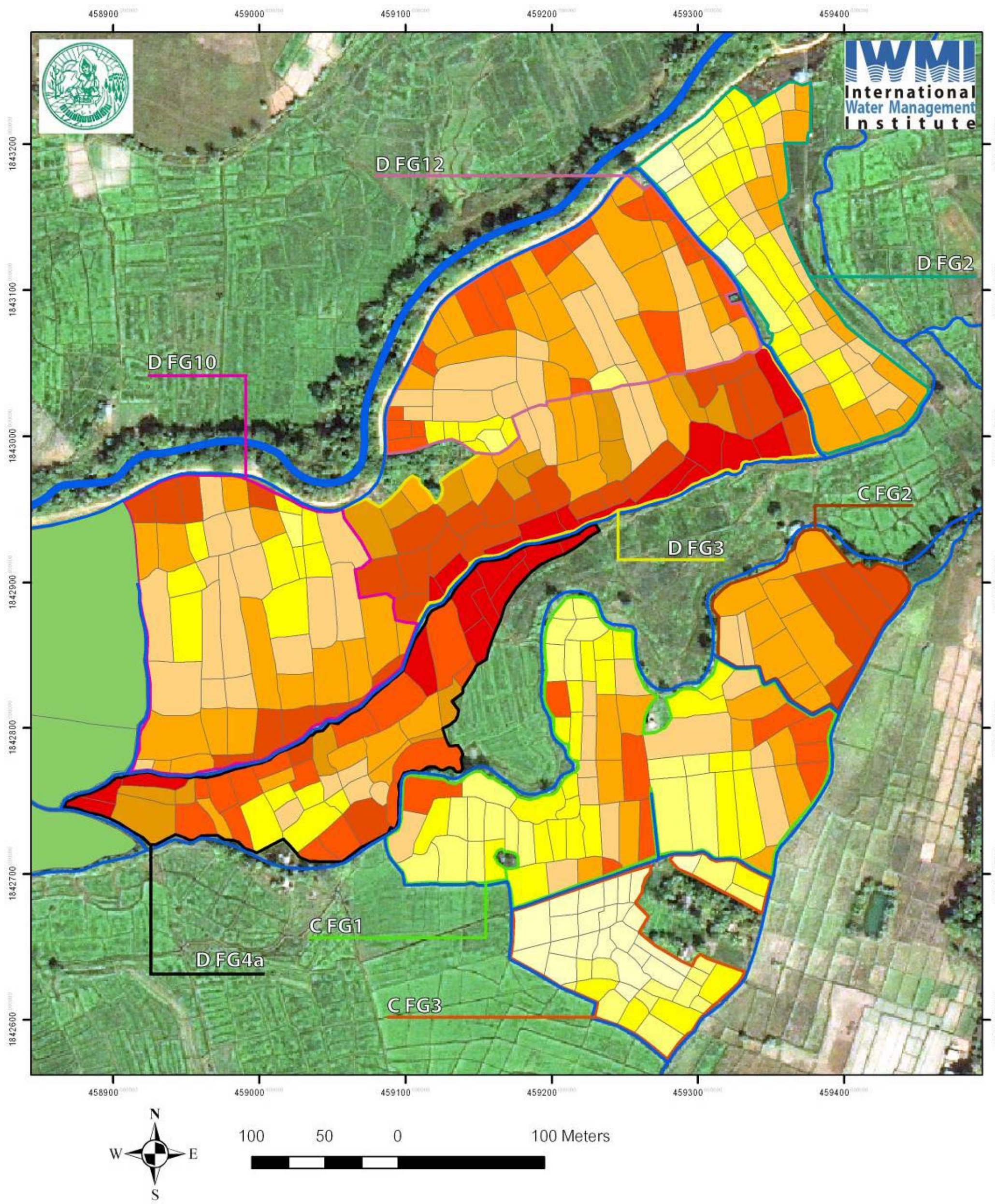


Figure A2c.6. *Irr-Cad* Predicted Mean Field Order Total soil Cd (PMFOT Cd): Field Groups DFG5, DFG6, DFG9, DFG9a, DFG10a, DFG11 and DFG18.

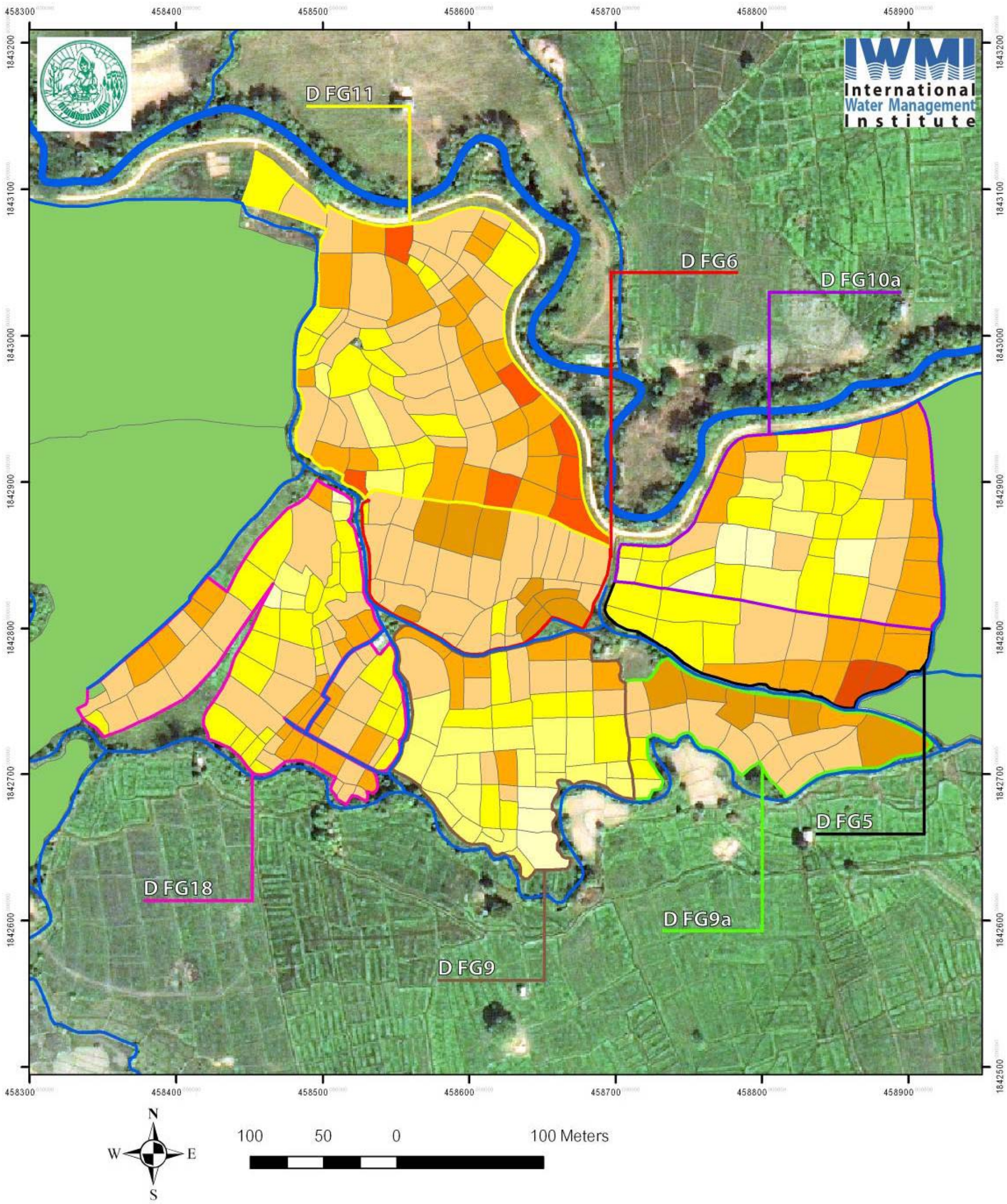


Figure A2c.7. *Irr-Cad* Predicted Mean Field Order Total soil Cd (PMFOT Cd): Field Groups DFG7, DFG8, DFG11a, DFG13, DFG14, DFG15, DFG16 and DFG17.

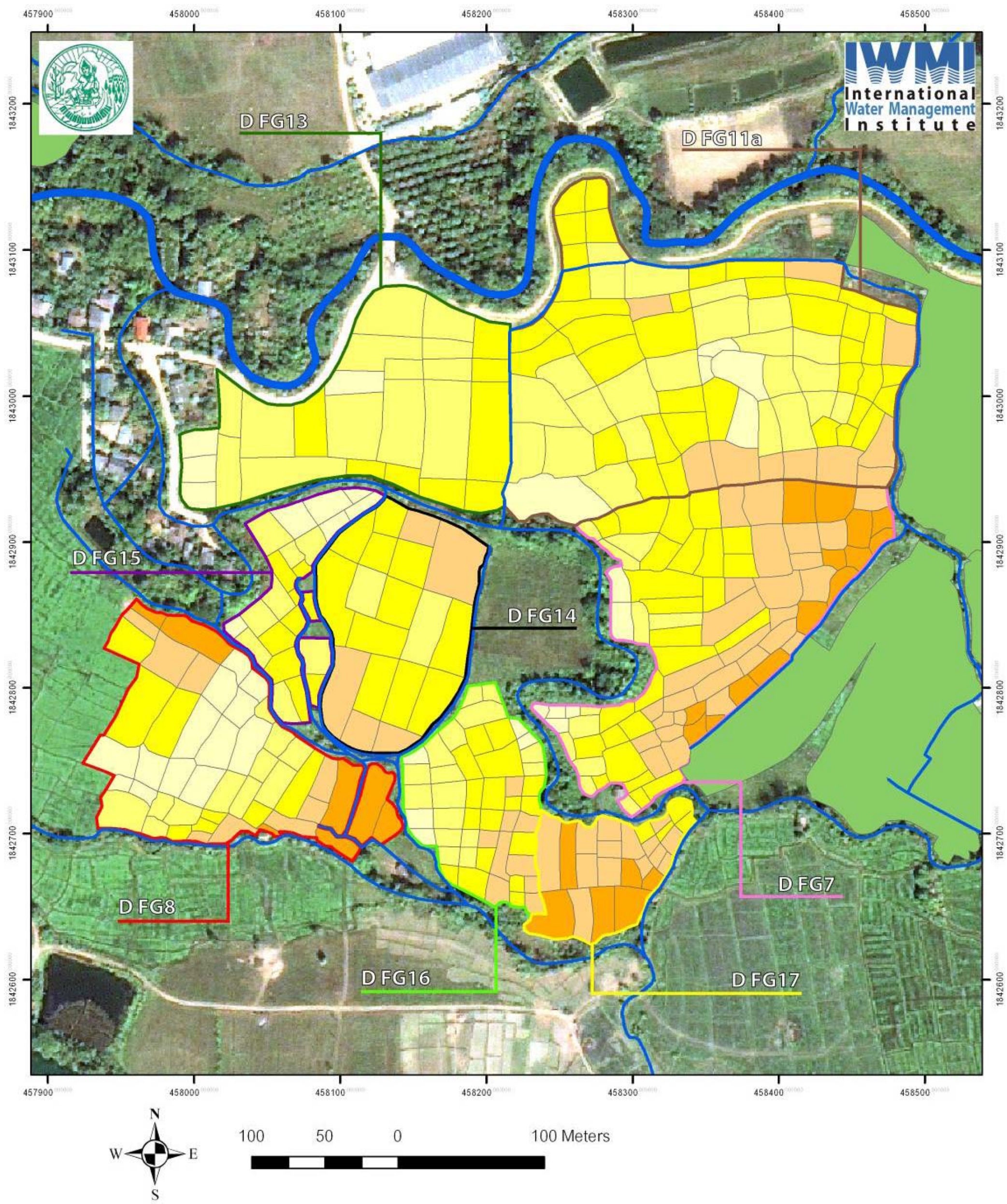


Figure A2c.8. *Irr-Cad* Predicted Mean Field Order Total soil Cd (PMFOT Cd): Field Groups EFG1, EFG2, EFG3, EFG4a, EFG4, EFG5 and EFG10.

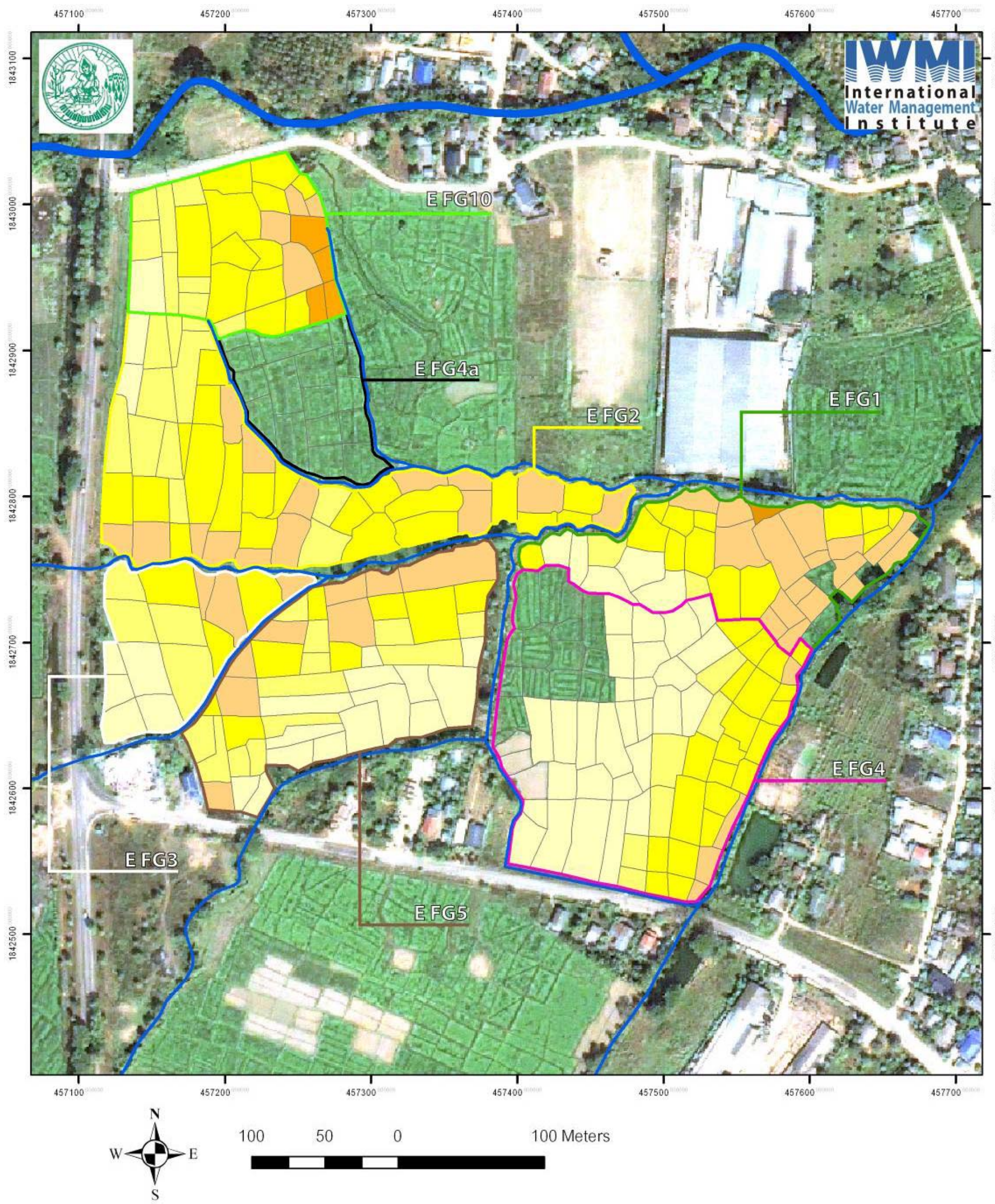
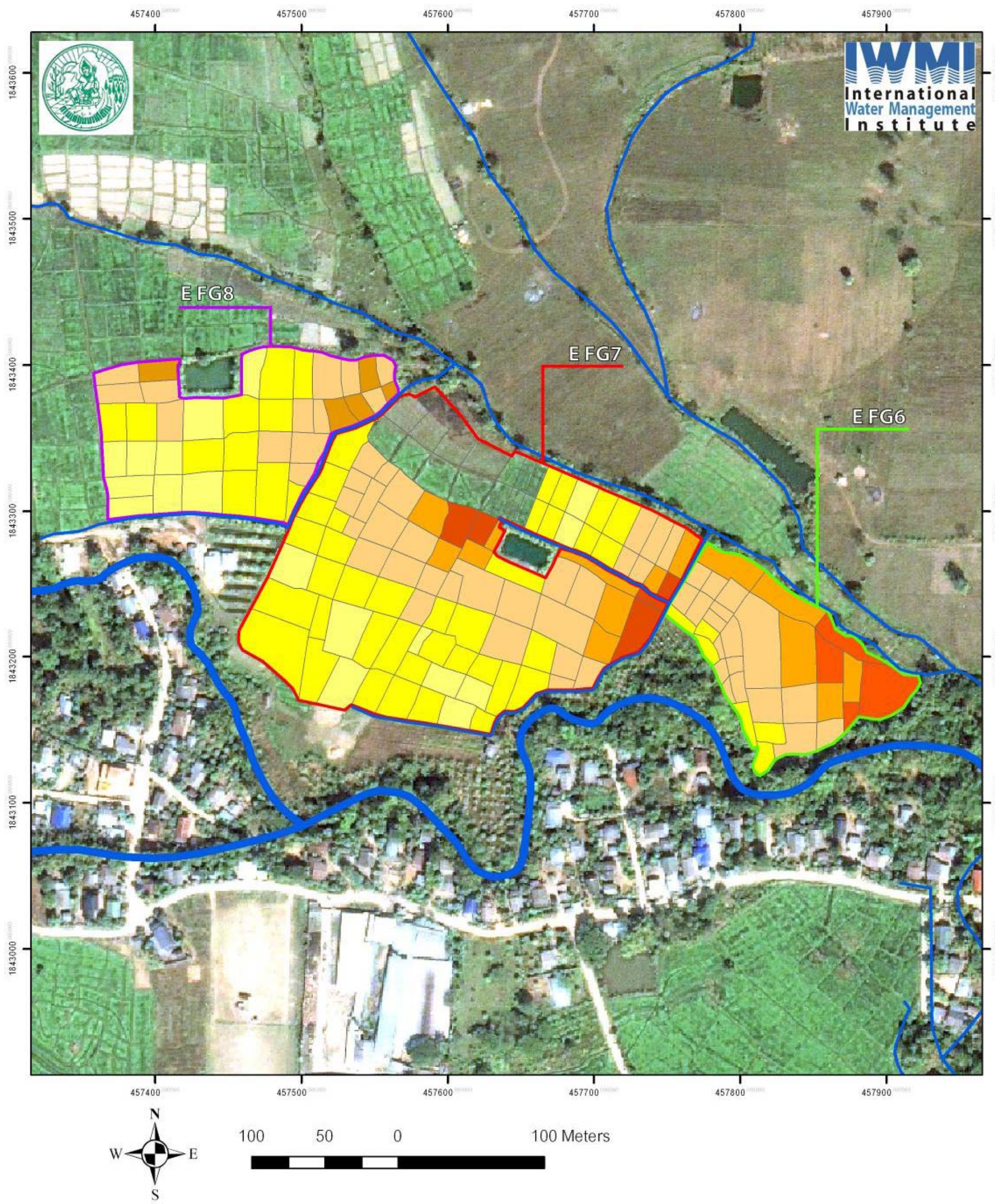
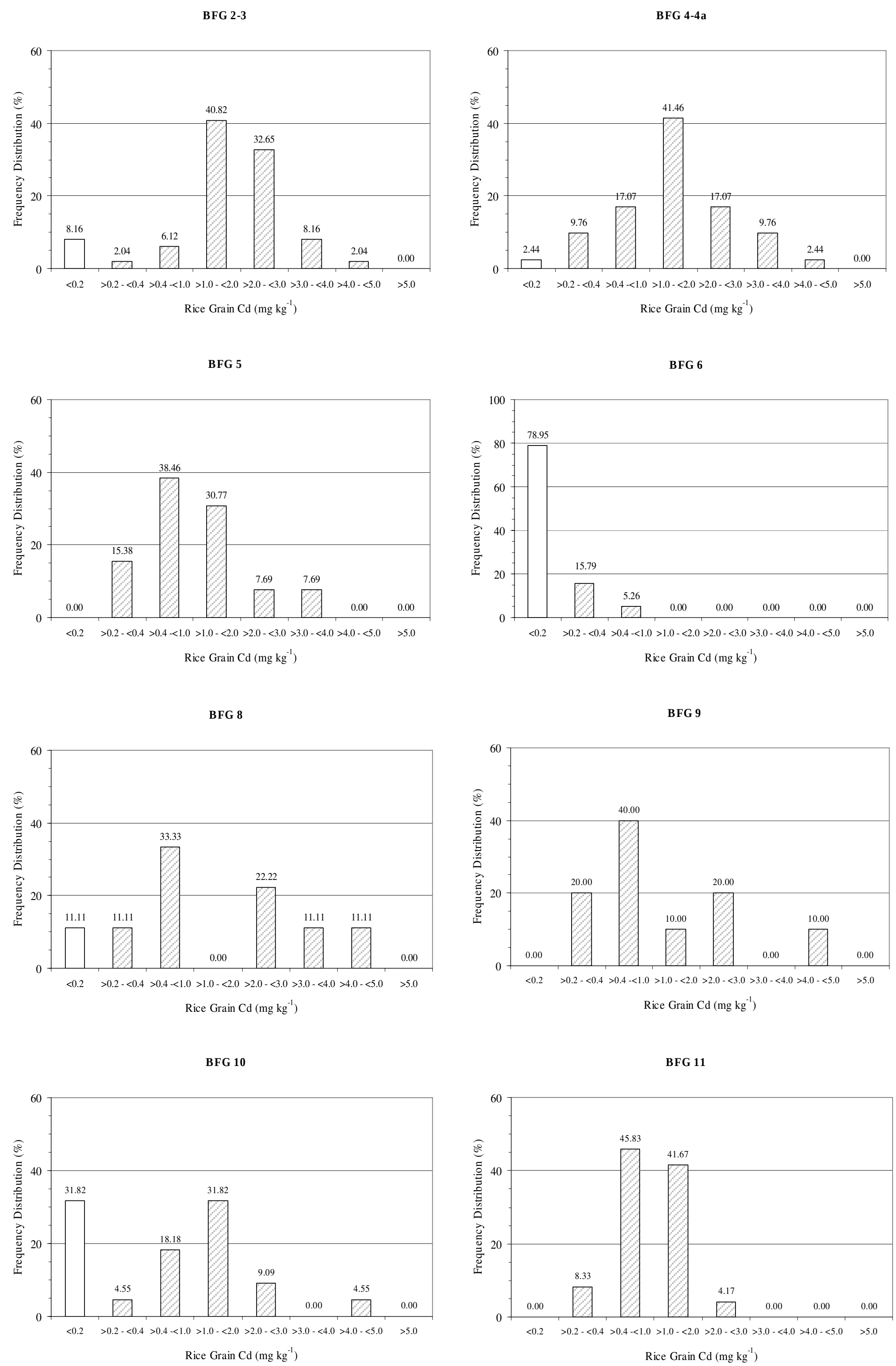


Figure A2c.9. *Irr-Cad* Predicted Mean Field Order Total soil Cd (PMFOT Cd): Field Groups EFG6, EFG7 and EFG8.

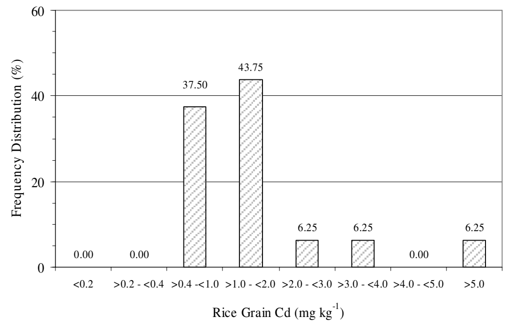


ANNEX 3a (A3a)

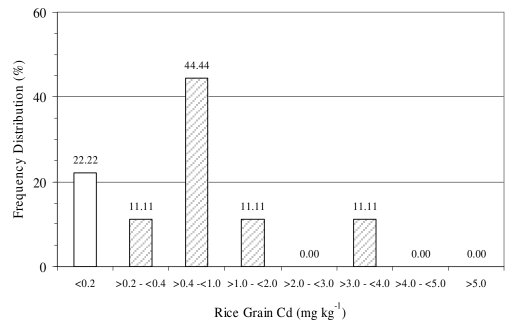
Field Group Specific Rice Grain Cd (mg kg^{-1}) Frequency Distribution (%)



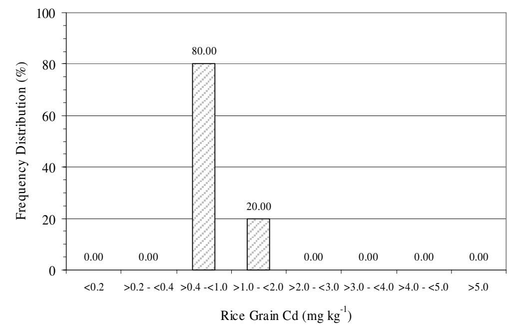
BFG 12



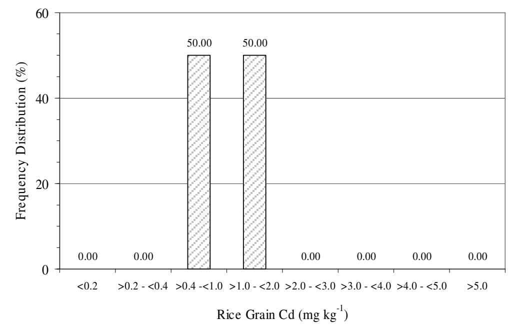
BFG 13



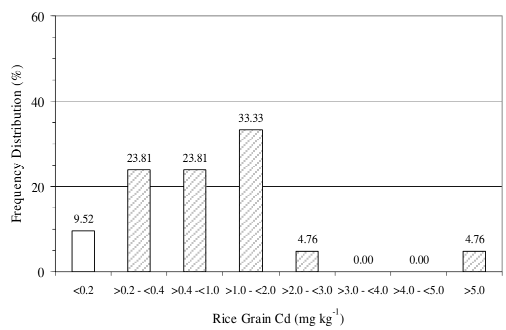
BFG 13a



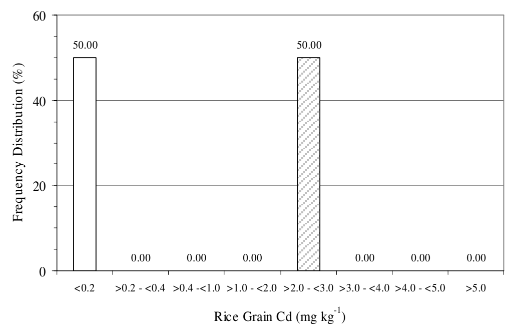
BFG 13b



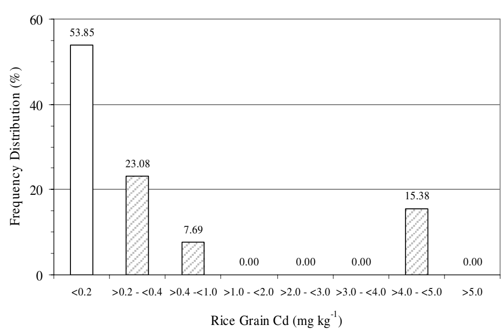
CFG 1

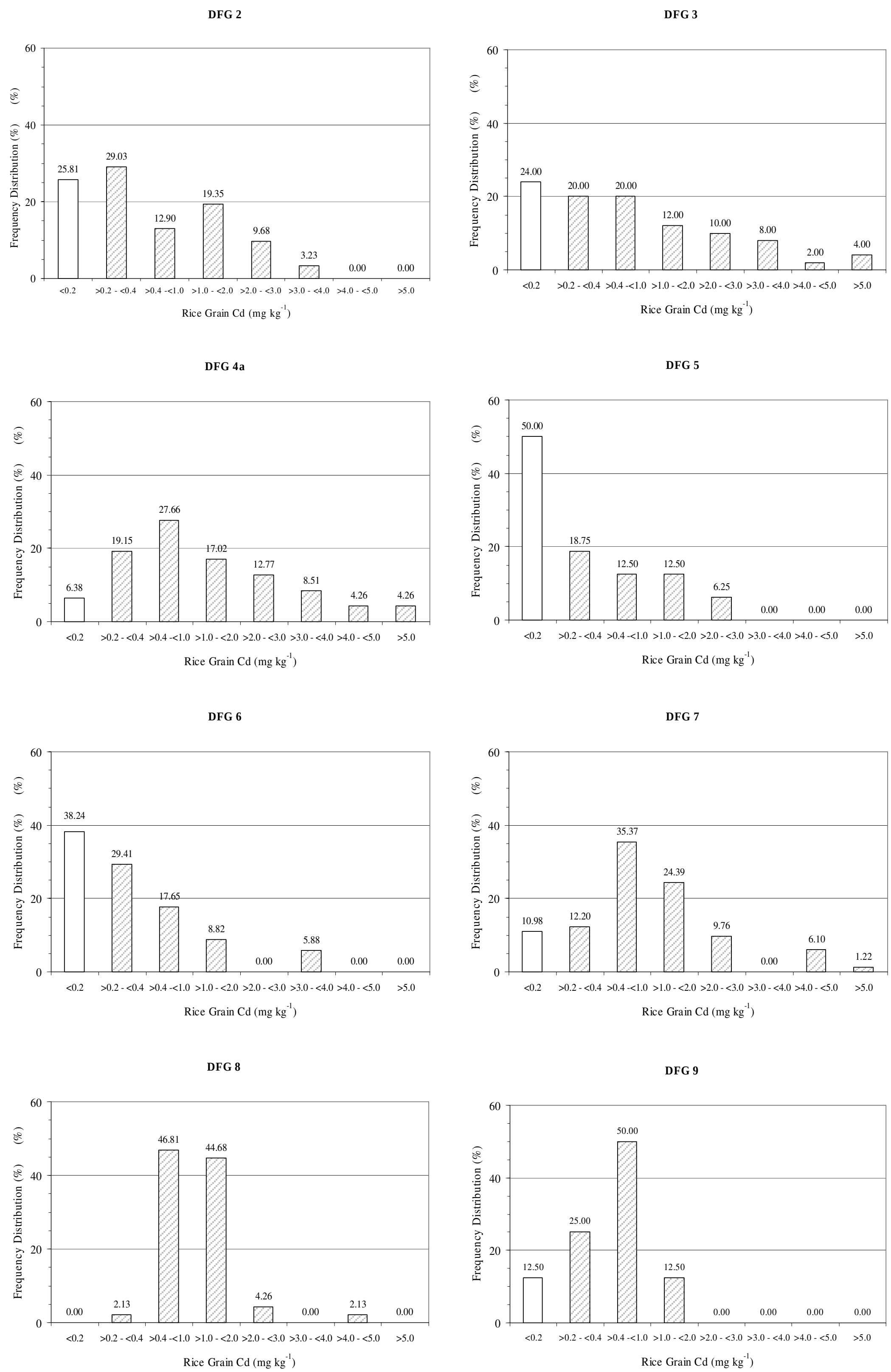


CFG 2

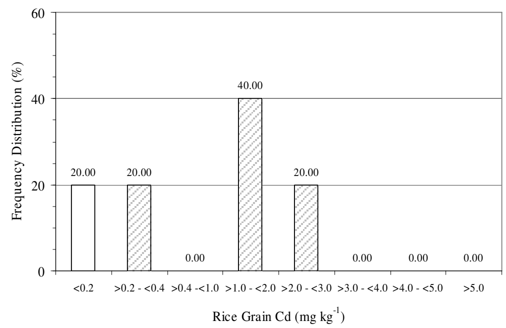


CFG 3

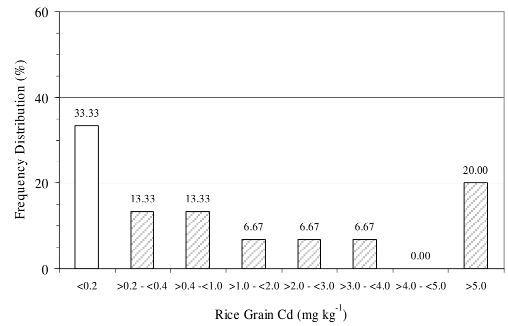



DFG 2
Frequency Distribution (%)
25.81
29.03
12.90
19.35
9.68
3.23
0.00
0.00
DFG 3
24.00
20.00
20.00
12.00
10.00
8.00
2.00
4.00
DFG 4a
6.38
19.15
27.66
17.02
12.77
8.51
4.26
4.26
DFG 5
50.00
18.75
12.50
12.50
6.25
0.00
0.00
0.00
DFG 6
38.24
29.41
17.65
8.82
0.00
5.88
0.00
0.00
DFG 7
10.98
12.20
35.37
24.39
9.76
0.00
6.10
1.22
DFG 8
0.00
2.13
46.81
44.68
4.26
0.00
2.13
0.00
DFG 9
12.50
25.00
50.00
12.50
0.00
0.00
0.00
0.00
<0.2
>0.2 - <0.4
>0.4 -<1.0
>1.0 - <2.0
>2.0 - <3.0
>3.0 - <4.0
>4.0 - <5.0
>5.0
Rice Grain Cd (mg kg-1)

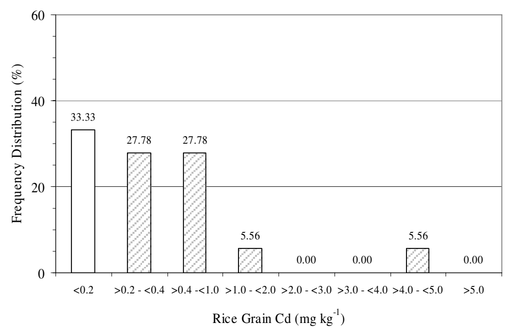
DFG 9a



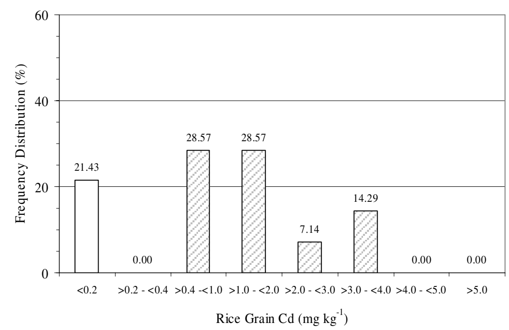
DFG 10



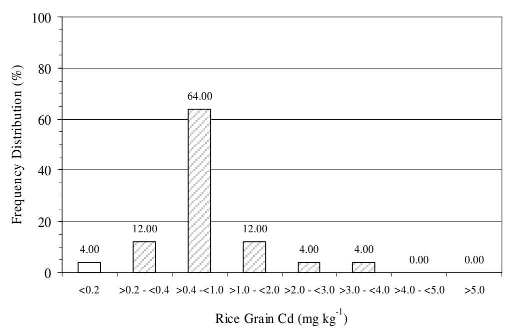
DFG 10a



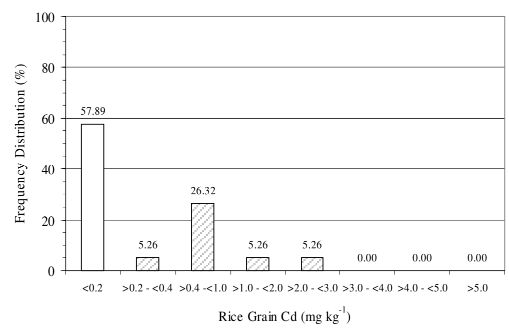
DFG 11



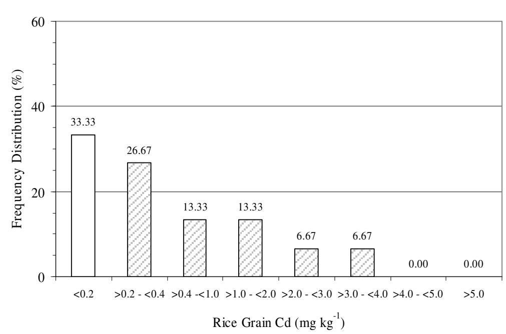
DFG 11a



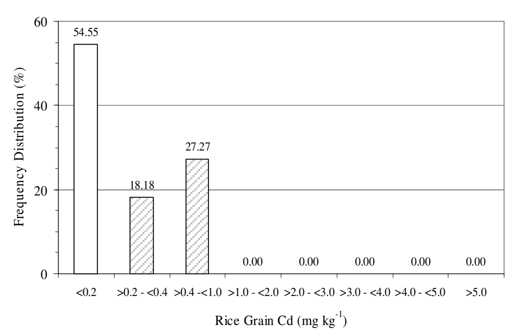
DFG 12



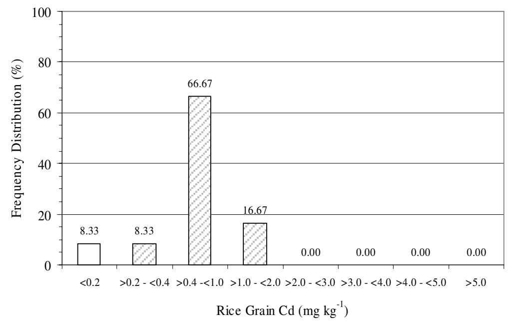
DFG 13



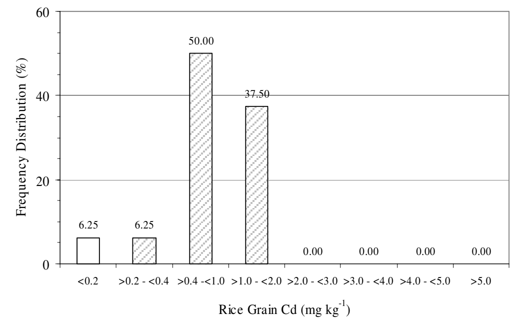
DFG 14



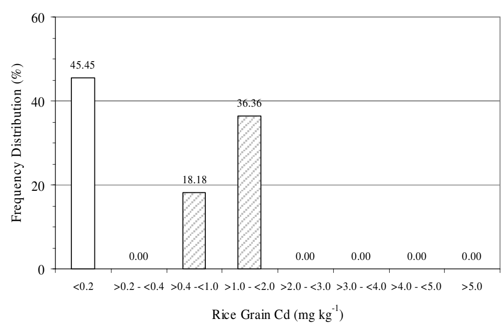
DFG 15



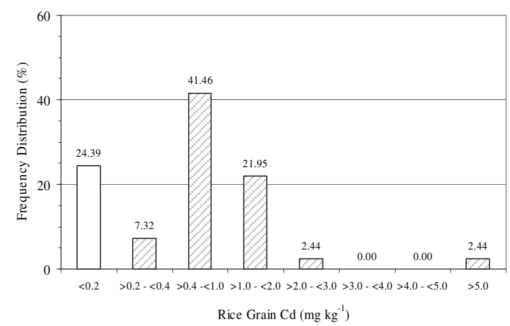
DFG 16



DFG 17



DFG 18



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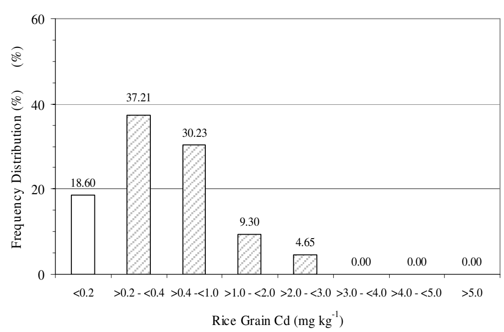

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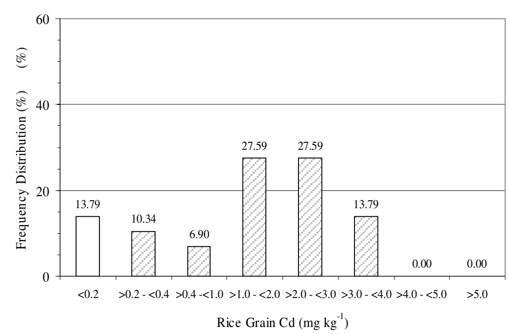

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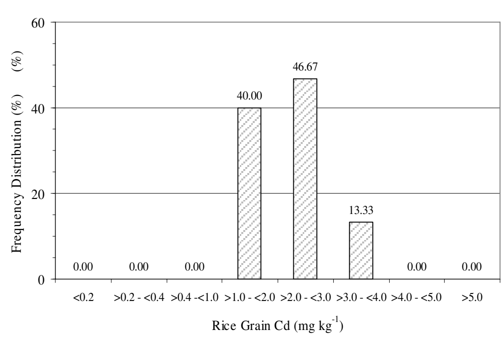

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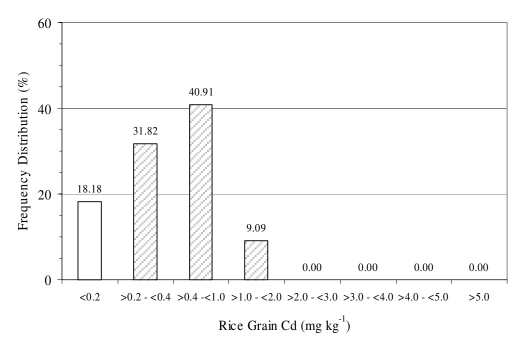

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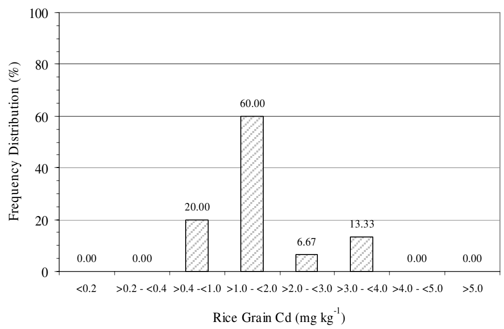

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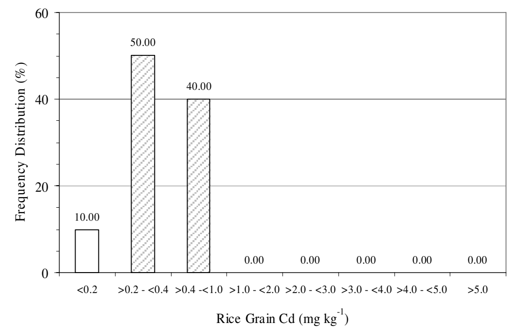

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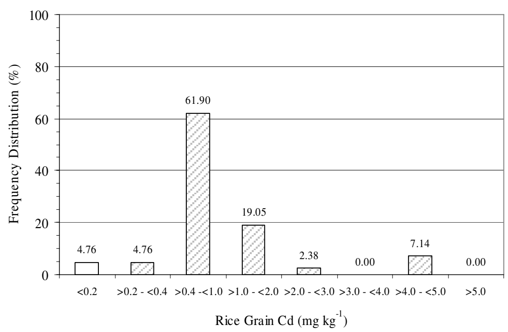

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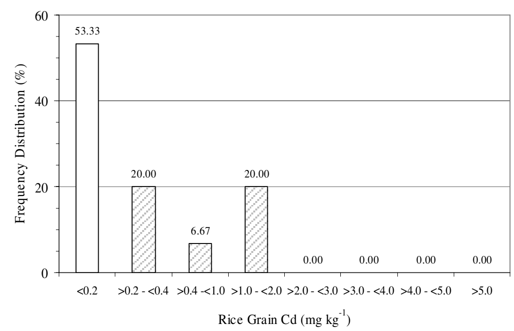

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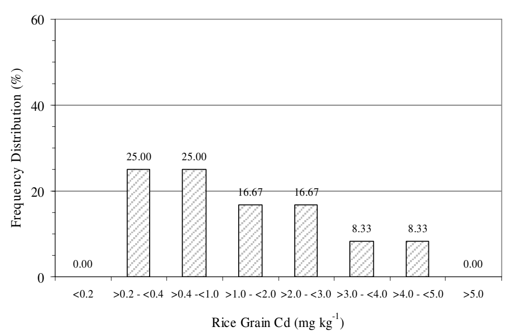
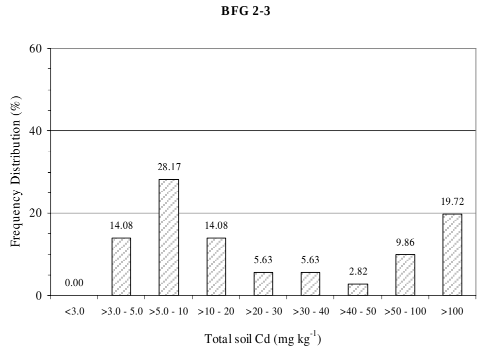
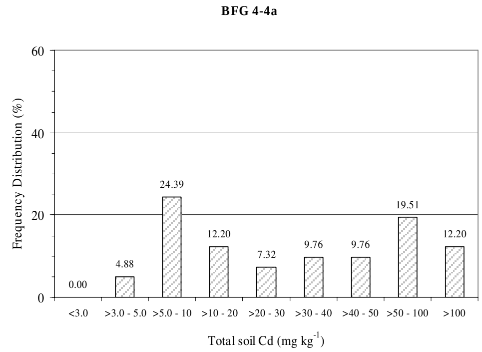
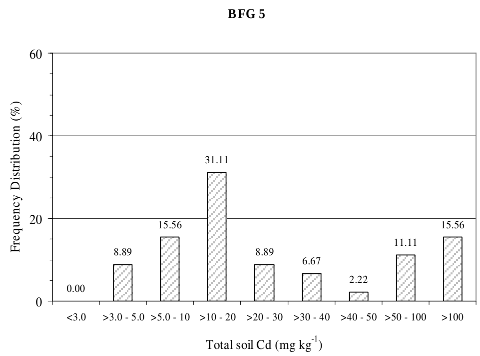


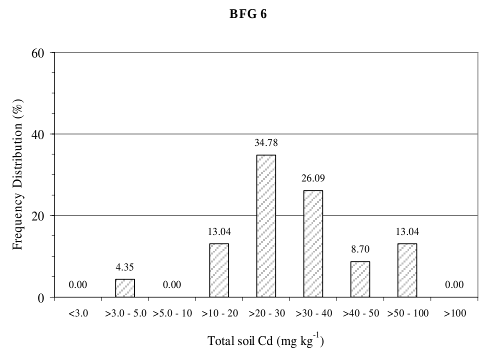
ANNEX 3b (A3b)

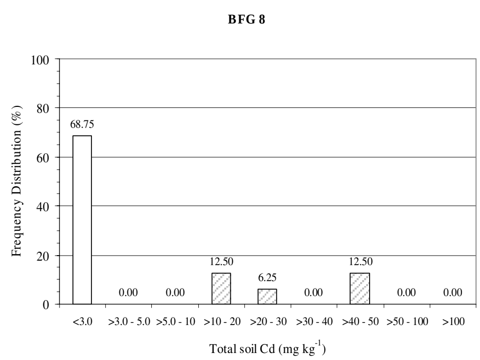
Field Group Specific total soil Cd (mg kg^{-1}) Frequency Distribution (%)

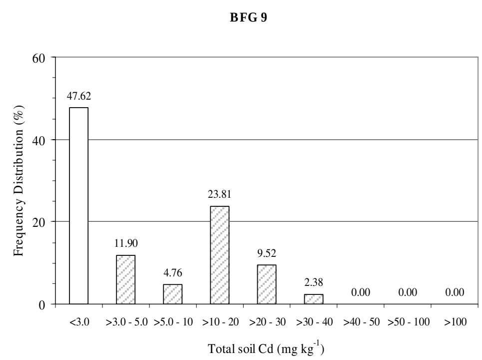


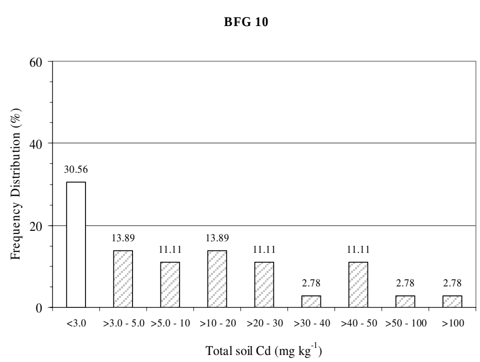


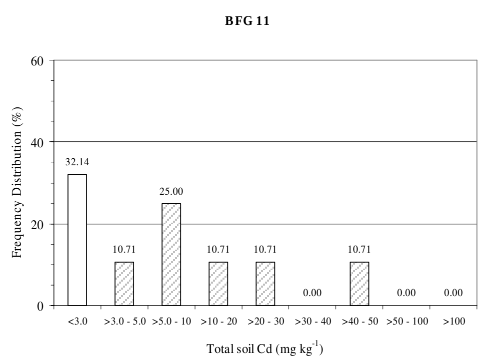












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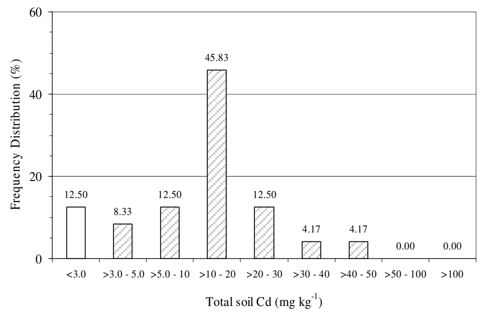

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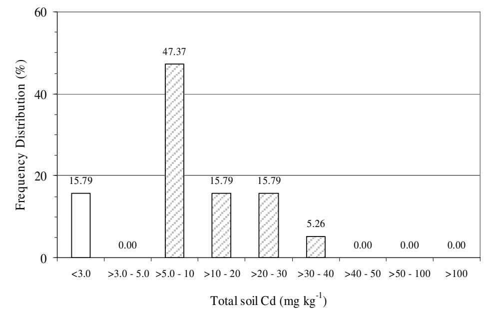

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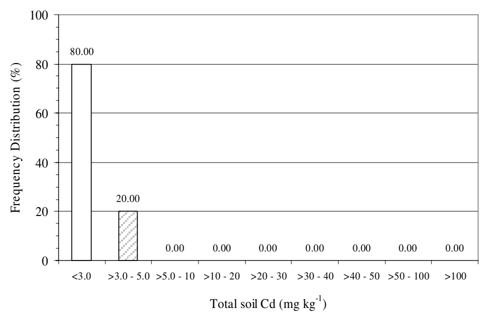

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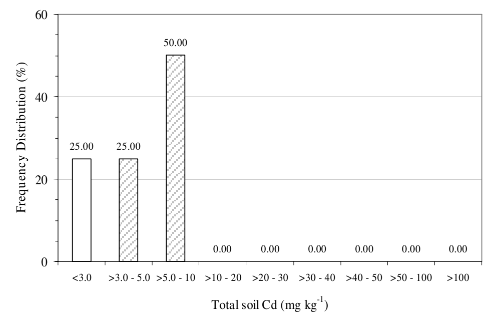

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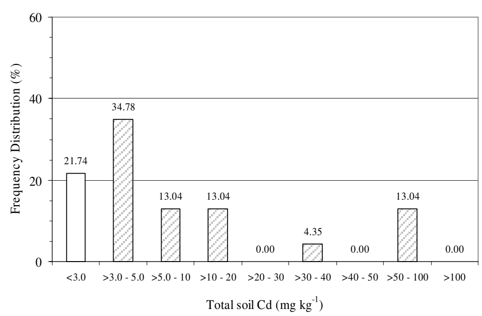

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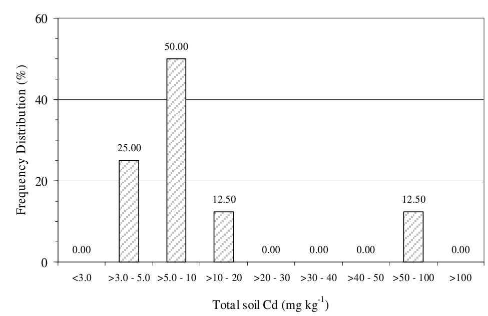

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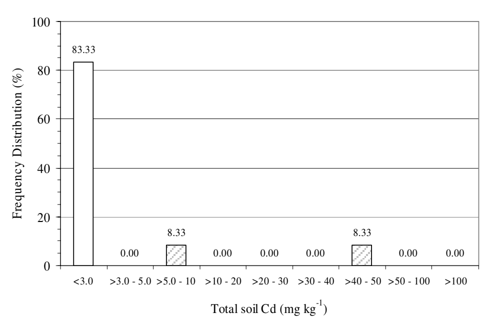

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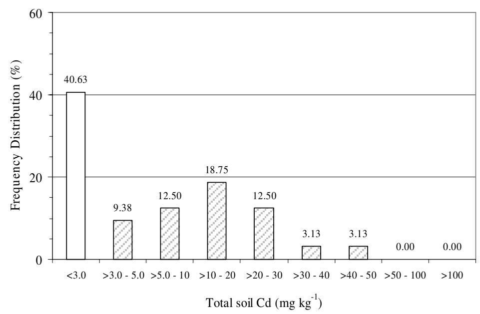

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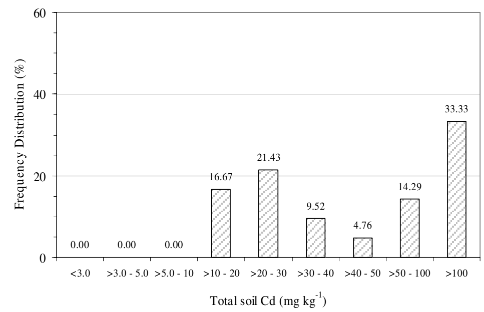

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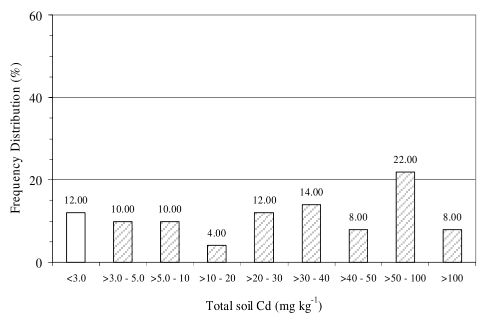

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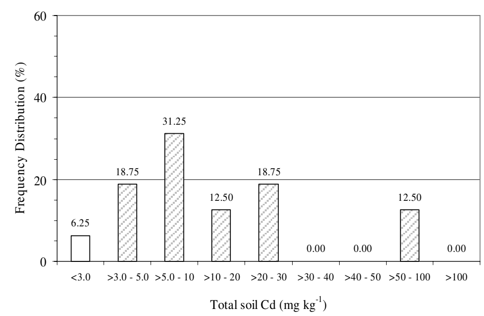

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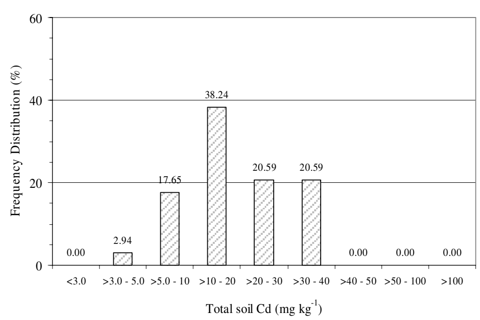

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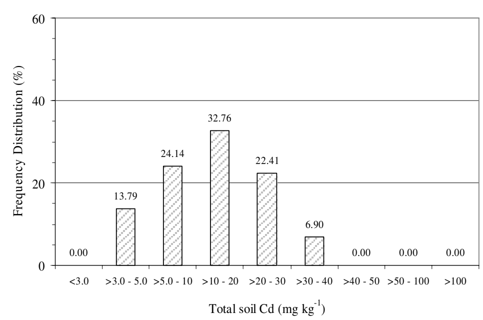

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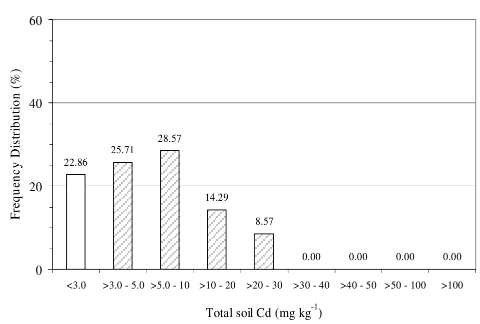

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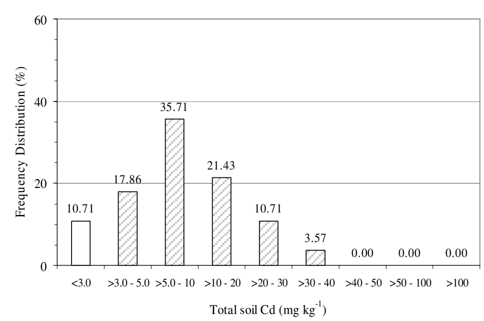

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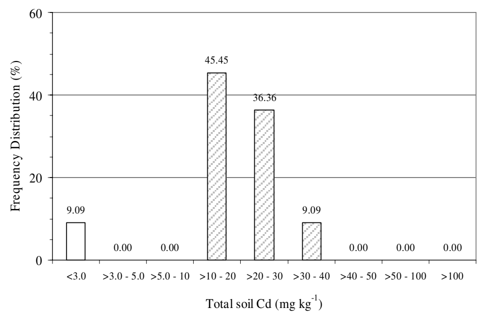

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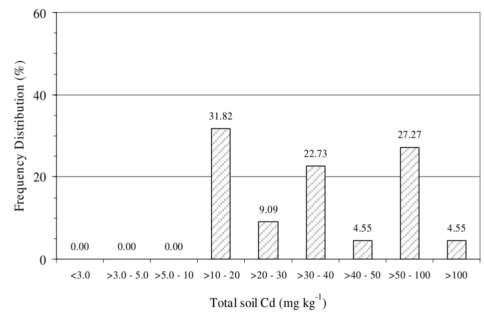

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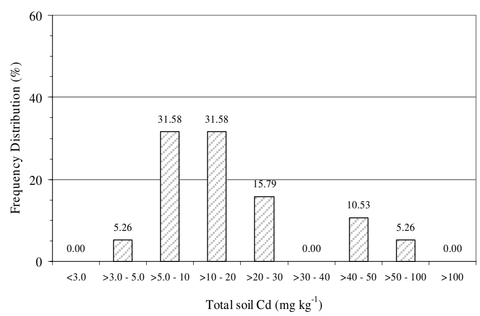

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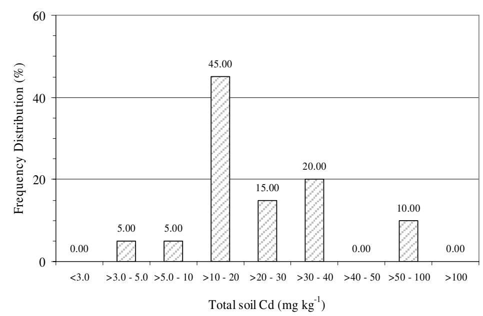

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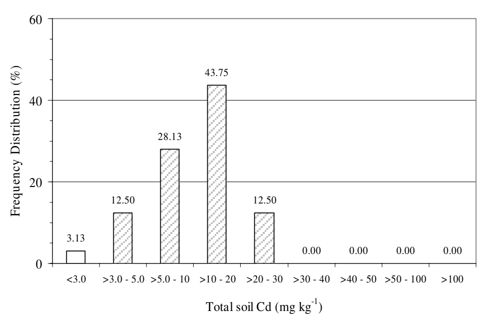

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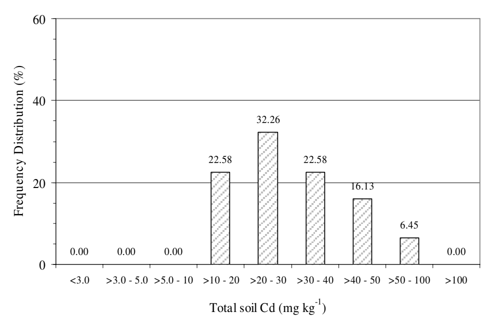

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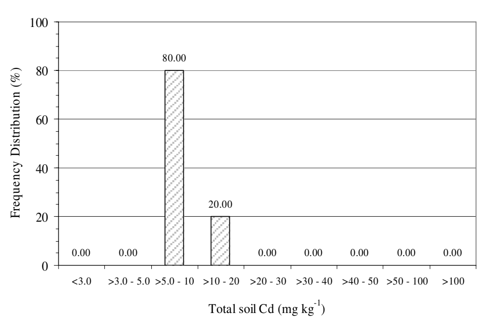

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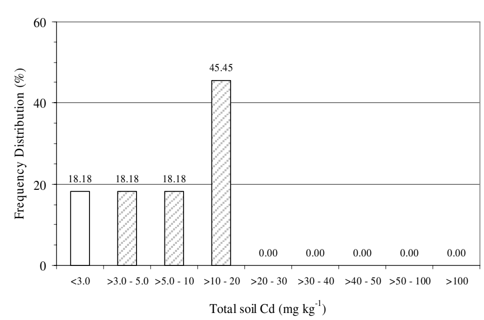

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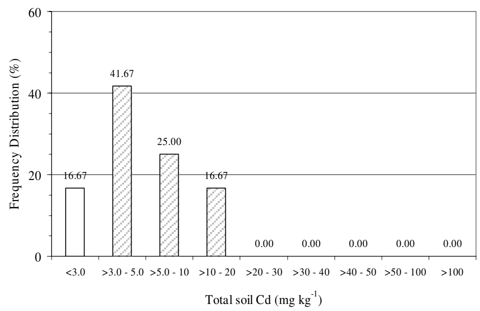

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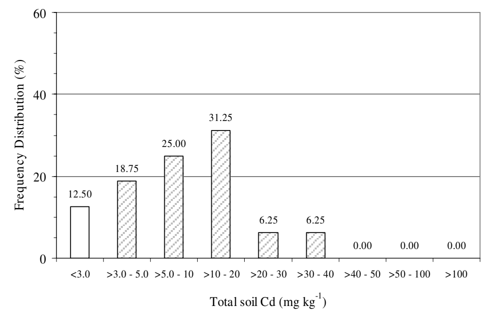

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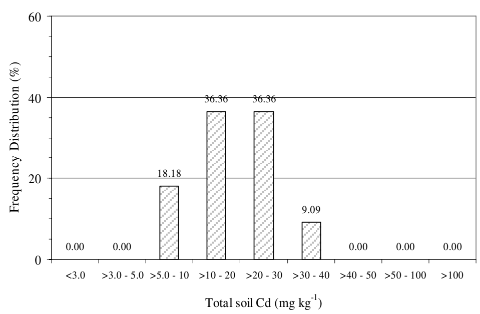

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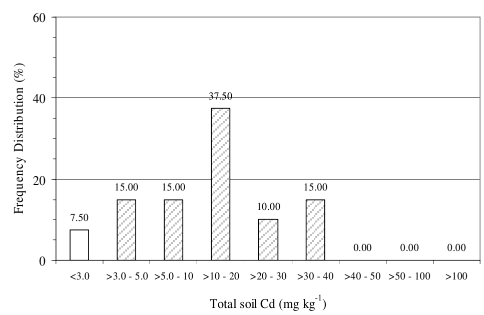

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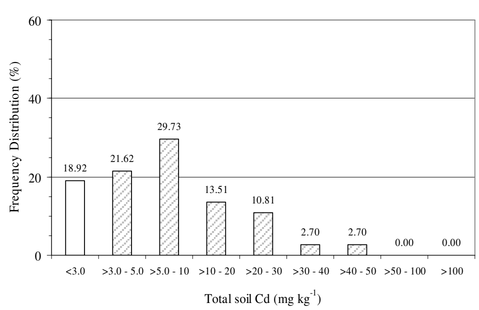

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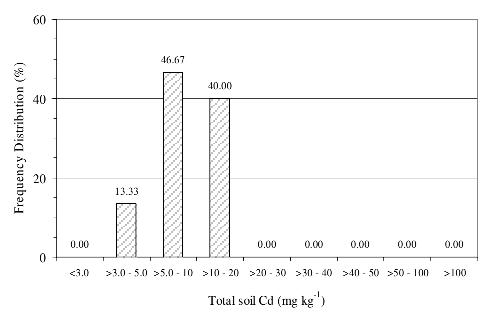

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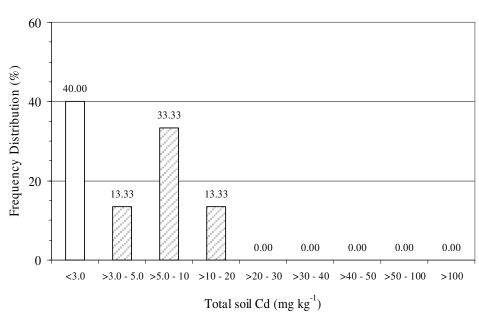

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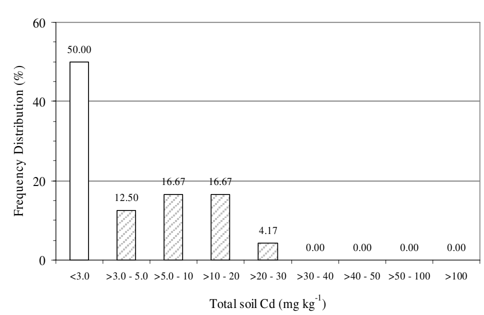

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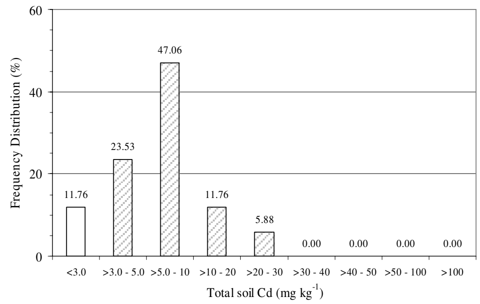

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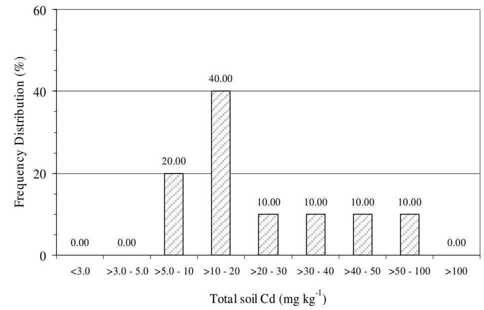

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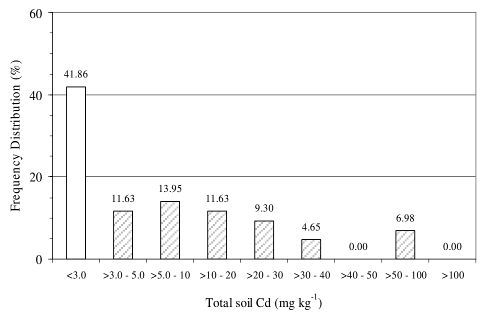

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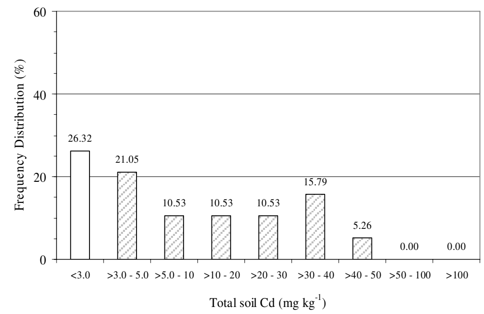

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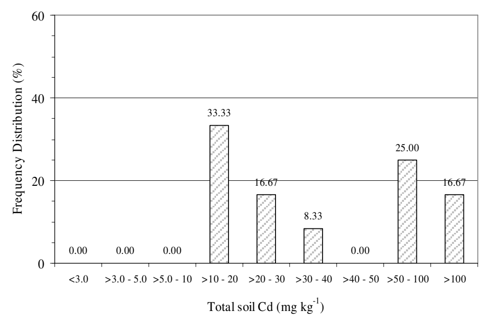

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