Distribution and Concentration of Major and Trace Elements in Paddy Soils and Rice Plant of Khorat Basin, Northeast Thailand

T. Inboonchuay[1], A. Suddhiprakarn[1,*], I. Kheoruenromne[1], S. Anusontpornperm[1] and R. J. Gilkes[2]

[1] *Department of Soil Science, Faculty of Agriculture, Kasetsart University, Bangkok 10900, Thailand*
[2] *School of Earth and Environment, The University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Australia*

**Corresponding author, Email: agrals@ku.ac.th*

Abstract

This study determined the distribution and concentration of major and trace elements in paddy soils and rice plants on diverse soil parent materials in Khorat basin, Northeast Thailand. Soils of 100 sites in areas of 16 soil series under paddy cultivation were sampled at three depths (Ap, Ap-60 and 60-100 cm). The soils were formed on alluvium, residuum derived from sedimentary rock, wash over residuum, wash deposits, and residuum and colluvium of basalt. Above ground parts of rice plants were collected from the site where soil was sampled. Physico-chemical properties of whole soils were determined by standard methods. Heavy metal contents were determined by extraction with aqua regia followed by ICP-OES analysis. Dry ashing of plant material was followed by acid digestion and ICP-OES. Soil texture varies from loamy sand to clay. Values of soil pH in water range from 3.6 to 9.3. Electrical conductivity of soil range from 0.01-3.88 dS m^{-1}. The organic matter content and total N vary from very low to high. Available P and K, CEC, EC and EA range from very low to very high and base saturation percentage from low to high. Most of the paddy soils developed on sedimentary rocks contain much kaolin, traces of illite and quartz. The median concentrations of As, Cd, Cu, Pb, Mo, and Zn are lower than that of normal soils. However, the maximum As concentrations of the soils on alluvium are higher than the critical level of soil quality standard for habitat and agriculture according to Pollution Control Department. The maximum concentrations of Co, Cr, Mn, Ni and V are higher than the critical concentration for plant growth in some paddy soils developed on basalt. Collectively, the results indicate that paddy soils in Khorat basin are without human health risk. The general levels of As, Cr, Cu, Pb and Zn in rice grain are within acceptable levels for human food. The spatial distributions of Co, Cr, Fe, Mn, Ni and V in paddy soils are higher in the southern part of the study area, which is dominated by residuum and colluvium from basalt. The higher As, Pb and Zn concentrations in northern and western parts of the study area reflect the alluvial parent materials. All of elements show a similar spatial distribution with low concentration in the eastern part of the basin. The spatial distribution trend of all metals is similar to that of the clay contents and CEC. Only Co concentration in leaf and grain has significant relationships with total concentration of Al, Ca, Co, Cr, Cu, Fe, Mg, Mn, P and Zn in topsoil. The large variation in chemical composition of the paddy soils in Khorat basin mostly reflects the different nature of their parent materials. Variations in chemical composition due to the contamination by fertilizer application and other agrochemical input are minimal or absent.

Keywords: trace element, paddy soils, spatial distribution, rice plant, Khorat basin

Introduction

Major and trace elements in virgin soil are generally dependent on the lithology of soil parent material and the geochemical and pedological processes. Some soils have been found to have a high background of some trace elements, which are toxic to plants and animals, due to extremely high concentrations of these elements in the parent materials (Adriano, 2001; Hardy and Cornu, 2006; Matula, 2009; Kabata-Pendias, 2011). The problem of soil pollution by heavy metal has received increasing attention in the last few decades (Akoto et al., 2008). The most important heavy metals with regard to potential hazards and the occurrence in contaminated soils are As, Cd, Cr, Hg, Pb and Zn (Asaah et al., 2006).

Rice is the most important food crop in Thailand and it is dominantly grown on lowland soils (Fageria et al., 1997; Dobermann and Fairhurst, 2000). Soils used for rice cultivation in Thailand vary considerably in mineralogy and geochemistry (Prakongkep et al., 2007). Some paddy soils have been polluted with trace elements, especially heavy metals. This is an increasing concern due to the food safety issue and potential health risks. It is also a potential problem for rice export (Wong et al., 2002). Zarcinas et al. (2004), in a study on heavy metals in soil and crops in Southeast Asia, found that the maximum concentrations of As, Cr and Ni in soils were higher than the critical concentrations for plant growth. Groundnut, rice and glutinous rice had elevated concentrations of all the metals assessed when compared to the other plants sampled.

Several studies on the geochemistry of Thai paddy soils revealed that the concentration of elements, physical and chemical properties in paddy soils mostly depends on soil parent materials (Prakongkep et al., 2007; Chittamart et al., 2010). Sinjanusong (2007) also found potential risk of Se toxicity in paddy soils distributed in the eastern part of the Sakon Nakhon Basin, Northeast Thailand. However, there was not any detailed report discussing distributionand status of heavy metals in Northeast Thailand. Rahman et al. (2014) studied heavy metals in Australian grown and imported rice and vegetables on sale in Australia. They found that the concentration of Cd, Cr, Cu, Ni, and Pb in Thai rice on sale in Australia were higher than Australian grown rice. Most of the heavy metals were found to be substantially higher in Thai rice than rice from other countries on sale in Australia.

Khorat basin is an important area for jasmine rice production. It is located in the lower part of Northeast Thailand. The soils, mostly derived from sandstone and siltstone, are typically light in texture and have low chemical fertility and poor moisture storage capacity. Major orders of soils are Ultisols, Alfisols and Inceptisols. Some soils have developed on basalt and basaltic colluvium (Moncharoen et al., 1987). Major land uses are rice cultivation in the flat lowlands covering approximately 45% of total area. Paddy soils in the Khorat basin typically have light texture, poor moisture storage capacity, high potential for erodibility and low fertility. The low soil fertility is caused by the parent materials, which are generally alluvial deposits, or in situ weathered sandstone, leading to sandy or sandy loam soil textures. Sometimes, severe problems arise from the high salt content of some soils. This study aims at determining type, concentration and distribution of major and trace elements in paddy soils and rice plant on diverse soil parent materials in Khorat basin and to determine relationship of major and trace elements concentration in paddy soils and rice plant, Northeast Thailand. This knowledge can be used in planning and developing agricultural management practices on rice based cropping for food safety and food security.

Materials and Methods

Soil and Plant Sampling and Geological Setting

The study encompassed 16 soil series of paddy soils in Khorat basin. One hundred sites (Fig. 1) under paddy cultivation were sampled at three depths (Ap, Ap-60 and 60-100 cm). Most of the soils were derived from wash deposits from sandstone, wash over residuum and residuum derived from clastic sedimentary rocksand some soil developed on basalt and alluvium. The Northeast Plateau is mostly underlain by Mesozoic rocks. The Plateau is rimmed by an escarpment of mostly steeply dipping sediments which form cuestas rising from 600-1000 m above sea level on its western and southern margins. It has a “saucepan morphology”, covering an area of about

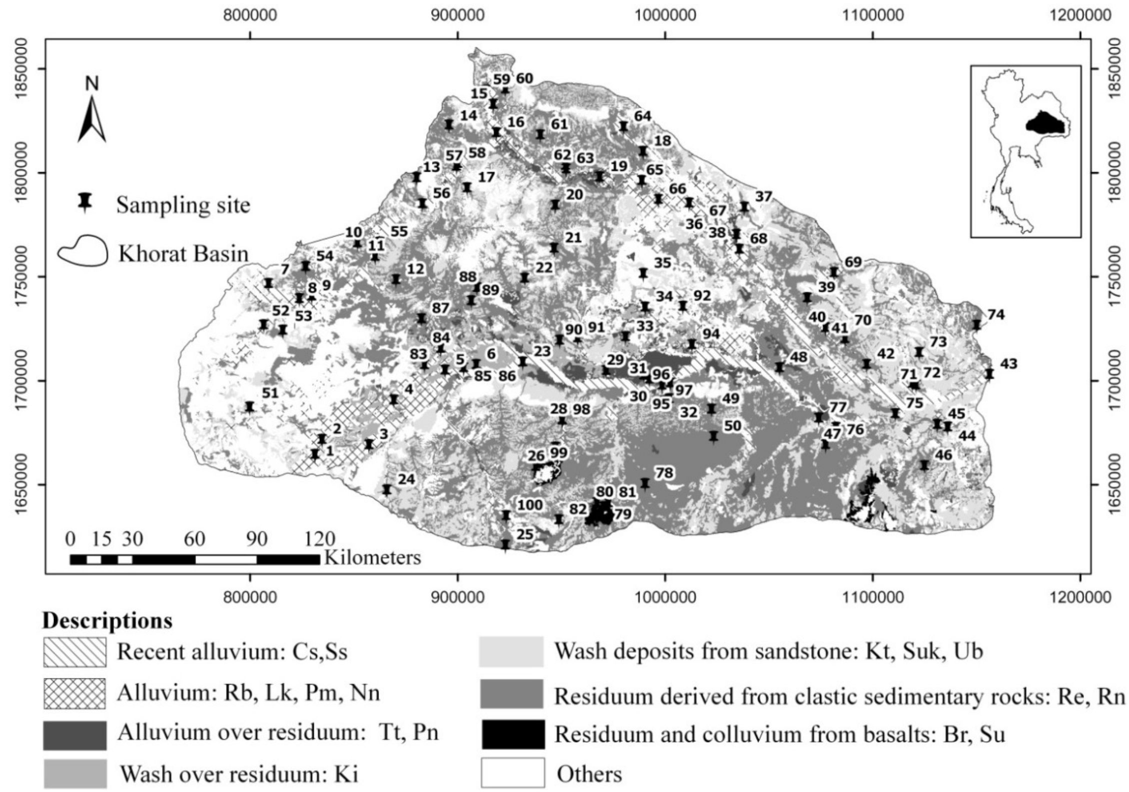

Figure 1 Parent materials and soil series of paddy soils in Khorat basin, Northeast Thailand.

170,000 km^2 (Prakongkep et al., 2007). All of the sampled soils in this region developed on the rocks of Khorat Group that comprises continental red and gray sandstone, siltstone and shale with some paralic and thick rock salt layers and gypsum beds with total thickness of more than 600 meters, ranging in age from the Late Triassic to the Cretaceous period (Ward and Bunnag, 1964). Rice plants were collected from each location by cutting at 10 cm above ground at the exact sites where soils were sampled. Rice plants were divided into 5 parts comprising stem, leaf, grain, husk and branch (Branch of rice plants are uppermost internode, panicle axis, primary and secondary branch). Rice grain samples were dehusked with a rice milling machine.

Analytical Methods

Physico-chemical properties of whole soils were determined using the procedures described by National Soil Survey Center (1996). Soil texture was determined using the pipette method. Soil pH was determined with a pH electrode in 1:1 suspension (soil: H_2O and soil: 1M KCl). Electrical conductivity (1:5 soil/water extract) by EC meter (Rayment and Lyons, 2011). Cation exchange capacity (CEC) was measured by the ammonium saturation method at pH 7. Total carbon and nitrogen were determined on an Elementar CNS (Vario Macro) analyzer. Chemical composition was determined by X-ray fluorescence (Norrish and Hutton, 1969). Heavy metal contents were determined by extraction with aqua regia followed by ICP-OES analysis (Lynch, 1999). The accuracy of determination was verified using a rigorous control system including reagent blanks and a certified international reference material (STSD-4) for aqua regia digestion and OREAS 43P for fused lithium meta/tetraborate glass discs. All samples were measured in duplicate. Dry ashing of plant material was followed by acid digestion and ICP-OES and the ashes were analyzed by XRD and SEM&EDS. Certified international reference materials were ASPAC41-13 (Pine needles) and ASPAC102-12 (Spinach leaves).

Data Analysis

Principal component analysis were used to determine elements of similar geochemical behavior and also to group soil samples on the basis of their geochemical affinity (Bellehumeur et al., 1994) with the Statistica Program (6.1) (StatSoft Inc., 2003). The inverse distance weight method was used to generate the spatial distribution map of soil properties and other elements. The Pearson correlation test (two-tailed) was used to identify relationships between element concentrations in paddy soils and rice plants.

Results and Discussion

Soil Analysis

General soil properties

Representative analytical data are presented in Table 1. Soil texture varies from loamy sand to clay. The clay content of the soils varies from 60 to 700 g kg^{-1}. The values of soil pH in water range from extremely acid to very strongly alkaline. The organic matter content and total nitrogen vary from very low to high. Available P and K, CEC, EC and EA range from very low to very high and base saturation percentage from low to high. The result indicated that the very wide range of values on soil properties was due to the soil diverse parent materials.

Major and trace element concentrations in paddy soil

The median concentrations of As, Cd, Cu, Pb, Mo, and Zn are lower than that of normal soils (Table 2). However, the maximum As concentrations of the soils on alluvium are higher than the critical value of soil quality standard for habitat and agriculture according to Pollution Control Department. The maximum concentrations of Co, Cr, Mn, Ni and V are higher than the critical concentration for plant growth in some paddy soils developed on basalt. These elements can be toxic to the rice plant and approaching critical concentrations for environmental concern (Alloway, 1995). However, the results indicate that paddy soils in Khorat basin is without human health risk. The median concentrations of elements in all paddy soils increase with depth and with the increase of clay content.

Multivariate analysis for soil properties and elements

Factor analysis and principal component analysis were used to determine elements of similar geochemical behavior and also to group soil samples on the basis of their geochemical affinity (Bellehumeur et al., 1994). Factor analysis of standardized raw data was used to identify affinity groups of elements, with texture, pH and CEC being included in the data set (David, 1986). The first two factors explain 60% of variation in data, which is acceptable considering the diversenature of these soils (Figure 2). The first group consists of sand, Si and Zr which simply relates to the texture of the soils. The second group is diffuse and consists of clay, CEC, OM, EA, Al, Ba, Ca, Cu, Mg, V and Zn. This group of properties relates to the clay content as many of these elements are constituents of clay minerals and oxides or occur as adsorbed species (Kabata-Pendias, 2010). The third group includes Cr, Co, Fe, Mn, Ni and P which relates to the soil on residuum and colluvium from basalt. The plot of soil samples in the factor diagram shows that the soils on residuum and colluvium derived from basalt have a homogeneous population that is well separated from other soils formed on other parent materials. Comparing with pulished data, Micó et al., (2006) reported a Fe affinity group (Fe, Ni, Co, Cr, Mn) for European soils and considered that this group is controlled by the lithology of source rocks. According to the literature concentrations As, Cd, Co, Cr, Cu, Mn, Ni, Pb, Ti and Zn in other uncontaminated paddy soils are also quite varied, presumably reflecting differences in parent material composition and possibly the application of fertilizers (Wong et al., 2002, Chandrajith et al., 2005, Prakongkep et al., 2007).

Plant Analysis

Major and trace element concentrations in rice plant parts

The general levels of As, Cr, Cu, Pb and Zn in rice grain are within acceptable levels for human food (Table 3). Principal component analysis for total element concentrations in rice plant materials revealed that Al, As, Ca, Cr, Fe, Mn, Mo and Pb are most abundant in rice leaf. Co Cu, K and Na are more abundant in stem and branch of rice plants.

Table 1 Range and median values of some properties of paddy soils in the Khorat Basin

Properties	Total (n=300)		Topsoil (n=100)		Subsoil (n=200)	
	Range	Median	Range	Median	Range	Median
Sand (g kg^{-1})	4-904	480	12-888	565	4.2-904	451
Silt (g kg^{-1})	19-675	241	31-674	251	19-603	234
Clay (g kg^{-1})	56-700	228	64-671	143	55-700	274
pH -H_2O	3.6-9.3	5.2	3.6-7.2	4.8	3.6-9.3	5.4
pH -KCl	3.1-7.5	4.0	3.3-6.2	3.9	3.1-7.5	4.0
EC-1:5 (dS m^{-1})	0.01-3.8	0.06	0.02-3.8	0.07	0.01-3.8	0.06
OM (g kg^{-1})	0.17-36	3.95	2.7-36	11.4	0.17-20	2.2
Total N (g kg^{-1})	0.05-1.7	0.38	0.24-1.7	0.64	0.05-1.2	0.29
Avail. P (mg kg^{-1})	1-85	3.8	2.6-85	7.8	1.0-33.8	3.0
Avail. K (mg kg^{-1})	0.18-442	24	2.8-442	30.2	0.18-245	22.5
CEC (cmol kg^{-1})	0.6-51	7.3	1.2-33	4.5	0.25-51	8.3
EA (cmol kg^{-1})	0.5-22	5.5	0.50-21	5.0	0.50-22	5.5
Base sat. (%)	3.7-96	46.8	3.7-90	41.8	5.1-96	51.7

Table 2 Range and median concentrations of elements in paddy soils sample (n=300), mean values for normal surface soils worldwide and critical concentrations for contaminated soils

Element	Range	Median	Normal soil[1]	PCD[2*]	US EPA[3]	CCME[4]	NYS DEC[5*]	Critical soil concentration[6]
Si (g kg^{-1})	174-505	419.4	250-410	n/a	n/a	n/a	n/a	n/a
Al	1.7-106	29.5	10-300	n/a	n/a	n/a	n/a	n/a
Fe	1.3-197	12.5	2-550	n/a	n/a	n/a	n/a	n/a
Ti	0.7-30.2	3.2	2.3-26	n/a	n/a	n/a	n/a	n/a
K	0.2-13.6	1.6	0.08-37	n/a	n/a	n/a	n/a	n/a
Ca	0.5-14.3	1.1	0.7-500	n/a	n/a	n/a	n/a	n/a
Mg	nd-15.3	0.7	0.4-9	n/a	n/a	n/a	n/a	n/a
Mn	0.11-5.37	0.22	0.3-0.53	1.8	n/a	n/a	n/a	1.5-3.0
Na	nd-7.8	0.7	0.15-25	n/a	n/a	n/a	n/a	n/a
As (mg kg^{-1})	0.01-15.8	1.3	4.4-9.3	3.9	n/a	12	n/a	20-50
Bi	0.01-19.8	0.6	0.1-0.4	n/a	n/a	n/a	n/a	n/a
Cd	nd-0.43	0.002	0.37-0.78	37	70	1.4	0.43	3-8
Co	0.1-130	5.0	4.5-12	n/a	n/a	40	n/a	25-50
Cr	2.6-237	19.1	12-83.0	300	230	64	11	75-100
Cu	0.05-34.8	5.2	13-24	n/a	n/a	63	270	60-125
Mo	nd-0.8	0.1	0.013-17	n/a	n/a	n/a	n/a	2-10
Ni	0.3-206	6.5	13-34	1600	1600	50	72	100
P	7.7-2299	42.8	35-5300	n/a	n/a	n/a	n/a	n/a
Pb	0.5-30.3	6.4	22-44	400	400	70	200	100-400
V	Nd-321	49.0	18-115	n/a	n/a	130	n/a	50-100
Zn	0.01-119	7.0	45-100	n/a	23600	200	1100	70-400

[1]Mean of total concentrations of elements in the surface horizon of normal worldwide soil, normal mean that the data do not include contaminated or mineralized soils (Kabata–Pendias, 2010; Essington, 2004)
[2]Higher concentrations may be toxic to plants depending on speciation (Alloway, 1995)
[3]Pollution Control Department, Thailand (PCD, 2004)
[4]The US Environmental Protection Agency (EPA, 2002)
[5]Canadian Council of Ministers of the Environment (CCME, 2007)
[6]New York State Department of Environmental Conservation (NYS DEC, 2006)
*Includes agricultural use, nd = not detectable, n/a = not available

Phosphorus is generally abundant in rice grain (Figure 3). The composition of rice ashes was determined using Scanning Electron Microscopy with Energy Dispersive Spectrometry. The results indicated that phosphorus, potassium, magnesium, calcium, chloride and silica. The results indicated that phosphorus, potassium, magnesium, calcium, chloride and silica are present in ash of stem, leaf, branch and husk. Most elements in plants are retained in the ash with most N and some S being lost (Perkiomaki, 2004; Yusiharni and Gilkes, 2012). Phosphorus, magnesium and potassium are the major components of the grain ash (Figure 4). Much of the P in aleurone grains is primarily in the form of K-Mg Phytate (Dikeman et al., 1981; Lott et al., 2000).

Spatial distribution of major and trace element in the paddy soils

Soil pH varies from extremely to moderately acid in the eastern part of the basin due to leaching of bases in high rainfall areas. However, the organic matter, total N, available K, CEC, Extractable Ca and Mg are low in eastern part of the basin. While EC and ExtractableNa are higher in western part of the basin due to salt- affected soils. The higher concentrations of Co, Cr, Fe, Mn, Ni and V in paddy soil are located in the southern part of the basin, which is dominated by basalt. The higher As, K, Pb and Zn concentrations in northern and western parts of the basin are due to the alluvial parent materials. All of elements show a similar spatial distribution with low concentration in the eastern part. The spatial distribution trend of all metals is similar to that of clay contents and CEC (Figure 5).

Table 3 Statistical summary of element concentrations (mg kg^{-1}) for rice plant parts (n=number of samples).

Elements (mg kg^{-1})	Al	As	Ca	Co	Cr	Cu	Fe	K	Mg	Mn	Mo	Na	P	Pb	Zn
Stem (n=75)															
Median	5.58	0.003	912	0.14	0.08	1.16	35	19222	738	160	0.10	527	921	0.07	20.8
Min	1.89	nd	347	0.03	0.02	0.50	10	10229	282	25	0.04	65.3	195	nd	2.23
Max	91.7	0.33	1564	1.57	0.25	18.7	167	25860	2064	764	3.33	4754	1904	0.36	90.0
Leaf (n=75)															
Median	46.0	0.37	4812	0.09	0.23	1.26	103	5722	809	425	0.45	206	983	0.07	5.29
Min	20.7	nd	2483	0.02	0.07	0.33	40	2663	273	55	0.14	59.4	266	Nnd	1.03
Max	534	1.38	6693	0.88	1.23	24.8	844	11910	2076	1974	7.73	1804	2002	0.52	11.5
Grain (n=75)															
Median	7.38	nd	82.9	0.03	0.08	1.86	6.9	2233	1192	18	0.29	73.3	2928	0.01	18.5
Min	2.47	nd	58.2	nd	0.05	0.44	4.6	1366	809	11	0.04	16.3	1789	nd	10.4
Max	37.2	nd	126	0.36	0.15	11.6	14	2889	1505	37	1.45	256	3448	0.08	25.6
Husk (n=75)															
Median	17.2	0.003	518	0.04	0.11	0.87	31	2187	324	94	0.08	56.6	567	0.03	14.0
Min	5.60	nd	200	0.01	0.04	0.15	11	791	137	17	nd	25.4	283	nd	7.42
Max	230	0.25	1347	0.73	0.76	6.47	421	3974	609	270	0.89	303	1092	0.45	22.8
Branch (n=75)															
Median	15.1	0.17	731	0.07	0.19	2.69	30	7699	306	107	0.11	365	516	0.04	13.0
Min	7.44	nd	357	0.02	0.08	0.18	10	3857	55.8	9.7	0.04	149	278	nd	1.82
Max	150	0.98	1471	0.92	2.70	21.0	270	12512	1100	478	1.45	1142	870	0.29	96.4
*Food safety Standard		0.15[ac]			1.0[a]	10[a]								0.2[abcd]	50[ad]

[a]National Food Institute, Thailand
[b]European communities
[c]Food standard Australia New Zealand
[d]FAO/WHO
*Food safety standard in rice and cereal. nd= not detectable

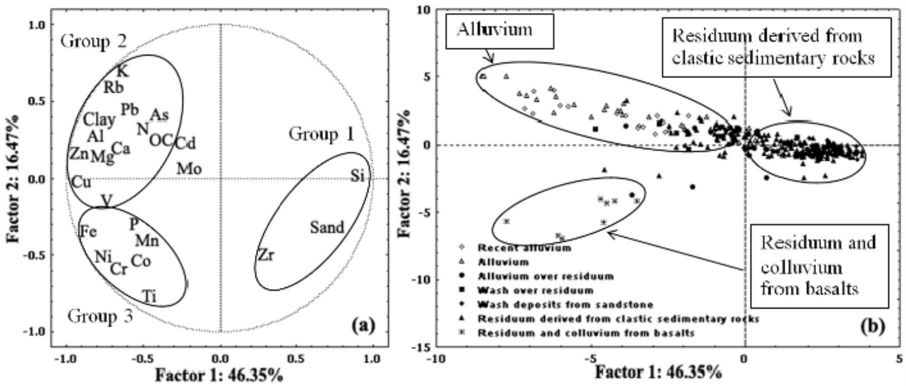

Figure 2 Factor analysis for the chemical composition and some properties for whole soil materials (a) distribution of chemical and other soil properties (variables) (b) distribution of soil samples (cases).

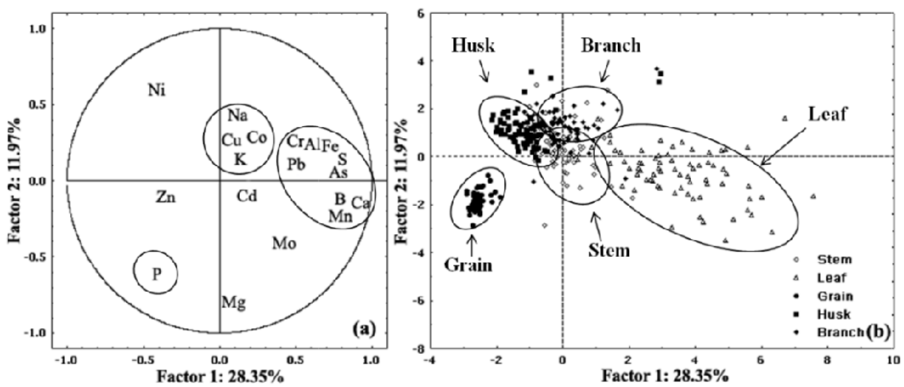

Figure 3 Factor analysis for the elements concentrations in rice plants (a) distribution of elements in plant materials (variables) (b) distribution of plant parts (cases).

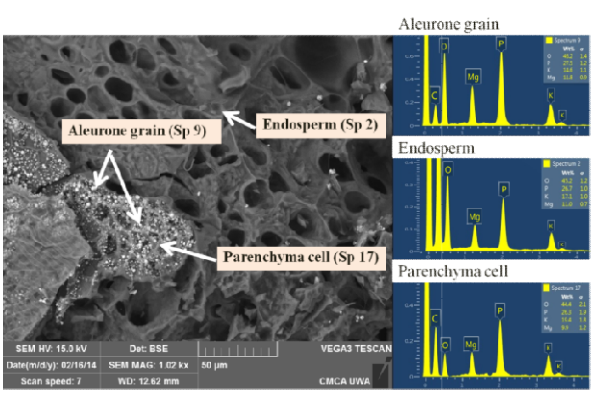

Figure 4 Scanning electron micrographs (SEM) and X-ray spectra of the indicated particles in rice grain ash.

Correlation coefficient matrix

The correlation analysis was calculated to determine the extent of the relationship between the major and trace elements in paddy soils and rice plants. The Pearson correlation matrix for elements in topsoil and rice grain is shown in Table 4. Only Co concentration in leaf and grain (Figure 6) has a significant positive correlation with total Co, Cr, Cu, Fe, Mn, Ni, P and Zn concentration in topsoil. For most of the elements, there was no significant correlation between the concentrations of elements in soil and those in crops. As already noticed by Zhao et al. (2009) and Keshavarzi et al. (2015), it may be concluded that the total element content in soil is not solely responsible for the observed concentrations in crops. It might be due to the complicated conditions and various parameters affecting the transfer of elements from soil to plant such as soil total element concentrations and plant species as already mentioned.

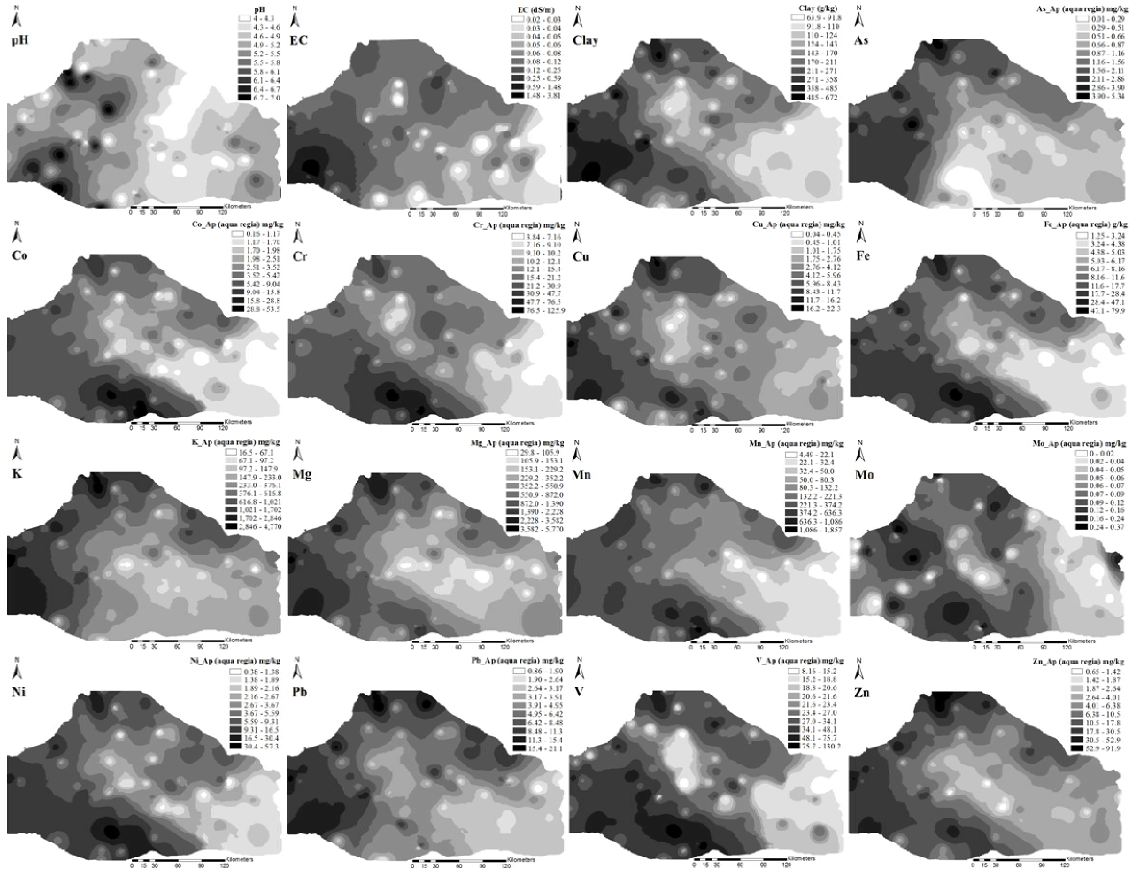

Figure 5 Spatial distribution maps of pH, clay content and elements of paddy soils in Khorat basin, Northeast Thailand.

Table 4 The correlation coefficients for relationships between major and trace element concentrations in grain and topsoil (n=75).

	Al_s	Ca_s	Co_s	Cr_s	Cu_s	Fe_s	K_s	Mg_s	Mn_s	Mo_s	Ni_s	P_s	Pb_s	Zn_s
Al_g	0.00	-0.12	0.16	0.08	0.04	0.03	-0.07	-0.05	0.00	0.18	0.01	-0.05	0.05	-0.03
Ca_g	-0.10	-0.14	-0.15	-0.20	-0.06	-0.18	0.03	-0.12	-0.16	0.09	-0.22	-0.24	0.12	-0.09
Co_g	0.32	0.23	**0.63**	**0.70**	**0.42**	**0.65**	-0.01	0.28	**0.54**	0.29	**0.71**	**0.75**	-0.03	**0.34**
Cr_g	0.13	0.05	0.15	0.12	0.07	0.14	-0.02	0.03	0.10	-0.02	0.09	0.02	0.07	0.05
Cu_g	0.12	-0.08	0.27	0.16	0.16	0.17	0.06	0.12	0.14	0.21	0.12	0.06	0.11	0.09
Fe_g	0.10	-0.01	0.04	0.03	0.09	0.03	0.14	0.09	0.00	0.07	0.00	-0.01	0.28	0.10
K_g	0.01	0.15	-0.11	-0.10	0.02	-0.03	0.10	0.04	0.00	-0.16	-0.05	-0.07	0.10	0.04
Mg_g	0.05	0.01	0.13	0.09	0.12	0.08	-0.02	0.07	0.18	-0.09	0.09	0.03	-0.04	0.09
Mn_g	0.02	-0.11	0.23	0.14	0.04	0.17	0.04	0.18	**0.33**	0.04	0.20	0.20	-0.05	0.16
Mo_g	-0.21	-0.21	-0.12	-0.14	-0.15	-0.17	-0.11	-0.15	-0.16	0.23	-0.18	-0.18	-0.17	-0.18
Ni_g	0.02	-0.12	0.13	0.17	-0.01	0.15	-0.08	0.04	0.10	0.17	0.10	0.10	-0.06	-0.02
P_g	0.08	0.09	0.09	0.08	0.09	0.08	0.00	0.07	0.15	-0.10	0.07	0.02	0.02	0.14
Pb_g	0.17	0.02	**0.38**	0.26	0.27	0.27	0.08	0.18	0.25	0.34	0.23	0.17	0.11	0.16
Zn_g	-0.18	-0.39	-0.16	-0.19	-0.16	-0.22	-0.27	-0.27	-0.26	-0.15	-0.22	-0.24	-0.14	-0.22

Bold letter indicates significance $P \leq 0.01$.

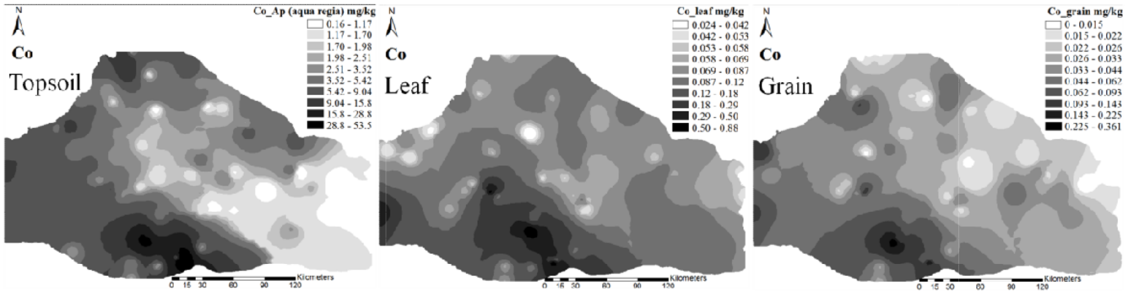

Figure 6 Spatial distribution maps of Co in the topsoil and rice plants (leaf and grain) of Khorat basin, Northeast Thailand

Conclusions

The median concentrations of As, Cd, Cu, Pb, Mo, and Zn are lower than that of normal worldwide soils. The soils on basalt have median concentrations of Co, Cr, Mn and V higher than that of normal soils. The maximum concentrations of Co, Cr, Ni and V are higher than critical concentrations for plant growth. These elements can be toxic to the rice plant. Concentrations of elements in all paddy soils increase with depth and with the increase of clay content. High concentrations of Co, Cr, Fe, Mn, Ni and V in paddy soils are located in the southern part of the study area, which is dominated by basalt. Spatial distribution trend of all elements are similar to that of clay contents and CEC. Levels of all elements in rice grain are generally within acceptable levels for human food. Large variations in chemical composition of paddy soils and rice plant mostly reflect different nature of the parent materials. Variations in the chemical composition due to the contamination by fertilizer and other agrochemical input are minimal or absent.

In this study, no direct relationship between metal concentrations in soils and crops was found, and we believe that besides the total metal content, parameters such as the physical, chemical, and biological properties of soil and plant species also play a role in the bioavailability of elements to crops.

Acknowledgments

This work was partially supported by the Center for Advanced Studies for Agriculture and Food, Institute for Advanced Studies, Kasetsart University under the Higher Education Research Promotion and National Research University Project of Thailand, Office of the Higher Education Commission, Ministry of Education, Thailand. The authors are grateful to the staff of School of Earth and Environment, The University of Western Australia for their kind assistance, especially Mr. Michael Smirk.

References

Adriano, D.C., 2001. Trace elements in terrestrial environments: Biogeochemistry, bioavailability and risks of metals, 2nd ed. Springer, New York.

Akoto, O., J.H. Ephraim and G. Darko. 2008. Heavy metals pollution in surface soils in the vicinity of abundant railway servicing workshop in Kumasi, Ghana. Int. J. Environ. Res. 2: 359-364.

Alloway, B.J. 1995. The origins of heavy metals in soils, pp. 38-57. In B.J. Alloway, ed., Heavy Metals in Soils. Blackie Academic and Professional Publ., New York.

Asaah, V.A., A.F. Abimbola and C.E. Suh. 2006. Heavy metal concentrations and distribution in surface soils of the Bassa industrial zone 1, Douala, Cameroon. Arabian J. Sci. Engineer. 31: 147-158.

Bellehumeur, C., D. Marcotte and M. Jébrak. 1994. Multi-element relationship and spatial structures of regional geochemical data from stream sediments, Southwestern Quebec. Canada. J. Geochem. Explor. 51: 11-35.

CCME (Canadian Council of Ministers of the Environment). 2007. Canadian Soil Quality Guidelines for the Protection of Environmental and Human Health, National Guideline and Standards Office, Quebec, Publication No. 1299.

Chandrajith, R., C.B. Dissanayake and H.J. Tobschall. 2005. The abundances of rarer trace elements in paddy (rice) soils of Sri Lanka. Chemosphere 58: 1415-1420.

Chittamart, N., A. Suddhiprakarn, I. Kheoruenromne and R.J. Gilkes. 2010. The pedo-geochemistry of Vertisols under tropical savanna climate. Geoderma 159: 304-316.

Davis, J.C. 1986. Statistics and Data Analysis in Geology. John Wiley & Sons, New York.

Dikeman, E., D.B. Benchtel and Y. Pomeranz. 1981. Distribution of element in rice kernel determined by X-ray analysis and atomic absorption spectroscopy. Cereal Chem. 58: 148-152.

Dobermann, A., and T. Fairhurst. 2000. Rice: Nutrient Disorders & Nutrient Management. IRRI, Philippines, PPI, U.S.A., and PPIC, Canada.

Essington, M.E. 2004. Soil and Water Chemistry: An Integrative Approach. CRC Press, LLC. USA.

Fageria, N.K., V.C. Baligar, and C.A. Jones. 1997. Growth and Mineral Nutrition of Field Crops, 2nd ed. New York: Marcel Dekker.

Hardy, M. and S. Cornu, 2006. Location of natural trace elements in silty soils using particle size fractionation. Geoderma 133: 295-308.

Kabata-Pendias, A. 2010. Trace Elements in Soils and Plants. CRC Press, USA.

Keshavarzi, B., F. Moore, M. Ansari, M.R. Mehr, H. Kaabi and M. Kermani. 2015. Macronutrients and trace metals in soil and food crops of Isfahan Province, Iran. J. Environ. Monit. Assess 187: 4113.

Lott, J. N.A., I. Ockenden, V. Raboy and G.D. Batten. 2000. Phytic acid and phosphorus in crop seeds and fruits: a global estimate. Seed Sci. Res. 10: 11-33.

Lynch, J. 1999. Additional provisional elemental values for LKSD-1, LKSD-2, LKSD-3, LKSD-4, STSD-1, STSD-2, STSD-3 and STSD-4 Geostandards Newsletter. J. Geostandards Geoanalysis 23: 251-260.

Matula, J. 2009. A relationship between multi-nutrient soil tests (Mehlich 3, ammonium acetate, and water extraction) and bioavailability of nutrients from soils for barley. Plant Soil Environ. 55: 173-180.

Micó, C., L. Recatalá, M. Peris and J. Sánchez. 2006. Assessing heavy metal sources in agricultural soil of an European Mediteranean area by multivariate analysis. Chemosphere 65: 863-72.

Moncharoen, L., T. Verasilp and H. Eswaran. 1987. Benchmark Soils of Thailand. Department of Land Development, Thailand.

National Soil Survey Center. 1996. Soil Survey Laboratory Methods Manual. United States Department of Agriculture, Natl. Soil Surv. Cent., Soil Surv. Lab., Soil Survey Investigation No. 42, Version 3.

Norrish, K. and J.T. Hutton. 1969. An accurate X-ray spectrographic method for the analysis of a wide range of geological samples. Geochim. Cosmochim. Acta 33: 431-453.

NYS DEC, 2006. New York State Brownfield Cleanup Program Development of Soil Cleanup Objectives Technical Support Document. New York State Department of Environmental Conservation and New York State Department of Health, Albany, NY. http://www.dec.ny.gov/chemical/34189.html.

Perkiomaki, J. 2004. Wood ash use in coniferous forests, a soil microbiological study into the potential risk of cadmium release. Metsantutkimuslaitoksen Tiedonantoja, 917. Finish Forest Research Institute. Research Papers 917.

Pollution Control Department, Thailand. 2004. Water Quality Standards. Source: http://www.pcd.go.th/info_serv/reg_std_water05.html, Accessed 2007 August 2.

Prakongkep, N., A. Suddhiprakarn, I. Kheoruenromne, M. Smirk and R.J. Gilkes. 2007. The geochemistry of Thai paddy soils in Thailand. Geoderma 144: 310-324.

Rahman, M.A., M.M. Rahman, S.M. Reichman, R.P. Lim and R. Naidu. 2014. Heavy metals in Australian grown and imported rice and vegetables on sale in Australia: Health hazard. Ecotoxicol. Environ. Safety 100: 53-60.

Rayment, G.E. and D.J. Lyons. 2011. Soil Chemical Methods-Australasia. CSIRO Publishing, Melbourne.

Singjanusong, P. 2007. The Selenium Distribution in Lowland Soils of Sakon Nakhon Basin. Ph.D. Thesis, Kasetsart University, Thailand.

StatSoft, Inc. 2003. Statistica (Data Analysis Software System), Version 6. StatSoft Pacific Pty Ltd, Melbourne, Australia.

US EPA. 2002. Supplemental guidance for developing soil screening levels for superfund sites. Office of Solid Waste and Emergency Response, Washington, D.C. Source: http://www.epa.gov/superfund/health/conmedia/soil/index.htm

Wong, S.C., X.D. Li, G. Zhang, S.H. Qi and Y.S. Min. 2002. Heavy metals in agriculture soils of the Pearl River Delta, South China. Environmental Pollution, 119: 33-44.

Ward, D.E. and D. Bunnag. 1964. Stratigraphy of the Mesozoic Khorat Group in Northeastern Thailand. Report of Investigation Vol. 6. Department of Mineral Resources, Bangkok.

Yusiharni, E. and R.J. Gilkes. 2012.Minerals in the ash of Australian native plants. Geoderma 189-190: 369-380.

Zarcinas, B.A., Pongsakul, P., McLaughlin, M.J. and Cozens, G. 2004. Heavy metals in soils and crops in South East Asia. 2. Thailand. Environ. Geochem. Health 26: 359-71.

Zhao, K., W. Zhang, L. Zhou, X. Liu, J. Xu and P. Huang. 2009. Modeling transfer of heavy metals in soil-rice system and their risk assessment in paddy fields. Environmental Earth Sciences 59: 519-527.

Manuscript received 28 March 2016, accepted 15 June 2016