Soil Fertility Status and

Factors Controlling Rainfed Rice Yield

in Northeast Thailand

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Apuntree Prueksapong

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1.1 Study background

1.1.1 Soil properties status of rice production

Thailand has long been ranked as the sixth-largest rice producer and the largest rice exporter in the world (FAO, 2019). But rice yield is low at around 3.1 t ha^{-1} compared to the yields of other major rice-producing countries such as China (6.9 t ha^{-1}), India (3.8 t ha^{-1}), Myanmar (3.8 t ha^{-1}), and Vietnam (5.5 t ha^{-1}) (Suwanmontri *et al*., 2021).

In Thai rice production, rainfed lowlands are the major rice ecosystem, occupying more than 80% of the total rice area. The northeast region is the country's largest rice cultivation area, covering approximately 61.5% of the rainfed ecosystem (OAE, 2018). Although rainfed lowland rice has low yield characteristics, it has so far been reported that the rainfed rice production in the northeast region is unstable with low yield, and the area has become one of the most significant yield gap areas in the world (Fischer *et al*., 2014).

The soil resources of the region are characterized as typical tropical sandy soil in which minor changes of soil properties can bring the significant differences in soil behavior. Therefore, it is essential that soil properties be explored. Apart from analyzing soil sample properties data, current information on soil orders, land use, and landform classification was used to elucidate soil property data. The soil-forming evidence diagnostic criterion for soil order taxonomy can be used to predict specific soil properties, such as pH (Lee *et al.*, 2003; Mayes *et al.*, 2012); organic matter (OM) content (Sakbaeva *et al.*, 2012); total phosphorus content (Linquist *et al.*, 2011); and available K (AK) levels (Darunsontaya *et al.*, 2012). Land use types and human-induced and soil management factors affect soil chemical properties (Hulugalle *et al.*, 1997), as reported for pH, OM, and available phosphorus (AP) in Tokat Province, Turkey (Kilic *et al.*, 2012). Landforms, various physical features of the land surface, affect soil properties such as pH, OM, AK, and total phosphorus in Shaanxi Province, China (Xiao-rong *et al.*, 2009), pH and OM in Nebraska (Brubaker *et al.*,1993).

Northeast Thailand is dominated by an undulating topography on which fields have been traditionally used for rice cultivation (Suebpongsang *et al.,* 2020; Hammecker *et al.,* 2012) with unavoidable effects of topography (Tsubo *et al*., 2006) on soil properties and hydrological conditions (Arunrat *et al.,* 2017; Boling *et al.,* 2008). The effects of even a few meters difference in topographical position on rice grain yield are evident (Homma *et al*. 2004; Haefele *et al*., 2006).

1.1.2 Importance of topography as a yield-controlling factor

Jasmine rice (KDML 105), accounting for 30% of Thailand's total rice exports, is predominantly produced in the northeast region. The rice yield in this region is only 1.8 to 2.5 t ha^{-1} (Naklang *et al*., 2010) because of many constraints in the region, including low soil fertility, i.e., strong acidity, low nutrient levels, and low water holding capacity, as well as unpredictable weather conditions. Surin Province is a major rice production area in northeast Thailand, with 62.5% of the land being devoted to rainfed production of mainly Thai jasmine rice (*Hom Mali*).

The sandy soil with gently undulating topography in northeast Thailand has variable water availability and soil fertility at different topographical positions. It is generally known that the water availability and soil fertility decreases toward the top of a toposequence (Tsubo *et al.*, 2006; Inthavong *et al*., 2011; Boling *et al*., 2008; Fukai *et al*., 1998; Suzuki *et al*., 2003; Homma *et al*., 2007; Boling *et al*., 2008; Haefele and Konboon, 2009). Hence, soil moisture conditions in rainfed paddy soil comprises one of the most serious constraints on rice production in northeast Thailand. Variations in soil moisture are caused by erratic rainfall combined with topographical position. Specifically, topographical location influences the movement of water into or out of the soil profile (infiltration and leaching), which in turn affects the morphological and physicochemical characteristics of the soil. Though water availability in the field varies with topographical positions and the rice production seems to be strongly influenced by them (Homma *et al*. 2004), the soils supporting rice production in northeast Thailand are scarcely ever reported in terms of the topographical positions.

The influence of topographical position on water and low soil nutrient status is considered to cause rice grain yield variation; yields apparently increase from the top to the bottom topographical positions (Fukai *et al*., 1998; Homma, 2002; Suzuki *et al*., 2003; Tsubo *et al*., 2006; Homma *et al*., 2007; Boling *et al*., 2008; Haefele and Konboon, 2009; Boling *et al*., 2010). Although numerous soil and water factors at different elevations in the toposequence have been investigated, the most critical factor controlling rice yield has not been identified. However, it is likely related to water stress and/or soil nutrient supply. Recognition of the yield-controlling factors that might be obscured in the toposequence could benefit rice yield by facilitating adjusting management practices to specific topographical positions.

1.2 Study objectives

The objectives of this study were: (1) to explore for the update of northeast Thailand regional soil properties data from collected soil sampling analyses, and evaluate their relationships to the existing soil/land classification data, (2) to determine how differences in the topographical positions influence soil characteristics, and (3) to examine the rainfed rice production constraints on soil properties and topographical position factors. To accomplish this, combinations of landform, land use, and soil order were tested to estimate soil properties, including pH, organic matter (OM) content, available phosphorus (AP), and available potassium (AK) (Chapter 2). To further understand the characteristic variation of paddy soils at different topographical positions, soil profile descriptions and soil physicochemical properties were analyzed within selected plots in farmers' fields in two districts of Surin province (Chapter 3). Then the yield-controlling factors were evaluated based on a rice-growing experiment in the plots (Chapter 4). Based on the findings from Chapters 2-4, Chapter 5 provides a general discussion on yield controlling factors in rainfed rice production in northeast Thailand and concluding remarks.

CHAPTER 2 Using land use, landform, and soil order classifications to determine soil properties in northeast Thailand

2.1 General

Northeast Thailand is the largest and poorest region in the country regarding soil fertility and farmers' income, even though 60.5% of the area is used for agriculture (OAE, 2013). To enhance agricultural production in this region, the Land Development Department of Thailand created regional categorical maps of soil order in 2005 and land use and landform types in 2007 via revised image interpretation, surveys, and field investigations; the regional soil database has also been regularly updated since 1990.

The primary soil orders in northeast Thailand are Ultisols, Alfisols, and Inceptisols, and the major agricultural land use types are paddy fields, cash crop fields, and fruit tree fields. The basic landforms are floodplains, alluvial plains, and peneplains. A large portion of the soil in the region is of poor quality due to its high sand content and salinity. The regional salinization was caused by underlying rock salt, including salt dome, being dissolved and dispersed by groundwater (Satarugsa *et al*., 2005, Sarntima *et al*., 2019).

The three types of soil/land classifications (soil order, land use, and landforms) can provide information on soil properties. For example, soil order includes soil-forming evidence diagnostic criterion, land use types include human-induced and soil management factors, and landforms include various physical features of the land surface. Identifying soil properties from these classifications can assist policymakers and farmers, especially in areas lacking soil laboratory data. A more robust understanding of soil properties via categorical classifications data can improve sustainable agriculture, soil management, soil fertility, and crop yields.

Soil properties are known to differ between soil orders (Lee *et al*., 2003; Linquist *et al*., 2011), land use types (Liu *et al*., 2007; Wang *et al*., 2009; Zhang *et al*., 2012), and landforms (Liu *et al*., 2007; Wang *et al*., 2009; Xiao-rong *et al*., 2009). The soil classification system of the United States Department of Agriculture (USDA), often referred to as Soil Taxonomy (Soil Survey Staff, 2014), is based on soil horizon diagnostic characteristics in specific pedogenic environments; therefore, the Soil Taxonomy can be used to predict specific soil properties, such as pH. For example, soil pH is usually the highest in Mollisols, lower in Alfisols, and even lower in Ultisols (Lee *et al*., 2003; Mayes *et al*., 2012); organic matter content (OM) is higher in Mollisols than

Inceptisols (Sakbaeva *et al*., 2012); total phosphorus content is higher in Mollisols than in Entisols and Alfisols (Linquist *et al*., 2011); and available K (AK) levels are higher in Oxisols than in Ultisols (Darunsontaya *et al*., 2012).

Land use types also affect soil chemical properties (Hulugalle *et al*., 1997). For example, the soil under long-term cultivation had lower OM and available phosphorus (AP) and higher soil pH than soil under short-term cultivation in Tokat Province, Turkey (Kilic *et al*., 2012). Landforms affect soil properties through their influence on soil moisture conditions, erosion, and sediment redistribution (Xiao-rong *et al*., 2009). AP levels were higher in lower elevation areas due to the erosion and accumulation of fine particles (De Gryze *et al*., 2008). Moreover, Brubaker *et al*. (1993) found higher soil OM and pH levels at lower elevations in Nebraska, USA. Like OM, AK and total phosphorus levels were greater at lower elevations, while pH and AP levels were greater in steeply sloped areas in Shaanxi Province, China (Xiao-rong *et al*., 2009).

Most studies to date have investigated the individual effects of these classification types on soil properties, but few studies have assessed the impacts of all three classification types in a specified region. Therefore, this study broadly classified the regional soils based on soil order, land use, and landform. Soil property information based on all existing classification schemes would benefit regional farmers. Therefore, this study used categorical classification data to estimate soil properties, including pH, organic matter content (OM), available phosphorus (AP), and available potassium (AK) in northeast Thailand.

2.2 Materials and methods

2.2.1 Soil sampling and analysis

This study used secondary data collected from a total of 30,471 soil samples (5.54 km^2 per sample density) at 0–20 cm depth in northeast Thailand in 2006 as part of the Precision Agriculture Project of the Land Development Department of Thailand. The sampling protocol was designed to evenly cover the entire area of the region and covered different soil orders, land use types, and landforms (Fig. 2.1).

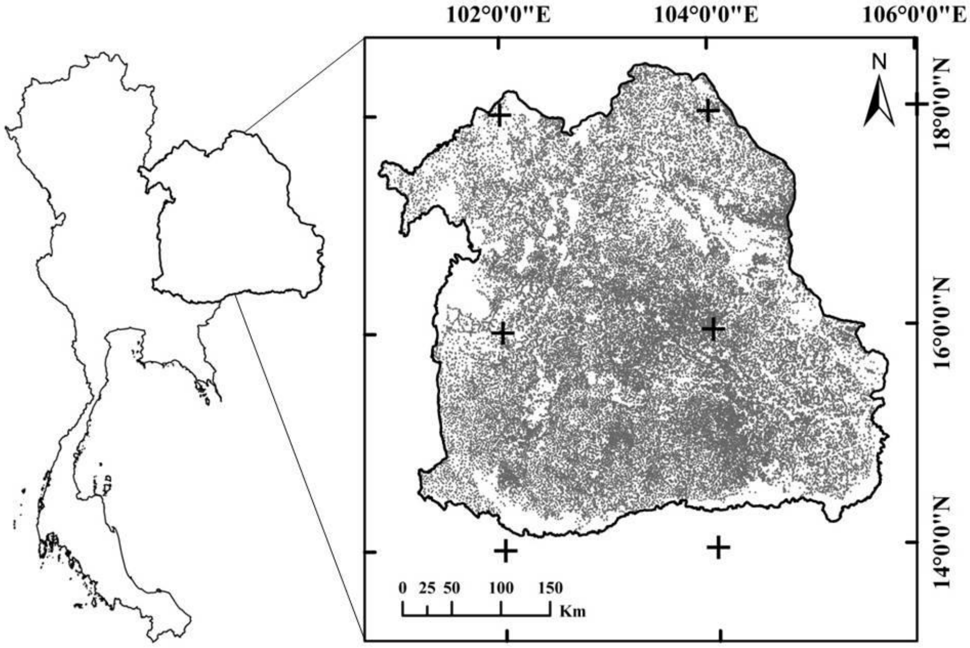

Fig. 2.1 Sampling locations.

Soil samples were air-dried and sieved for particle size classes. Soil pH was measured using a glass electrode with a 1:1 soil:H_2O mixture, and organic matter content (OM) was determined using the wet oxidation method (Walkley and Black, 1947). The AP content was determined using the Bray-II method (Bray and Kurtz, 1945), and the AK content was determined by flame photometry (Model 420 Sherwood Scientific, Cambridge, UK) after extraction with 1 mol L^{-1} ammonium acetate (pH = 7.0).

2.2.2 Categorical classification data

We used the following categorical classification data provided by the Land Development Department of Thailand: (1) the 2005 soil order map with a scale of 1:25,000 based on USDA Soil Taxonomy (Soil Survey Staff, 2014); (2) the 2007 land use map with a scale of 1:25,000, interpreted using LandsatTM at 30-m resolution; and (3) the 2007 landform map derived from a digital elevation model, which was converted from a 1:20,000 scale digital topographic map (10-m contour interval), with image interpretation and field investigations. Information on particle size classes (coarse, medium, fine, and mixed (over 15% gravel content by weight)) was also used in the landform classification because particle size generally depends on the geological context of the soil (i.e., soil texture is related to landform position and the soil parent material). All categorical data of soil order, land use, and landform classification are presented in Table 2.1.

Table 2.1 Categorical classification data.

Soil order	Land use	Landform
1-Alf: Alfisols	1-Paddy: paddy fields	1-FpBs: floodplain basins
2-Ent : Entisols	2-Cash : cash crops fields	2-FpLv : floodplain levees
3-Ept: Inceptisols	3-Peren: perennial crops	3-AluC: coarse particle size, low alluvial plains
4-Oll: Mollisols	4-Orch: orchards	4-AluM: medium particle size, low alluvial plains
5-Ox : Oxisols	5-Past : pastures	5-AluF : fine particle size, low alluvial plains
6-Ult: Ultisols	6-Veg: vegetable fields	6-DnC: coarse particle size, denudation peneplains
7-Ert: Vertisols	7-IntF: integrated farms	7-DnM: medium particle size, denudation peneplains
8-Od: Spodosols		8-DnF: fine particle size, denudation peneplains
		9-DnS: mixed gravels, denudation peneplains
		10-Salt: salinity areas*
		11-Slp: slope areas

* This landform includes the area salinized by underlying rock salt, including the salt dome.

2.2.3 Statistical analyses

The soil property data (pH, OM, AP, and AK) were found to be non-parametric based on the normality testing by the Anderson–Darling method; therefore, Kruskal-Wallis rank tests were applied at a significance level of $P < 0.05$ to identify the differences in soil properties among different soil orders, land use types, and landforms. Linear regression analysis was also applied to explain the soil properties in all categories of each classification data. The criteria used to interpret soil properties were the land classification division and FAO project staff (1973) and soil survey division staff (1993). All statistical analyses were performed using R statistical software (R Development Core Team, 2009).

2.3 Results

2.3.1 Descriptive statistics of soil properties

Generally, the soils in the study region were very strongly acidic (low pH), with moderate AP levels and low OM and AK contents (Table 2.2). The positive skew coefficient of pH was lower than that of OM, AP, and AK. Their high skewness coefficients with long right-tailed distributions suggest that lower values of these parameters were more frequently observed (Table 2.2). The soil properties with high coefficients of variation (CV) were OM, AP, and AK (CV ≥ 35%), while soil pH was moderately variable (CV = 15–34%).

Table 2.2 Descriptive statistics of soil properties.

Soil properties	pH	OM (%)	AP (mg kg^{-1})	AK (mg kg^{-1})
n	30471	30471	30471	30471
Mean	5.25	0.83	12.99	38.39
Median	5.05	0.64	5.12	20.37
Mode	4.90	0.39	2.07	10.45
Maximum	10.10	17.84	970.38	2530.04
Minimum	3.10	0.01	0.14	1.86
Standard deviation	0.84	0.71	32.22	63.01
Coefficients of variation (%)	15.92	85.59	248.04	164.12
Kurtosis	1.84	36.81	197.18	280.13
Skewness	1.29	3.59	11.11	10.89

2.3.2 Differences in soil properties according to each classification

The differences in the soil properties under each classification (soil order, land use, and landform) and the number of observations are shown in Table 2.3. The dominant soil types under landform were 4-AluM (24%), 6-DnC (23%), and 3-AluC (20%); under land use was paddy fields (75%); and under soil order was Ultisols (79%). The results showed that the soil pH, OM, AP, and AK were significantly different between the classifications.

The number of significantly different groups of pH values differentiated by soil order, land use, and landform was 6, 5, and 8, respectively (Table 2.3). The range of median values in each group, which indicates how well the classification differentiated the soil property values, was 2.2 (very strongly acidic to neutral) for soil order, 0.6 (very strongly acidic to strongly acidic) for land use, and 1.0 (very strongly acidic to moderately acidic) for landform.

OM values differed significantly in 5, 5, and 5 groups amount based on soil order, land use, and landform, respectively (Table 2.3). The range of median values in each group was 0.9% (low to moderately low) for soil order, 0.9% (low to moderately low) for land use, and 1.0% (low to moderately low) for landform.

The numbers of significantly different groups of AP values differentiated by soil order, land use, and landform were 4, 4, and 4, respectively (Table 2.3). The range of median values in each group was 5.4 mg kg^{-1} (low) for soil order, 9.8 mg kg^{-1} (low to medium) for land use, and 2.9 mg kg^{-1} (low to medium) for landform.

The numbers of significantly different groups of AK values differentiated by soil order, land use, and landform were 4, 4, and 7, respectively (Table 2.3). The range of median values in each group was 62.9 mg kg^{-1} (very low to medium) for soil order, 53.2 mg kg^{-1} (very low to medium) for land use, and 51.1 mg kg^{-1} (very low to medium) for landform.

Table 2.3 Median (±MAD) of soil property value by single classifications [a].

Level	Soil order				Land use				Landform			
pH												
Neutral (6.6–7.3)	4-Oll	(102)	6.9±0.7	f								
Slightly acid (6.1-6.5)												
Moderately acid (5.6-6.0)	5-Ox	(448)	5.7±1.2	e					8-DnF	(980)	5.8±1.2	h
Strongly acid (5.1-5.5)	2-Ent	(71)	5.5±1.0	de	2-Cash	(5468)	5.5±0.9	e	9-DnS	(2441)	5.3±0.9	g
	7-Ert	(813)	5.4±1.0	d	4-Orch	(383)	5.4±0.9	de	1-FpBs	(1162)	5.2±0.7	fg
	3-Ept	(1125)	5.3±0.9	d	5-Past	(217)	5.2±0.9	cd	2-FpLv	(100)	5.3±0.8	efg
	1-Alf	(4484)	5.1±0.7	c	6-Veg	(160)	5.1±0.7	bcd	7-DnM	(2775)	5.2±0.7	ef
									10-Salt	(640)	5.1±0.7	de
Very strongly acid (4.5-5.0)	6-Ult	(23417)	5.0±0.6	b	7-IntF	(46)	5.0±0.7	abc	6-DnC	(6858)	5.0±0.6	cd
	8-Od	(11)	4.7±0.1	a	3-Peren	(1551)	5.0±0.6	ab	11-Slp	(140)	5.0±0.6	cd
					1-Paddy	(22686)	4.9±0.6	a	5-AluF	(2217)	5.0±0.6	c
									4-AluM	(7189)	4.9±0.6	b
									3-AluC	(5969)	4.8±0.4	a
Significantly different levels				6				5				8
OM (%)												
Moderately low (1.1-1.5)	4-Oll	(102)	1.5±1.2	e	7-IntF	(46)	1.5±0.8	e	8-DnF	(980)	1.5±0.9	e
	5-Ox	(448)	1.2±1.1	d	4-Orch	(383)	1.1±0.9	d	1-FpBs	(1162)	1.1±0.8	d
	7-Ert	(813)	1.1±0.7	c								
Low (0.5-1.0)	3-Ept	(1125)	1.0±0.8	b	6-Veg	(160)	0.8±0.4	c	9-DnS	(2441)	1.0±0.8	d
	8-Od	(11)	0.9±0.6	a	3-Peren	(1551)	0.7±0.5	c	2-FpLv	(100)	1.0±0.8	d
	2-Ent	(71)	0.7±0.5	a	2-Cash	(5468)	0.7±0.5	b	11-Slp	(140)	0.8±0.5	c
	6-Ult	(23417)	0.6±0.4	a	1-Paddy	(22686)	0.6±0.4	a	5-AluF	(2217)	0.8±0.5	c
	1-Alf	(4484)	0.6±0.4	a	5-Past	(217)	0.6±0.4	a	7-DnM	(2775)	0.6±0.5	b
									4-AluM	(7189)	0.6±0.4	b
									10-Salt	(640)	0.6±0.4	a
									3-AluC	(5969)	0.5±0.4	a
									6-DnC	(6858)	0.5±0.3	a
Significantly different levels				5				5				5

[a] Values followed by the same small letter in a column are not significantly different at the 5% level by Kruskal-Wallis. Number of samples is shown in the blankets.

Soil order; 1-Alf: Alfisols, 2-Ent: Entisols, 3-Ept: Inceptisols, 4-Oll: Mollisols, 5-Ox: Oxisols, 6-Ult: Ultisols, 7-Ert: Vertisols, 8-Od: Spodosols, Land use; 1-Paddy: paddy, 2-Cash: cash crop, 3-Peren: perennial crop, 4-Orch: orchard, 5-Past: pasture, 6-Veg: vegetable, 7-IntF: Integrated Farm, Landform; 1-FpBs: Floodplain Basin, 2-FpLv: Floodplain Levee, 3-AluC: Alluvial plain-Coarse particle size, 4-AluM: Alluvial plain-Medium particle size, 5-AluF: Alluvial plain-Fine particle size, 6-DnC: Peneplain-Coarse particle size, 7-DnM: Peneplain-Medium particle size, 8-DnF: Peneplain-Fine particle size, 9-DnS: Peneplain-Mixed particle size, 10-Salt: Saline areas, and 11-Slp: Slope area

Table 2.3 (continued).

Level	Classification type											
	Soil order				Land use				Landform			
AP (mg kg^{-1})												
Medium (11-15)					6-Veg	(160)	14.5±16.3	d				
Low (3-10)	4-Oll	(102)	10.4±11.8	d	7-IntF	(46)	8.2±8.9	c	8-DnF	(980)	8.0±8.9	d
	2-Ent	(71)	9.2±10.2	cd	4-Orch	(383)	7.1±4.7	c	2-FpLv	(100)	7.9±8.7	d
	5-Ox	(448)	8.8±8.9	cd	2-Cash	(5468)	7.0±7.4	c	5-AluF	(2217)	6.3±5.9	c
	7-Ert	(813)	6.1±6.0	bc	5-Past	(217)	6.6±6.8	c	6-DnC	(6858)	6.1±6.0	c
	1-Alf	(4484)	6.0±6.0	b	1-Paddy	(22686)	5.1±4.4	b	10-Salt	(640)	6.0±5.8	bc
	3-Ept	(1125)	5.9±5.8	b	3-Peren	(1551)	4.7±4.0	a	1-FpBs	(1162)	5.7±5.5	bc
	6-Ult	(23417)	5.2±4.4	a					7-DnM	(2775)	5.6±5.3	bc
	8-Od	(11)	5.0±4.4	a					9-DnS	(2441)	5.2±4.7	b
									11-Slp	(140)	5.1±4.4	ab
									4-AluM	(7189)	5.0±4.4	a
									3-AluC	(5969)	5.0±4.4	a
Significantly different levels				4				4				4
AK (mg kg^{-1})												
Medium (61-90)	4-Oll	(102)	81.0±76.4	d	7-IntF	(46)	70.3±44.5	d	8-DnF	(980)	63.5±54.1	g
Low (30-60)	5-Ox	(448)	55.5±52.6	c	4-Orch	(383)	40.8±44.5	d	1-FpBs	(1162)	52.0±49.0	f
	7-Ert	(813)	54.7±53.4	c	2-Cash	(5468)	32.4±26.7	c	9-DnS	(2441)	40.6±35.5	e
	3-Ept	(1125)	44.6±43.0	b	5-Past	(217)	30.7±29.7	bc	2-FpLv	(100)	39.5±39.3	e
	2-Ent	(71)	36.5±38.5	b					11-Slp	(140)	36.2±37.1	e
Very low (<30)	1-Alf	(4484)	20.2±20.8	a	6-Veg	(160)	29.5±33.4	bc	5-AluF	(2217)	27.3±25.2	d
	6-Ult	(23417)	19.4±16.3	a	3-Peren	(1551)	26.6±22.2	b	7-DnM	(2775)	26.1±20.8	d
	8-Od	(11)	18.1±22.2	a	1-Paddy	(22686)	17.1±16.3	a	10-Salt	(640)	19.7±16.3	c
									6-DnC	(6858)	18.5±15.8	c
									4-AluM	(7189)	17.3±13.3	b
									3-AluC	(5969)	12.4±10.4	a
Significantly different levels				4				4				7

[a] Values followed by the same small letter in a column are not significantly different at the 5% level by Kruskal-Wallis. Number of samples is shown in the blankets.

Soil order; 1-Alf: Alfisols, 2-Ent: Entisols, 3-Ept: Inceptisols, 4-Oll: Mollisols, 5-Ox: Oxisols, 6-Ult: Ultisols, 7-Ert: Vertisols, 8-Od: Spodosols, Land use; 1-Paddy: paddy, 2-Cash: cash crop, 3-Peren: perennial crop, 4-Orch: orchard, 5-Past: pasture, 6-Veg: vegetable, 7-IntF: Integrated Farm, Landform; 1-FpBs: Floodplain Basin, 2-FpLv: Floodplain Levee, 3-AluC: Alluvial plain-Coarse particle size, 4-AluM: Alluvial plain-Medium particle size, 5-AluF: Alluvial plain-Fine particle size, 6-DnC: Peneplain-Coarse particle size, 7-DnM: Peneplain-Medium particle size, 8-DnF: Peneplain-Fine particle size, 9-DnS: Peneplain-Mixed particle size, 10-Salt: Saline areas, and 11-Slp: Slope are

2.3.3 Regression analysis for estimating soil properties

The simple linear regression models inferring the estimation of soil properties by each classification type were all significant (Table 2.4). The pH regression models in the order of highest to lowest coefficients of determination (R^2) and smallest to largest root mean square errors (RMSE) were landform, land use, and soil order; for OM were landform, soil order, and land use; for AP were land use, landform, and soil order; and for AK were landform, soil order, and land use (Table 2.4).

Table 2.4 Validation data of single regression model for soil property prediction.

Model	Regression coefficients			
	R^2	RMSE	AIC	Intercept
pH				
Soil order	0.04	0.82	74270	5.39****
Land use	0.05	0.82	74009	5.15****
Landform	0.07	0.81	73467	5.52****
OM				
Land use	0.01	0.71	65528	0.79****
Soil order	0.04	0.70	64704	0.83****
Landform	0.10	0.68	62618	1.28****
AP				
Soil order	0.01	32.05	297787	16.59****
Landform	0.02	32.00	297652	15.14****
Land use	0.02	32.00	297607	11.18****
AK				
Land use	0.03	61.95	337947	32.15****
Soil order	0.05	61.55	337558	44.64****
Landform	0.07	60.67	336682	75.88****

Significance codes:* P< 0.05,** P< 0.01,*** P< 0.001,**** P< 0.0001.
RMSE: Root means square error, R^2: Adjusted coefficient of determination, AIC: Akaikes' information criterion.

The partial regression coefficients of the different classification categories and their significance levels are listed in Table 2.5. The coarse and medium particle landform categories were negatively correlated with OM and AK. They were not correlated with AP and pH, except for 6-DnC and 7-DnM, which were positively correlated with pH. All land use categories were positively correlated with pH, except for 3-Peren and 7-IntF, which showed no significant correlation. Land use categories negatively correlated with OM and AP, and 1-Paddy negatively correlated with AK. The absolute values of land use and landform categories correlated with pH and OM were similar but showed a lower correlation than AP and AK. This study observed positive coefficients between the soil order categories and soil properties. The coefficients of the soil order categories showed the highest absolute values of all the classifications, but fewer soil order categories were correlated with OM and AP (Table 2.5).

2.4 Discussion

2.4.1 Characteristics of soil properties by descriptive statistics

The values of all analyzed soil properties (pH, OM, AP, and AK) showed positively skewed distributions, which is similar to previous results in Asian tropical soils (Kawaguchi and Kyuma, 1974), USA regional soils (Brejda *et al.*, 2000), and Swiss midland fields (Hausherr Lüder *et al.*, 2018). This distribution is likely caused by the degree of leaching and runoff between the various landforms and land use types. The lower skewness coefficient of soil pH may be due to its measurement on the logarithmic scale.

The high skewness of the soil property values indicates the gather of high-value areas and scatter of low-value areas, which causes the mean parameter values to be higher than the median (Grego *et al.*, 2006). These localized high values are not necessarily outliers but could be caused by natural variations—such as the depositional environment of pedogenic or hydrologic processes (Young *et al.*, 1999)—or management-induced variations (Vasu *et al.*, 2017).

Soil pH showed moderate variability, while OM, AP, and AK showed high variability, which agrees with the findings of previous studies (Hedia and Elkawy, 2016; Yan *et al*., 2019). Low soil pH is predominantly caused by the severe weathering and leaching of sand-textured acidic parent materials. The wide range of soil property values observed in this study may be due to the dominant sandy and high-salinity characteristics of the soil in this region (Hedia and Elkawy, 2016).

The soil pH was higher in saline areas than in low alluvial terrace landforms (3-AluC, 4-AluM, and 5-AluF) due to resilication, which increases the soil pH for silica dissolution under highly saline and poorly drained soil conditions (Buol *et al*., 2011). In agreement with this study, previous research in the region identified the soil to be strongly acidic (Haefele *et al*., 2006; Haefele and Konboon, 2009), low in OM (Kawaguchi and Kyuma, 1976; Prueksapong *et al*., 2017), low in AP (Kawaguchi, 1966; Kheoruenromne *et al*., 1998), and low in AK (Kawaguchi, 1966; Haefele *et al*., 2006; Haefele and Konboon, 2009). These reports highlight the prolonged chemical degradation in the study region (Fukui, 1996; Noble *et al*., 2004; Lorsirirat and Maita, 2006).

Table 2.5 Partial regression coefficient of linear regression model for soil property prediction.

Model	Regression coefficients							
	pH		OM		AP		AK	
Landform								
1-FpBs	0.020	****	0.021	****	0.367	*	1.200	***
2-FpLv	0.016	**	0.038	****	1.311	****	-	
3-AluC	-		-0.009	**	-		-1.557	****
4-AluM	-		-		-		-1.045	***
5-AluF	0.008	*	0.007	**	0.404	**	-	
6-DnC	0.006	*	-0.012	****	-		-1.095	****
7-DnM	0.010	***	-0.005	*	-		-0.827	***
8-DnF	0.028	****	0.031	****	0.910	****	1.141	****
9-DnS	0.015	****	0.015	****	0.320	**	-	
10-Salt	0.013	****	-0.009	***	0.291	**	-0.828	***
11-Slp	-		-		-		-	
Land use								
1-Paddy	0.010	**	-0.018	****	-0.936	****	-0.706	*
2-Cash	0.023	****	-0.015	****	-0.635	****	-	
3-Peren	-		-0.012	***	-0.925	****	-	
4-Orch	0.015	***	-		-0.680	****	0.576	*
5-Past	0.017	****	-0.017	****	-0.357	*	0.716	**
6-Veg	0.016	****	-0.012	***	-		-	
7-IntF	-		-		-		-	
Soil order								
1-Alf	-		-		-		-	
2-Ent	0.323	**	-		-		22.761	**
3-Ept	0.178	**	-		-		-	
4-Oll	0.357	****	0.101	*	5.393	**	20.691	****
5-Ox	0.098	**	-		-		-	
6-Ult	-		-		-		-	
7-Ert	0.090	***	-		-		5.462	**
8-Od	-		-		-		-	

Significance codes: * P< 0.05,** P< 0.01,*** P< 0.001,**** P< 0.0001.

2.4.2 Differences in soil properties according to each classification

We compared the numbers of significantly different levels of each soil property grouped by each classification system (soil order, land use type, and landform). The soil property levels distinguished by the soil order, land use, and landform classifications were higher for pH (5–8) than for OM (5), AP (4), and AK (4–7) (Table 2.3). Therefore, the single classification systems estimated pH most effectively. Among the single classification types, landform was the strongest at explaining the variability in the measured soil properties. The landform classification model showed the highest R^2 for pH, OM, and AK, as well as the second-highest R^2 for AP (Table 2.4). The landform is highly influenced by severely depleted material, as the soils in tropical climates (high temperature and precipitation) are predominantly derived from weathered sandstones containing high sand and sodium content and low OM content (Kawaguchi, 1966). The landform regulates drainage characteristics, including relief, the parent material, and morphostratigraphy (Zinck, 2013), which in turn affects the measured soil properties.

The higher soil pH in the peneplains compared with the alluvial plains highlights the influence of landforms on soil pH (Table 2.3). Similar to a previous study in Shaanxi Province, China (Hao *et al*., 2014), the soil pH of higher landforms was greater than that of the lower landforms. The soil pH in peneplains and alluvial plains comprising fine particles was higher than those comprising medium and coarse particles (Table 2.3). This indicates the occurrence of acidification under high precipitation, which leaches more base cations from coarse-textured than fine-textured soils.

The OM content in landforms of different particle sizes revealed that under the present regional climatic conditions and unique soil parent material, OM content was regulated by particle size rather than topographical elevation (except for floodplain landforms). The highest OM contents were observed in landforms comprising fine particles (8-DnF, 5-AluF), followed by medium-sized particles (7-DnM, 4-AluM), and then coarse particles (6-DnC, 3-AluC) (Table 2.3). This is because high surface activities prevent the decomposition of OM (Hassink *et al*., 1993). A higher OM content in peneplain landforms (8-DnF) compared with that of the lowest-elevation landforms and floodplains (1-FpBs, 2-FpLv) (Table 2.3) is likely due to severe erosion and the high salinity of the regional patch areas. Accordingly, the lowest OM content was also observed in high-salinity areas because exchangeable sodium disperses soil aggregates and accelerates OM loss (Islam *et al*., 2014).

The highest AP content was observed in the landform composed of the finest particles (8-DnF) due to the larger particle surface area for phosphorus absorption (De Gryze *et al*., 2008) and the minimum fixation at $pH > 5.5$ (Table 2.3). The lowest AP content in alluvial plains composed of coarser particles (4-AluM, 3-AluC) may be due to phosphorus loss from severe erosion (Changnoi, 2014) and downward leaching. The AP content level is likely related to the imbalance between input and output factors and the conserved capability of each landform.

The AK content in landforms of different particle sizes inferred that both topographical elevation and particle size regulated AK content. Higher AK contents occurred on both peneplains and alluvial plains comprised of fine particles (8-DnF, 5-AluF), followed by medium-sized particles (7-DnM, 4-AluM), and then coarse particles (6-DnC, 3-AluC). The AK content was higher in peneplains than alluvial plains in all particle sizes (Table 2.3). Potassium is readily adsorbed on the exchangeable sites of fine particle surfaces (Wang *et al.*, 2009; Ngwe *et al.*, 2012). A higher AK content in floodplains (1-FpBs, 2-FpLv) than in alluvial plains (3-AluC, 4-AluM) may be due to the higher wetting and drying cycle rate, which lowers K fixation (Hashemi and Abbaslou, 2016). The lower AK content in alluvial plain soils may be due to the lower soil OM content and potassium adsorption sites (Wang and Huang, 2001). In agreement, Ngwe *et al.* (2012) reported a positive correlation between AK and OM content.

Land use types can also distinguish the soil levels of pH, OM, AP, and AK; however, the diverse number of land use practices may limit its ability to infer soil characteristics. Moreover, as this study employed land use data from 2007, different land use practices before this date may have also affected the current soil properties. Many studies have reported the impacts of varying land use types on soil pH (Abbasi *et al.*, 2007; Khormali and Shamsi, 2014; Fayissa *et al.*, 2015), while other studies (Moges *et al.*, 2013; Rokunuzzaman *et al.*, 2016) have reported no significant soil pH difference between land use types. In this study, the soils of cash crop and orchard sites were strongly acidic, with pH values significantly higher than those of other land use types (Table 2.3). This result was similar to that of Kiflu and Beyene (2013), who found higher soil pH values in maize crop fields and banana orchards than the grassland soil. The significantly lower pH values may be attributed to the long-term application of nitrogenous fertilizers, which accelerate soil acidification, especially when ammonium fertilizers are applied to vast paddy fields. The higher pH values of orchard soils may be attributed to the lower use of nitrogen fertilizers and the higher application of organic fertilizers than other land use types. Regular liming practices by slash-and-burn ash deposition and the application of lime materials on cash crop fields may also contribute to the higher pH values (Juo *et al.*, 2003).

OM variations between different land use types have been previously reported (Liu *et al.*, 2015). In this study, soil OM increased from paddy fields to vegetable fields and orchards (Table 2.3). This may be related to the influence of different management practices on OM content, such as plowing in paddy fields, crop residues and mulching in vegetable fields, compost application, and the return of leaf litter in orchards.

This study found that land use classification could differentiate soils with different AP levels, with decreasing AP content in the order of intensive agriculture (vegetable fields) > moderate-intensive agriculture (cash crops, integrated farms, orchards, and pastures) > low-intensity agriculture (paddies and perennial crops) (Table 2.3). In agreement, Kong *et al*. (2006) found a positive correlation between AP content and land use intensification. Another study found the highest AP content in vegetable fields and the lowest in perennial crop fields in the Yanhuai Basin, China (Zhang *et al*., 2012), likely due to the high application rates of phosphatic fertilizers and manure. In this study, AP only showed moderate levels in vegetable crop fields, whereas low AP levels were observed in all other land use types. This suggests that soil management has intensified in all investigated land use types. Land use classification was the most robust method for differentiating AP because it statistically identified more pairs of land use types with significant differences; however, the number of significantly different levels under land use was equal to that of soil order and landform. In addition, the land use classification could better identify the highest and lowest AP contents in 6-Veg and 3-Peren, respectively.

Land use is the primary cause of AK variations (Akbas *et al*., 2017) due to the different management practices (Mallarino, 1996). This study observed higher AK values in areas of intensive agricultural practices (Roger *et al*., 2014), which is similar to the spatial trend of AP. The higher AK content in orchards than in pastures was supported by Jalali and Khanlari (2013). The higher AK content in cash crops than in perennial crops was also supported by Uzoho and Ekeh (2014). The lower AK content compared with AP content in vegetable fields infers lower K fertilizer application based on the crop requirements (Table 2.3).

Soil order classification typically considers the soil characteristics of the topsoil and the deeper soil profile layers. However, this study observed the widest median range for pH and AK under the soil order classification (Table 2.3), suggesting that soil order is useful for explaining topsoil properties (Kovačević *et al*., 2010). As the soil order classification considers soil pH (Sakbaeva *et al*., 2012), a higher soil pH was estimated for Mollisols and Alfisols, with base saturations of > 50% and > 35%, respectively. In contrast, a lower pH was estimated for Ultisols with base saturations of < 35% (Table 2.3). Entisols in northeast Thailand are mostly classified as the Psamments suborder (Vijarnsorn and Eswaran, 2002), particularly the Quartzipsamments great group (Kheoruenromne *et al*., 1998). Therefore, the low degree of leaching of base cations from younger (less weathered) soil and successive liming may increase the pH in Entisols. Younger soils with higher pH were also reported in previous studies; for example, the pH of Entisols was higher than that of Ultisols and Alfisols in Florida, USA (Lee *et al*., 2003), and the pH of Inceptisols was higher than that of Alfisols in Kyrgyzstan (Sakbaeva *et al*., 2012). The low pH in Spodosols is related to their intense leaching, which increases the acidity of the spodic horizon and the eluviation of aluminum and iron oxides. Although this study only identified six significant levels under the soil order classification, which was lower than the number under the landform classification, soil order could identify both levels, with the highest and the lowest values corresponding to 4-Oll and 8-Od, respectively.

The highest OM content in Mollisols (Table 2.3) is likely related to Ca-associated organic matter accumulation, which is the principal process of Mollisol formation (Aydinalp, 2003; Sakbaeva *et al*., 2012). Vertisols, which also showed relatively high OM values (Table 2.3), are usually clay-rich, facilitating OM accumulation. In Oxisols, the presence of iron and aluminum oxides contributes to increased OM accumulation (Chimchart *et al*., 2013). Among the tropical lowland soils, Spodosols typically have low OM (Tan *et al*., 1970). In northeast Thailand, the Spodosols, usually defined as Oxyaquic Haplorthods, are naturally infertile soils with low water-holding capacities due to the high portion of sandy material in their upper horizons; this reduces biomass and minimizes the return of lost soil OM, which limits the soil's ability to associate with OM. The low OM in Alfisols and Ultisols generally reflects their lower topsoil clay content (Beery and Wilding, 1971).

The estimated AP content based on soil order classification reflects the degree of leaching and clay content of the soil. The higher soil AP in Mollisols than in Vertisols, Entisols, and Alfisols (Table 2.3) was in accordance with previous soil observations in Sacramento Valley, USA (Linquist *et al*., 2011). Mollisols have high base saturations and have high amounts of Ca-fixed P due to their high Ca content (Sharpley and Buol, 1987). The higher AP content in Oxisols than in Alfisols is due to the higher clay content of the former, which adsorbs more P. MacDonald *et al.* (2012) reported that the phosphorus content of different soil orders is more closely linked to their clay content rather than their weathering stage. The lowest AP content in Spodosols may be due to their low clay content and stronger P binding with Al and Fe oxides under more acidic conditions (Sollins *et al.*, 1996).

Based on the soil order classification, the estimated AK content reflects the degree of leaching and cation exchange capacity (CEC) in soils, supported by the high AK content, pH, and OM in Mollisols (Table 2.3). In northeast Thailand, the higher AK content in Oxisols than in Ultisols was associated with the higher clay content of the former, which usually has a sandy topsoil texture (Darunsontaya *et al.*, 2012). The high clay and OM content associated with the high CEC in Vertisols causes an increase in AK content. The AK content of the soil was positively correlated with clay content, OM, and CEC (Nursyamsi *et al*., 2008; Ngwe *et al*., 2012). The higher AK content in Vertisols than Inceptisols and the lower AK content in Alfisols and Ultisols were similar to soil observations from the central plain and northeast regions of Thailand (Ngwe *et al*., 2012). The lowest AK content in Spodosols was due to their low pH and low CEC, which was influenced by the lowest OM content among all the examined soil orders.

2.4.3 Soil property estimation by regression analysis

The effectiveness of each classification category to explain soil pH occurred in the order of landform > land use > soil order (Table 2.4). Salako *et al*. (2007) also found higher pH values in upland silty soils than in lowland sandy soils. However, upland silty soils typically have lower acidity than lowland sandy soils (Obalum and Chibuike, 2017). Soil texture deviated by slope position, and landscape elevation contributed to soil pH (Salako *et al*., 2006). Other studies have reported that a decrease in pH is related to erosion-induced landforms (Schindelbeck *et al*., 2008), especially in soils with high sand content. Additionally, the weathering and leaching conditions of induced landforms are accelerated by the tropical monsoon climate of northeast Thailand. Soil pH in northwestern China was also found to be influenced by landform, soil type, and land use, as well as their interactions (Hao *et al*., 2014). Only the interaction between landform and soil type was significantly different in the soil pH values.

The effectiveness of each classification category to explain OM content occurred in the order of landform > soil order > land use (Table 2.4). Previous studies have shown that landform, soil order, and land use significantly influence OM content (Rezaei and Gilkes 2005; Lehtinen *et al*., 2014; Baskan *et al*., 2016). OM distribution has been linked to the accumulation of fine soil particles, deposition from higher elevation landforms, and surface erosion (Funakawa *et al*., 2006). Higher OM content in upland silty soils than in lowland sandy soils was also reported by Salako *et al*. (2007). These studies support the finding that negative partial regression coefficients are related to landforms comprising coarse and medium particles. Many studies have identified land use to have a more significant impact on OM content than landforms (Tsui *et al*., 2004; Guo *et al*., 2011). However, landforms also influence land use type (Liu *et al*., 2007), particularly in dry tropical areas where land use is more diverse over denudation landforms than over fluvial landforms (Métay *et al*., 2017); this was also identified in northeast Thailand.

The effectiveness of each classification category to explain AP content occurred in the order of land use > landform > soil order (Table 2.4). A previous study also reported the significant impacts of land use type and topography on AP content (Zhang *et al*., 2011). Kim *et al*. (2006) found that AP was influenced more by land use than soil texture and soil parent materials. The partial regression coefficients in this study inferred a negative relationship between AP and land use but a positive relationship with landform. A lower AP content is related to higher P loss from erosion and runoff induced by specific landforms and the lower content of sand-sized particles on the soil surface (White and Hammond, 2006).

The effectiveness of each classification category to explain AK content occurred in the order of landform > soil order > land use (Table 2.4). In the soils of northeast Thailand, higher AK content was associated with higher clay content (Darunsontaya *et al*., 2012; Akbas *et al*., 2017), as well as its parent material and degree of weathering (Bertsch and Thomas, 1985). In addition, soil AK is adsorbed by the negative charges of OM and clay particles (Sharpley and Buol, 1987; Salako *et al*., 2006; Nursyamsi *et al*., 2008; Ngwe *et al*., 2012). This was evident from the higher AK content in upland sandy soils compared with lowland soils (Uzoho *et al*., 2016). This study observed negative partial regression coefficients between AK and landforms comprising coarse and medium particles, as well as paddy fields (land use) (Table 2.5). Therefore, the occurrence of K forms is associated with landforms and soil fractions—depending on the weathering processes—while land use also plays a significant role (Sharma *et al*., 2006).

This study found that landform, land use, and soil order classifications could significantly explain the variability of soil properties; however, the R^2 was as low as 10% (Table 2.4). These low coefficients may be partly attributed to the inconsistent estimation scales for soil properties and the auxiliary classification information. The soil sampling spatial resolution was finer than that of the auxiliary information; therefore, mapping the auxiliary information at a finer scale would enable a more accurate evaluation of soil properties. The application of more advanced prediction models, such as artificial intelligence, can also address the scale mismatch (Reichstein *et al*., 2019; Tao *et al*., 2020), but it is beyond the scope of the current research. In addition, more systematic, direct, and rapid methods for soil analysis in farming fields can significantly improve crop management in the region.

2.5 Conclusions

This study conducted a multiple comparison analysis to identify the significant differences in topsoil pH, OM, AP, and AK values in northeast Thailand determined by soil order, land use, and landform classifications. Based on a nonparametric multiple range test and regression analysis, landforms of different particle sizes were the strongest classification type explaining the variability in the measured soil properties (pH, OM, and AK), except for AP, which was most significantly explained by land use. These results suggest that the soil properties in northeast Thailand are predominantly affected by landform-induced leaching and erosion-deposition processes. However, despite the significant correlations, this study identified low regression coefficients between the classification categories and soil properties. Therefore, three alternative means for improvement recommendation are: (1) modify the scale of auxiliary information, (2) develop stronger prediction models at the optimal study scale, and (3) provide soil analytical services for farming fields.

The result of this study identified the soil to be strongly acidic (Haefele *et al.*, 2006; Haefele and Konboon, 2009), low in OM (Kawaguchi and Kyuma, 1976; Prueksapong *et al.*, 2017), low in AP (Kawaguchi, 1966; Kheoruenromne *et al.*, 1998), and low in AK (Kawaguchi, 1966; Haefele *et al.*, 2006; Haefele and Konboon, 2009). These reports highlight the prolonged chemical degradation in the study region (Fukui, 1996; Noble *et al.*, 2004; Lorsirirat and Maita, 2006), indicating that the land has long been utilized with inadequate soil conservation. The reasons explained, firstly; the crucial benefits of the rainfed lowland rice system on growing rice in submerged soils have a great ameliorative effect on chemical fertility: largely by bringing pH in the neutral range, resulting in better availability of plant nutrients and accumulation of organic matter soil fertility and prolong of productivity maintenance (Sahrawat, 2005). Secondly, the main factor in agriculture production in the region is the rainfall resource water availability. Due to climate change, an annual erratic rainfall becomes a limitation for other land use but less limitation for growing season rice crop. The area may have been used only once a year to produce traditional rice crops, mainly for consumption purposes. Since the regional soils are predominantly sandy texture that capably affected by landform-induced leaching and erosion-deposition processes. Nevertheless, the regional rice yields have gradually declined.

CHAPTER 3 Profile description, properties, and classification of paddy soils at different topographical positions in Surin Province, Thailand

3.1 General

The prehistoric evidences of rice cultivation are found in northeast Thailand (White, 1995). Since then, the management of paddy soils has been important for sustainable productivity and food security. The northeast Thailand is dominated by an undulating topography with uplands that rise to a height of 240 m and lowlands at 170 m, where fields have been traditionally used for rice cultivation (Hammecker *et al*., 2012) with unavoidable effects of topography (Tsubo *et al*., 2006) on soil properties and hydrological conditions (Boling *et al*., 2008). The effects of topography, such as position on a slope, are evident even a few meters difference (Homma *et al*., 2004) and can determine whether the acceptable yield is gained or not (Haefele *et al*., 2006).

Surin Province, northeast Thailand, is a major rice production area, with 62.5% of the land being devoted to rainfed production of mainly Thai jasmine (Hom Mali) rice. The rice yield in this region is only 1.8 to 2.5 t ha^{-1} (Naklang *et al*., 2010) because of many constraints, including low soil fertility, i.e., strong acidity, low nutrient levels, and low water holding capacity, as well as unpredictable weather conditions.

Soil moisture conditions in rainfed paddy soil comprise one of the most significant constraints on rice production in northeast Thailand. Variations in soil moisture are caused by erratic rainfall combined with topographical positions. Specifically, topographical location influences the movement of water into or out of the soil profile (infiltration and leaching), which in turn affects the morphological and physicochemical characteristics of the soil. Though water availability in the field varies with topographical positions (Homma *et al*., 2004) and the rice production seems to be strongly affected by them (Homma *et al*., 2004), the soils supporting rice production in northeast Thailand are scarcely reported in terms of the topographical positions.

This study was conducted to present the characteristics of Surin paddy soils at different topographical positions based on the profile description and soil physicochemical properties at two districts in Surin Province. To accomplish this, two sets of soil pedons at high and low topography were evaluated to determine how differences in the topographical positions influence soil characteristics.

3.2 Materials and Methods

3.2.1 Site and profile descriptions

Covering 8,120 km^2, Surin is located at a longitude of 14°20′–15°28′ north and latitude of 103°5′–104°6′ east in the southern part of northeast Thailand. The central and northern parts of the province are undulating flood plains. The climate is tropical Savannah, Aw in Köppen climate classification, with three seasons: winter from October or November to January, summer from February or March to May, and a rainy season from May or June to October. The average annual rainfall and temperature are 1,572 mm and 27.0°C, respectively.

The four investigated pedons are located in typical rainfed paddy fields on undulating landscapes with sandy texture. The Tha Tum (TT) pedons at high (TT-H) and low (TT-L) topography are located 1.5 km apart from each other at N 15°13′26″, E 103°32′40″ and N 15°14′09″, E 103°33′01″, respectively, with an 18-m difference in elevation. TT-H located on the top of a small gentle hill, where rice cultivation was found to be failed. TT-L located at the lowest wide terrace on a lower position of a gentle slope. Chom Phra (CP) pedons at high (CP-H) and low (CP-L) topography are located 1.3 km apart at N 15°09′11″, E 103°38′00″ and N 15°09′03″, E 103°37′16″, respectively, with an 18-m difference in elevation. CP-H located on upper part of a hill beside a secondary dry deciduous dipterocarp forest. CP-L located in a wide lowland area (Fig. 3.1). Rice yield in TT and CP districts in 2011-2013, which was relatively low (1.8 – 2.7 t ha^{-1}), was not significantly different.

The geology of Surin had been described by the Department of Mineral Resources of Thailand (2010). At TT district, soils developed from Quaternary alluvial deposits. Parent materials on high terraces consisted of gravel beds and sands. On lower terraces, parent materials were orangish brown silt-medium sand and clay overlain on gravel beds. At CP district, soils developed from the Khok Kruat Formation in the Cretaceous period. The Khok Kruat Formation is unconformably underlain by the Maha Sarakham Formation in the Khorat Group. Parent materials were sandstone, siltstone, and mudstone moderately sorted with some calcareous cements.

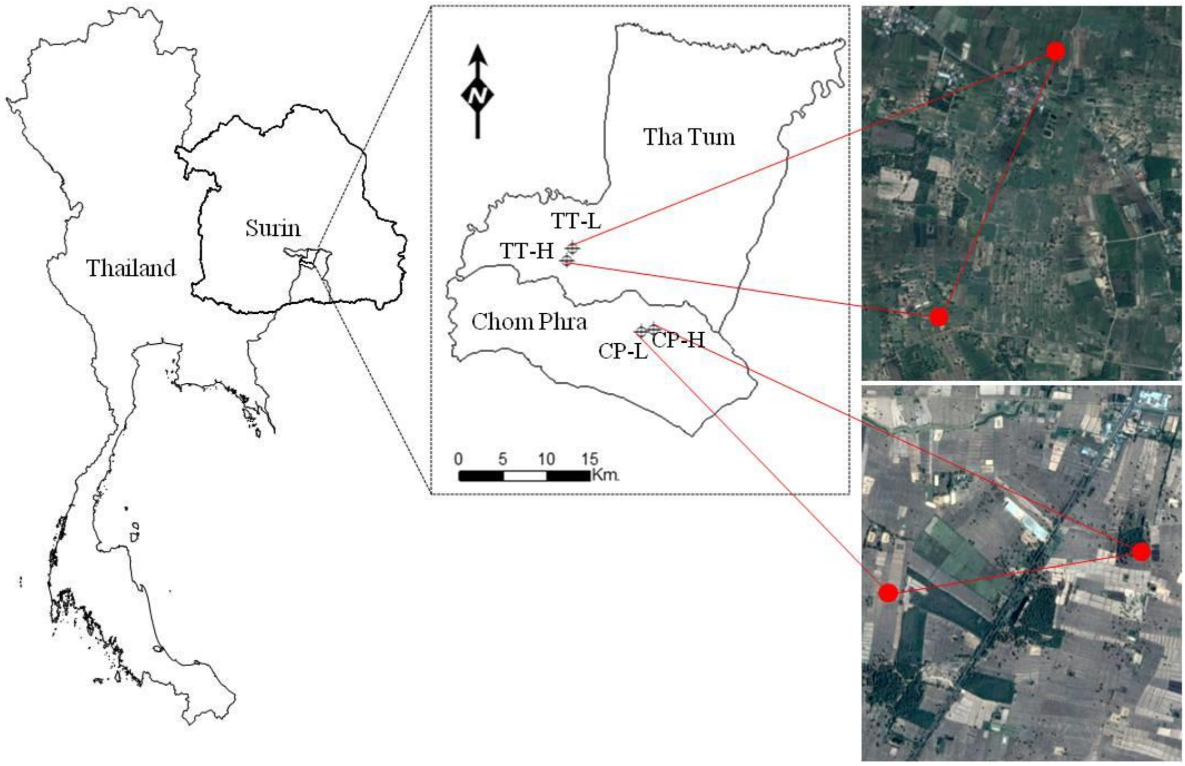

Fig. 3.1 Location of Surin Province and four studied sites. (source: Google Earth Images©2015 CNES/Astrium, 10/19/2015).

3.2.2 Soil analysis

Soil samples were air-dried and passed through a 2-mm sieve. pH was measured with a glass electrode using a soil to solution (H_2O, 1 M KCl) ratio of 1:1. Exchangeable bases were extracted with 1 M ammonium acetate (pH 7.0). The contents of Ca and Mg were determined by atomic absorption spectrometry (GBC, Sens AA, Dandenong, Australia), while those of K and Na were determined by flame photometry (Model 420 Sherwood Scientific, Cambridge, UK). To determine the cation exchangeable capacity (CEC), residual soil after ammonium acetate extraction was washed with ethanol, and the remaining $NH_4^+$was extracted with 10% NaCl and then determined by the Kjeldahl distillation method. Exchangeable acidity (Al and H) was extracted with 1 M KCI and measured by titration. The dry combustion method using an NC analyzer (Variomax, Elementar Analysen system GmbH, Hanau, Germany) was employed to determine the total carbon (TC) and total nitrogen (TN) contents. Available phosphorus (AP) was determined by the Bray-II method (Bray and Kurtz, 1945). Sieving was employed to measure the coarse and fine sand fractions, while the pipette method was used for silt and clay fractions (Gee and Bauder,1986).

Soil water retention at 33 and 1,500 kPa were determined using a pressure plate apparatus (Dane and Hopmans, 2002). Soils were classified based on USDA Soil Taxonomy (Soil Survey Staff, 2014) and the Unified Soil Classification System of Japan 2nd Approximation (2002) (USCSJ) (The Fourth Committee for Soil Classification and Nomenclature of the Japanese Society of Pedology, 2003).

3.3 Results

3.3.1 Physical and chemical characteristics

The physical and chemical properties of the four profiles are shown in Table 3.1. In TT-H, soil pH was very strongly acidic (<5.0) except for in the BAg and Bg1 horizons in the upper part of the subsoil, where pH was strongly acidic (≤5.5). The clay content was highest in the Ap2 horizon, then decreased with depth. TC, TN, and AP were highest at the surface soil, then decreased with depth. TC and TN were higher in the second horizon. Base saturation was lowest in the bottom horizons (Bg2 and Bg3), while Bg1 had base saturation exceeding 50%. The exchangeable acidity was highest and the pH value was lowest in the bottom horizon (Bg3). The values of CEC were the highest in the Ap2 horizon, where clay content was also highest. Available water was low throughout the profile.

In TT-L, pH increased with depth from 4.6 in the topsoil (Ap) to 7.5 at the bottom horizon (Btg2). The clay content and CEC increased with depth from 1 to 13% and from 1.6 to 5.0 $cmol_c$ kg^{-1}, respectively. TC, TN, and AP were highest in the topsoil, then decreased with depth. This profile exhibited very high base saturation with high exchangeable Na concentrations in deeper horizons. Sand content decreased with depth, while available water was lower in topsoils than subsoils.

In CP-H, soil pH was strongly acidic (≤5.0) and decreased slightly with depth. The clay content was highest in the middle horizon of the profile (Btg1). This horizon (Btg1) may retard percolation, resulting in the accumulation of exchangeable Ca and Mg and, therefore, higher base saturation in the upper horizons.TC, TN, and AP were highest in the top horizons, then decreased with depth. Additionally, TC and TN accumulated in the second horizon. Base saturation was moderate at the top of the profile and decreased with depth, while pH and exchangeable acidity increased with depth. Available water in topsoils was lower than in subsoils.

Table 3.1 Physical and chemical characteristics of the four pedons.

Site	Particle size distribution			pH		TC[a]	TN[b]	AP[c]	CEC[d]	Exchangeable cations					Base	Water content		Avail.
Horizon	Sand	Silt	Clay	H_2O	KCl					K	Na	Ca	Mg	Al + H	saturation	1500 kPa	33 kPa	Water
	---------- (%) ----------					(g kg^{-1})		(mg kg^{-1})	---------- (cmol$_c$ kg^{-1}) ----------						(%)	---------- (%) ----------		
TT-H																		
Ap1	79	15	7	4.8	3.9	2.9	0.24	2.8	1.1	0.03	0.02	0.83	0.28	0.73	105	3	6	3
Ap2	78	14	8	4.9	3.9	3.0	0.27	2.7	3.4	0.03	0.02	0.91	0.33	0.52	38	4	7	4
BAg	80	14	7	5.5	4.5	1.6	0.15	2.3	2.8	0.04	0.02	1.08	0.39	0.31	55	3	6	3
Bg1	79	17	5	6.0	4.7	0.81	0.07	1.8	1.5	0.02	0.01	0.70	0.27	0.10	66	2	5	2
Bg2	81	14	5	4.8	4.0	0.64	0.05	1.1	1.6	0.02	0.03	0.29	0.12	0.73	29	2	4	2
Bg3	80	16	4	4.5	3.7	0.70	0.06	0.90	2.3	0.03	0.02	0.20	0.18	1.14	19	3	6	3
TT-L																		
Ap	79	20	1	4.6	4.1	2.4	0.21	3.6	1.6	0.05	0.12	0.41	0.14	0.31	44	2	5	3
BAg	72	21	7	6.5	5.3	1.3	0.11	1.2	2.6	0.04	0.65	1.06	0.34	0.10	81	3	7	4
Bg	66	30	4	6.5	5.3	1.2	0.10	0.80	2.7	0.03	1.13	0.97	0.38	0.10	92	4	8	5
Btg1	60	29	11	6.5	5.2	0.88	0.11	0.85	3.9	0.03	2.04	1.40	0.53	0.10	103	4	12	8
Btg2	57	30	13	7.5	6.1	0.78	0.07	0.75	5.0	0.04	2.70	1.70	0.59	0.10	101	6	14	8
CP-H																		
Ap1	77	20	3	5.0	4.2	3.6	0.29	10	2.1	0.04	0.02	0.72	0.27	0.31	50	3	6	3
Ap2	71	24	5	4.9	4.4	4.3	0.34	5.3	2.6	0.04	0.03	0.63	0.33	0.52	39	4	8	5
Bg	64	29	7	5.0	3.9	2.0	0.15	1.1	2.7	0.03	0.03	0.96	0.51	0.31	57	5	11	5
Btg1	54	10	36	4.8	3.8	1.5	0.13	1.1	3.7	0.02	0.02	0.79	0.50	0.52	36	5	11	6
Btg2	56	33	11	4.4	3.5	1.1	0.10	0.95	4.5	0.03	0.03	0.36	0.50	1.76	21	7	14	7
Btg3	61	29	11	4.4	3.5	0.77	0.08	1.4	4.5	0.04	0.03	0.19	0.47	2.17	16	6	13	6
CP-L																		
Apg1	54	38	8	4.6	3.8	5.5	0.40	5.3	5.7	0.08	0.05	1.43	0.42	1.14	34	6	15	9
Apg2	50	42	8	4.8	3.7	3.6	0.27	3.9	5.3	0.04	0.03	1.35	0.43	0.93	35	6	15	10
BAg	54	36	10	6.5	5.2	2.0	0.14	0.80	5.8	0.06	0.03	3.03	0.70	0.10	66	6	15	9
Bg1	57	34	10	6.7	5.3	1.2	0.10	1.1	5.9	0.07	0.03	2.96	0.69	0.10	64	6	15	9
Bg2	56	33	11	6.7	5.3	0.58	0.06	0.90	6.2	0.12	0.04	2.93	0.68	0.10	61	6	15	9
Bg3	56	34	10	6.2	4.8	0.50	0.07	1.0	6.4	0.06	0.03	3.07	0.70	0.31	60	7	17	10
Btg	50	34	16	5.8	4.7	0.75	0.08	1.0	9.3	0.09	0.03	3.94	0.85	0.10	53	10	21	11

[a] total carbon; [b] total nitrogen; [c] available phosphorus; [d] cation exchangeable capacity.

In CP-L, the topsoil horizons were strongly acidic, with the lowest base saturation and the highest exchangeable acidity in the profile. Clay content increased slightly with depth, similar to CEC. TC, TN, and AP were highest in the topsoil, then decreased with depth. Available water was high throughout the profile. Among profiles, this soil was the most fertile, having the highest clay and TC contents, CEC, exchangeable Ca and Mg concentrations, and available water content, especially in the bottom horizons. Sand content was the lowest in this profile.

Higher silt and clay content, TC, TN, AP, and CEC were observed in the CP profiles than the TT profiles. The profiles at lower positions, i.e. TT-L and CP-L, had higher CEC, base saturation, and exchangeable cations than those at higher positions (TT-H and CP-H). Still, all the pedons had at least one horizon with base saturation exceeding 50% between 10 and 100 cm depth, which is the criterion of Eutric subgroup in USCSJ. The primary exchangeable cations were Na in TT-L, while Ca and Mg were in the other profiles. Regression analysis revealed a strong positive relationship between the available water and silt plus clay content ($y = 0.23x - 2.2$, $r^2 = 0.89$) for all horizons (Fig. 3.2).

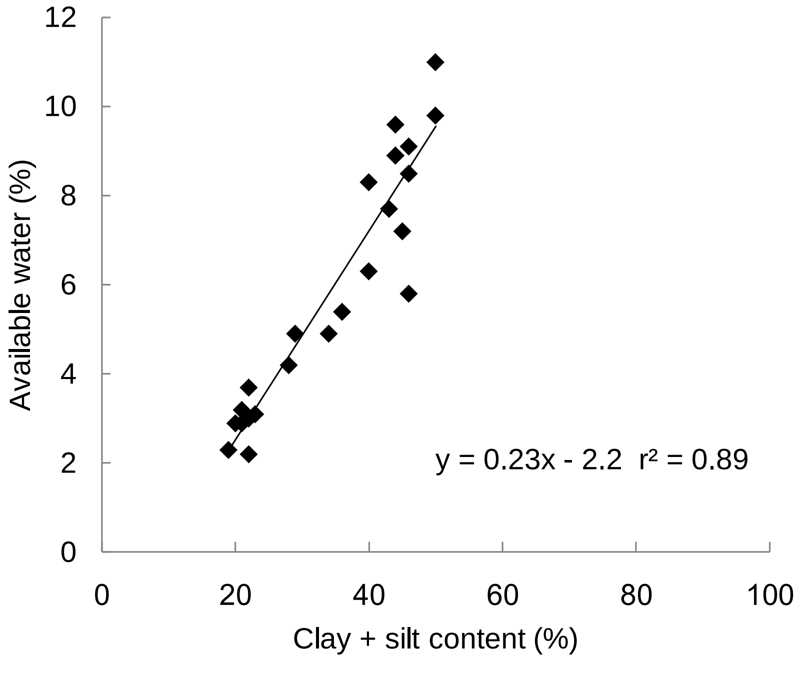

Fig. 3.2 Relationship between available water and clay plus silt content.

3.3.2 Morphological characteristics

TT-H exhibited six horizons (Table 3.2, Fig. 3.3). The two top horizons had a thickness of 18 cm and the same grayish-brown color (7.5YR 4/2). The soil texture of the surface horizon was loamy sand, while that of the underlying horizon was sandy loam. The four subsoil horizons were dull orange to dull brown (5YR6–7/4–6 to 7.5YR5/4), having the red-yellow color properties in USCSJ. Below the surface horizon, mottled colors appeared prominent, ranging from orange to brown (5YR6/8 to 7.5YR 4–5/6–8), except for a distinct color (5YR6/8) in the Bg2 horizon. Mn concretions existed in the BAg horizon. Horizons throughout the profile had subangular blocky structures with smooth boundaries, except for a wavy boundary between BAg and Bg1. The texture was loamy sand throughout the profile, except for sandy loam in horizon Ap2. TT-H was classified in USDA Soil Taxonomy as Oxyaquic Haplustept, and in USCSJ as Eutric Cambic Red-Yellow soil.

TT-L exhibited five horizons (Table 3.3, Fig. 3.3). The topsoil horizon had a thickness of 12 cm and a dull orange (5YR 6/4) color. The four subsoil horizons were brownish-grey to grayish brown (5YR5/1–2 to 7.5YR6/1–2), having the red-yellow color properties in USCSJ. Below the surface horizon, mottled colors appeared, primarily consisting of bright brown to yellow-orange (7.5YR5–7/8). Mn concretions existed in the bottom horizon (Btg2). Thin clay cutan was observed at Btg1 and Btg2 below 28 cm of soil, which was identified as the argillic horizon in USDA Soil Taxonomy. All horizons had subangular blocky structures and smooth boundaries, except for horizon Btg1, which had an angular blocky structure. The topsoil was loamy sand, while the profile downward was sandy loam. TT-L was classified in USDA Soil Taxonomy as Oxyaquic Haplustalf, and in USCSJ as Eutric Argic Red-Yellow soil.

CP-H exhibited six horizons (Table 3.4, Fig. 3.3). The two top horizons had a thickness of 17cm, with the surface (Ap1) horizon being separated by an orangish color and coarser texture than Ap2. Among the four subsoil horizons, only Bg was grayish brown and had the red-yellow color properties in USCSJ, while the rest were light brownish gray. Prominent mottled colors appeared in each horizon. The subsoil texture was sandy loam. Mn concretions existed in the Btg1 horizon, while thin clay cutan on ped surfaces was found from Btg1 to Btg3. Firm consistency was observed in the Bg horizon, while non-sticky and non-plastic materials were observed throughout the profile. CP-H was classified in USDA Soil Taxonomy as Typic Haplustult, and in USCSJ as Eutric Argic Red-Yellow soil.

CP-L exhibited seven horizons (Table 3.5, Fig. 3.3). Topsoil horizons were 15 cm thick with a brownish-grey (7.5YR4/1) color. The texture of the surface horizon was sandy loam, while that of the underlying horizon was loam. Subsoil was brownish gray to light brownish gray (5YR4–5, 7/1 to 7.5YR7/1). Prominent mottled colors appeared in every horizon. Mn concretions existed in the bottom horizon (Btg). A relatively clear thin clay cutan was observed at below 70 cm. Subangular blocky structure and sandy loam texture were present in all horizons except Apg2 and Btg, with angular blocky structures and loamy textures. CP-L was classified in USDA Soil Taxonomy as Oxyaquic Haplustalf, and in USCSJ as Eutric Argic Red-Yellow soils.

Comparing the pedons at higher and lower positions in each district revealed higher matrix chroma and fewer mottles in the profiles at higher positions. In the TT-L and CP-L profiles, the subsoils showed slight stickiness, while no stickiness was observed in the TT-H and CP-H profiles. No mottles or very few mottles in the top horizons were observed in the TT-H and TT-L profiles. On the other hand, mottles were found from the top horizons in the CP-H and CP-L profiles. The matrix chroma was higher, and there were fewer mottles in TT-H than in the other profiles. No angular blocky structure was found in the TT-H profile, whereas it was found in the two loamy horizons (Apg2, Btg) in CP-L and the two bottom horizons in TT-L and CP-H.

Fig. 3.3 Photograph of Tha Tum profiles at high topographical position (TT-H).

Table 3.2 Profile of Tha Tum pedon at high topographical position (TT-H).

Horizon	Depth (cm)	Description
Ap1	0-10	Grayish brown (7.5YR4/2) loamy sand; very few faint mottles; weak coarse subangular blocky structure; very friable, nonsticky, slightly plastic; many fine roots; very strongly acid clear, smooth boundary to,
Ap2	11-18	Grayish brown (7.5YR4/2) sandy loam; few prominent brown (7.5YR4/6) mottles; moderate coarse subangular blocky structure; friable, nonsticky, slightly plastic; common fine roots; very strongly acid; abrupt, smooth boundary to,
BAg	19-24	Dull brown (7.5YR5/4) loamy sand, common prominent bright brown (7.5YR5/8) mottles; moderate very fine subangular blocky structure; slightly firm, nonsticky, slightly plastic; very few fine roots; very few Mn concretions, strongly acid; clear, wavy boundary to,
Bg1	25-42	Dull reddish brown (5YR7/4) loamy sand, few prominent orange (5YR6/8) mottles; moderate medium subangular blocky structure; slightly firm, nonsticky, slightly plastic; very few fine roots; medium acid; gradual, smooth boundary to,
Bg2	43-65	Orange (5YR7/6) loamy sand; common distinct orange (5YR6/8) irregular mottles; coarse medium subangular blocky structure; friable, nonsticky, slightly plastic; very few fine roots; very strongly acid; gradual, smooth boundary to,
Bg3	>65	Dull orange (5YR6/4) loamy sand; many prominent orange (5YR6/8) irregular mottles; weak medium subangular blocky structure; friable, nonsticky, slightly plastic; very strongly acid; gradual, smooth boundary.

Fig. 3.4 Photograph of Tha Tum profiles at low topographical position (TT-L).

Table 3.3 Profile of Tha Tum pedon at low topographical position (TT-L).

Horizon	Depth (cm)	Description
Ap	0-12	Dull orange(5YR6/4) loamy sand; weak coarse subangular blocky structure; very friable, nonsticky, slightly plastic; common fine roots; very strongly acid; abrupt, smooth boundary to,
BAg	13-20	Brownish gray (5YR5/1) sandy loam; common prominent orange (7.5YR6/8) irregular mottles; moderate coarse subangular blocky structure; friable, slightly sticky, slightly plastic; very few very fine roots; slightly acid; gradual, smooth boundary to,
Bg	21-28	Grayish brown (5YR5/2) sandy loam; common prominent yellow orange (7.5YR7/8) irregular mottles; moderate coarse subangular blocky structure; friable, slightly sticky, slightly plastic; slightly acid; gradual, smooth boundary to,
Btg1	29-60	Grayish brown (7.5YR6/2) sandy loam; common prominent bright brown (7.5YR5/8) irregular mottles; thin clay cutan on ped surfaces; moderate coarse angular blocky structure; friable, slightly sticky, slightly plastic; slightly acid; mildly alkaline (field pH 7.5); gradual, smooth boundary to,
Btg2	>60	Brownish gray (7.5YR6/1) sandy loam; common prominent bright brown (7.5YR5/8) irregular mottles; thin clay cutan on ped surfaces; weak coarse subangular blocky structure; firm, slightly sticky, slightly plastic; distinct 1 cm of Mn concretions, mildly alkaline; clear, smooth boundary.

Fig. 3.5 Photograph of Chom Phra profiles at high topographical position (CP-H).

Table 3.4 Profile of Chom Phra pedon at high topographical position (CP-H).

Horizon	Depth (cm)	Description
Ap1	0-7	Dull orange(7.5YR7/3) loamy sand; few prominent orange (5YR6/8) irregular mottles; weak coarse subangular blocky structure; very friable, nonsticky, nonplastic; common very fine roots; very strongly acid; clear, smooth boundary to,
Ap2	8-17	Brownish gray (7.5YR5/1) sandy loam; few prominent orange (7.5YR6/8) mottles; friable; weak coarse subangular blocky structure; friable, nonsticky, nonplastic; few very fine roots; very strongly acid; abrupt, smooth boundary to,
Bg	18-21	Grayish Brown (7.5YR6/2) sandy loam; common prominent bright brown (7.5YR5/8) mottles; moderate coarse subangular blocky structure; firm, nonsticky, nonplastic; few very fine roots; very strongly acid; abrupt, smooth boundary to,
Btg1	21-36	Light brownish gray (5YR7/2) sandy loam; many prominent orange (5YR6/8) irregular mottles; thin clay cutan on ped surfaces; moderate medium subangular blocky structure; friable, nonsticky, nonplastic; very few very fine roots; very few distinct Mn concretions; very strongly acid; clear, smooth boundary to,
Btg2	36-60	Light brownish gray (5YR7/2) sandy loam; many prominent bright reddish brown (5YR5/8) irregular mottles; thin clay cutan on ped surfaces; weak coarse angular blocky structure; friable, nonsticky, nonplastic; very strongly acid; diffuse, smooth boundary to,
Btg3	61-90	Light brownish gray (7.5YR7/2) sandy loam; many prominent bright brown (7.5YR5/8) irregular mottles; thin clay cutan on ped surfaces; weak coarse angular blocky structure; friable, nonsticky, nonplastic; very strongly acid; diffuse, smooth boundary.

Fig. 3.6 Photograph of Tha Tum profiles at low topographical position (CP-L).

Table 3.5 Profile of Chom Phra pedon at low topographical position (CP-L).

Horizon	Depth (cm)	Description
Apg1	0-10	Brownish gray (7.5YR4/1) sandy loam; common prominent yellow orange (7.5YR7/8) mottles; moderate medium subangular blocky structure; friable, nonsticky, slightly plastic; common fine roots; very strongly acid; clear, smooth boundary to,
Apg2	11-15	Brownish gray (7.5YR4/1) loam; many prominent yellow orange (7.5YR7/8) mottles; moderate coarse angular blocky structure; slightly firm, nonsticky, slightly plastic; common few fine roots; very strongly acid; abrupt, smooth boundary to,
BAg	16-20	Brownish gray (5YR4/1) sandy loam; common prominent reddish brown (5YR4/8) mottles; moderate coarse subangular blocky structure; firm, nonsticky, slightly plastic; very few very fine roots, few Mn mottles; slightly acid; clear, smooth boundary to,
Bg1	21-30	Brownish gray (5YR5/1) sandy loam; common prominent orange (5YR7/8) irregular mottles; moderate coarse subangular blocky structure; slightly firm, slightly sticky, slightly plastic; very few very fine roots; slightly acid; clear, smooth boundary to,
Bg2	31-50	Light brownish gray (7.5YR7/1) sandy loam; many prominent orange (7.5YR6/8) irregular mottles; moderate coarse subangular blocky structure; friable, slightly sticky, slightly plastic; very few very fine roots; slightly acid; diffuse, smooth boundary to,
Bg3	51-70	Light brownish gray (7.5YR7/1) sandy loam; common prominent yellow orange (7.5YR7/8) irregular mottles; moderate coarse subangular blocky structure; friable, slightly sticky, slightly plastic; very few very fine roots; very faint cutan, medium acid; clear, smooth boundary to,
Btg	>70	Light brownish gray (5YR7/1) loam; common prominent orange (5YR7/8) irregular mottles; thin clay cutan on ped surfaces; weak coarse angular blocky structure; friable, slightly sticky, slightly plastic, few distinct Mn concretions; medium acid; diffuse, smooth boundary.

3.4 Discussion

The color of the TT-H profile ranged from dark to light from the soil surface to the Bg2 horizon, and the chroma over two of the subsoil horizons (Bg1-3) was obviously different from that of the other profiles, indicating that crystalline Fe oxides were present on the soil particle surfaces. The low abundance of mottles indicated that the soil might have a short period of reducing condition. The rapid move of water due to high sand content could lead to water deficiency during the rice-growing season. The highest pH at Bg1 might result from seasonal upward water movement causing a supply of basic cations from lower horizons.

The colors of horizons in the TT-L profile were more homogeneous than those in the other profiles. The topsoil had a low clay content, pH, base saturation, and CEC, which was obviously different from the underlying horizons. Small particles were presumably transported downward from the surface and deposited on the horizon below. The base saturation was high in the deeper horizons exceeding 90%, which had a high amount of exchangeable Na. The large amount of exchangeable Na in typical paddy soils in northeast Thailand was also reported by Miura *et al*. (1992). Sodium was the dominant basic cation and increased with depth, indicating that it probably originated from the parent materials or groundwater. The Na distribution in the profile is considered to be a sign of incipient salinization, reflecting the upward transport of dissolved salts from the underlying groundwater that occasionally occurs in low topographical positions in northeast Thailand (Kohyama and Subhasaram, 1993).

The CP-H profile had higher clay contents than the TT-H, with clay cutan in the lower B horizons. This may have caused slower drainage and greater reducing conditions, and thus lower chroma and common-to-moderate mottling in the profile. Nevertheless, the profile showed low pH values from top to bottom, indicating intense leaching. The higher clay content also contributed to the high TC, TN, and AP by enabling the accumulation or adsorption of these elements.

The CP-L profile showed the lowest chroma and common-to-high-mottling throughout the horizons, indicating the strongest reducing conditions among the investigated profiles. This may have been caused by the lower topographical position and higher clay contents. The high clay content also contributed to the high TC, TN, AP, and CEC values. The pH(H_2O) was near neutral in the B horizons, indicating restricted drainage. Because of the higher clay content accompanying high TC, TN, AP, and CEC values, as well as the higher pH, this soil was considered to be the best for crop growth among the studied profiles.

The colors of the soil matrix and mottles indicated the drainage condition of the profiles. The brighter color of the matrix chroma and fewer mottles of the TT-H indicated better drainage conditions than the other profiles. A brighter appearance of the matrix chroma was also observed in the profiles at a higher position than those at lower positions within each site, indicating better drainage conditions or leaching at higher positions. In the paddy fields lying on sloping land, both surface- and ground-water flow from higher to lower positions. Thus paddy fields at higher positions have lower amounts of available water (Homma *et al*., 2004; Tsubo *et al*., 2006), and they generally experience a higher water stress (Haefele and Konboon, 2009) because the fields at higher elevations receive less water input from upper areas, have higher percolation rates, and thus lose standing water earlier than lower positions (Tsubo *et al*., 2006).

Soil texture, as well as the topographical positions, is considered as the main factor controlling the water conditions of the profiles, as is suggested by Wijnhoud *et al*.(2003). At the deeper horizons of pedons at the low positions, clay content was higher, and slightly sticky properties were observed, likely due to clay accumulation. The increase in clay content in the subsoil is generally found in northeast Thailand (Oberthür and Kam, 2000). The horizons with clay accumulation limited the water percolation, resulting in higher water availability. Retarding water loss, soil clay content could be a good index of water availability in paddy soils (Tsubo *et al*., 2007). The regression equation (Fig. 3.2) helped illustrate that there was less water storage in the subsoil of high sand content pedons, indicating that TT-H would face more drought than the other pedons during dry spells. Additionally, soil textures were coarser on higher than lower topographical positions within each site, which is similar to the report on northeast Thailand that decreases of clay content along with elevation (Homma *et al*., 2003; Boling *et al*., 2008). It results from the selective transportation of finer particles from high to low topographical positions (Homma *et al*., 2003). Moreover, the soils at lower positions showed slight stickiness as opposed to those at higher elevations with no stickiness, which may contribute to higher water retention even in the same plasticity and soil texture class (Rawls and Pachepsky, 2002).

The leaching conditions reflected the acidity and exchangeable cation contents. The most acidic soils were found at the bottom horizons of both the TT-H and CP-H profiles according to the higher exchangeable acidity and lower base saturation, indicating the extent of leaching in this position. Kheoruenromne *et al*. (1998) reported that sandy soils with low CEC, low water holding capacity, and rapid infiltration rate would induce a serious leaching problem. Conversely, the profiles at lower positions had higher pH values and exchangeable cations. At TT-L, the content of exchangeable Na was high, probably due to the upward movement of groundwater. Nevertheless, the Na did not come to the surface horizons because of the disconnection of capillaries in the low clay content horizons. The high exchangeable Ca and Mg in the lower horizons of CP-L may have been due to weak leaching.

Rice yield under the rainfed condition of this region seems not different between the districts but between the topographical positions. Soils at lower topographical positions have higher rice yields. More available water and better fertility properties such as exchangeable cations, available phosphorus, CEC, and organic carbon content of the soils at lower positions were considered to result in higher rice yield.

This study result clarified the relationship between the topographical position of soils and three main constraints for lowland rice production in paddy soils of northeast Thailand under the strong influence of sandy parent materials and tropical savanna climate (Kheoruenromne *et al*., 1998). The constraints are, first, the strong acidity of soils (Kawaguchi and Kyuma, 1974; Kheoruenromne *et al*., 1998; Haefele *et al*., 2006; Boling *et al*., 2008; Haefele and Konboon, 2009; Saenya *et al*., 2015), second, the low nutrient level and associated soil properties, i.e., low TN, TC, CEC (Kawaguchi and Kyuma, 1974; Haefele *et al*., 2006; Boling *et al*., 2008; Haefele and Konboon, 2009; Saenya *et al*., 2015), low AP (Kawaguchi and Kyuma, 1974; Kheoruenromne *et al*., 1998; Haefele *et al*., 2006; Prakongkep *et al*., 2008; Boling *et al*., 2008; Haefele and Konboon, 2009; Saenya *et al*., 2015), and low Exchangeable K (Kawaguchi and Kyuma, 1974, Kheoruenromne *et al*., 1998; Haefele *et al*., 2006; Boling *et al*., 2008), and third, the low water holding capacity of soils (Kheoruenromne *et al*., 1998; Saenya *et al*., 2015). All of these constraints were more serious at high topographical positions.

3.5 Conclusion

The morphological, physical, and chemical properties of the profiles on the higher and lower topographical positions in Tha Tum and Chom Phra in Surin province were investigated. The soils were sandy and infertile, with high acidity, low nutrient levels, and low water holding capacity. The four studied profiles explained the influence of water movements such as stagnation and drainage. Sand content is crucial to available water and leaching. Because small particles were translocated by water, soil fertility properties such as exchangeable cations, available phosphorus, +, and organic carbon content were low in the pedons at higher positions. The soils at high topographical positions indicated a risk for nutrient depletion and water deficiency, with more acidity under leaching conditions. In contrast, one profile at low topographical positions showed the potential for salinity problems.

CHAPTER 4 Yield-controlling factors in rainfed paddy fields in northeast Thailand

4.1 General

The rainfed lowland in northeast Thailand, characterized by sandy soil with gently undulating topography, has variable water availability and soil fertility at different elevations. A decrease in water availability toward the top of the toposequence is associated with less downward water movement (Inthavong *et al*., 2011). The same trends were found for soil fertility that decreased within the toposequence because of limited water resources in higher areas (Fukai *et al*., 1998; Suzuki *et al*., 2003; Homma *et al*., 2007; Boling *et al*., 2008; Haefele and Konboon, 2009).

The influence of topographical position on water and low soil nutrient status is considered to cause rice grain yield variation; yields apparently increased from the top to the bottom topographical positions (Fukai *et al*., 1998; Homma, 2002; Suzuki *et al*., 2003; Tsubo *et al*., 2006; Homma *et al*., 2007; Boling *et al*., 2008; Haefele and Konboon, 2009; Boling *et al*., 2010). Although numerous soil and water factors at different elevations in the toposequence have been investigated, the most critical factor controlling rice yield has not been identified, though it is likely related to water stress and/or soil nutrient supply. Recognition of the yield-controlling factors that might be obscured in the toposequence could benefit rice yield by adjusting management practices to specific toposequence positions.

The objectives of this study were to clarify the factors controlling rice yield including topographical position, soil physicochemical properties and hydrological conditions, and to find a relationship between these factors in rainfed lowland rice fields in northeast Thailand. To achieve the objectives, this study collected soil samples in rainfed lowland rice fields in undulating topography and applied correlation analysis to determine the most important yield-controlling factors and the relationship between them.

4.2 Materials and methods

4.2.1 Site characterization

The experimental sites were selected in Tha Tum and Chom Phra districts of Surin (Fig. 4.1). They demonstrate the typical landscape of the region with gently undulating topography and similar slope gradient. Surin is located at latitude 14°20′–15°28′ N and longitude 103°5′–104°6′ E in the southern part of northeast Thailand, covering 8,120 km^2. The geographical characteristics of Surin Province include the highland on Korat Plateau with the southern part close to the mountain range of Phanom Dong Rak and a gradual slope from the mountain range down to the valley of the Mun River located in northern Surin. The central and northern parts of the province are undulating flood plains. The climate is tropical Savannah, Aw in the Köppen climate classification, with three seasons: winter from October or November to January, summer from February or March to May, and a rainy season from May or June to October. The average annual rainfall and temperature are 1572 mm and 27.0°C, respectively. The soil classification in USDA Soil Taxonomy (Soil Survey Staff, 2014) at low topographical positions of both Tha Tum and Chom Phra is Oxyaquic Haplustalf, but the soil orders at high topographical positions are Oxyaquic Haplustept in Tha Tum and Typic Haplustult in Chom Phra (Prueksapong *et al*., 2015).

In both districts, the farmers apply fertilizer once only when water is standing in the fields, or not at all in the case of drought. The application rates were not the same among years because of the variable budget of the farmers. The average of the fertilizer doses, if used, was 188 kg ha^{-1} of 16–16–8 (N–P_2O_5–K_2O) and 94 kg ha^{-1} of urea.

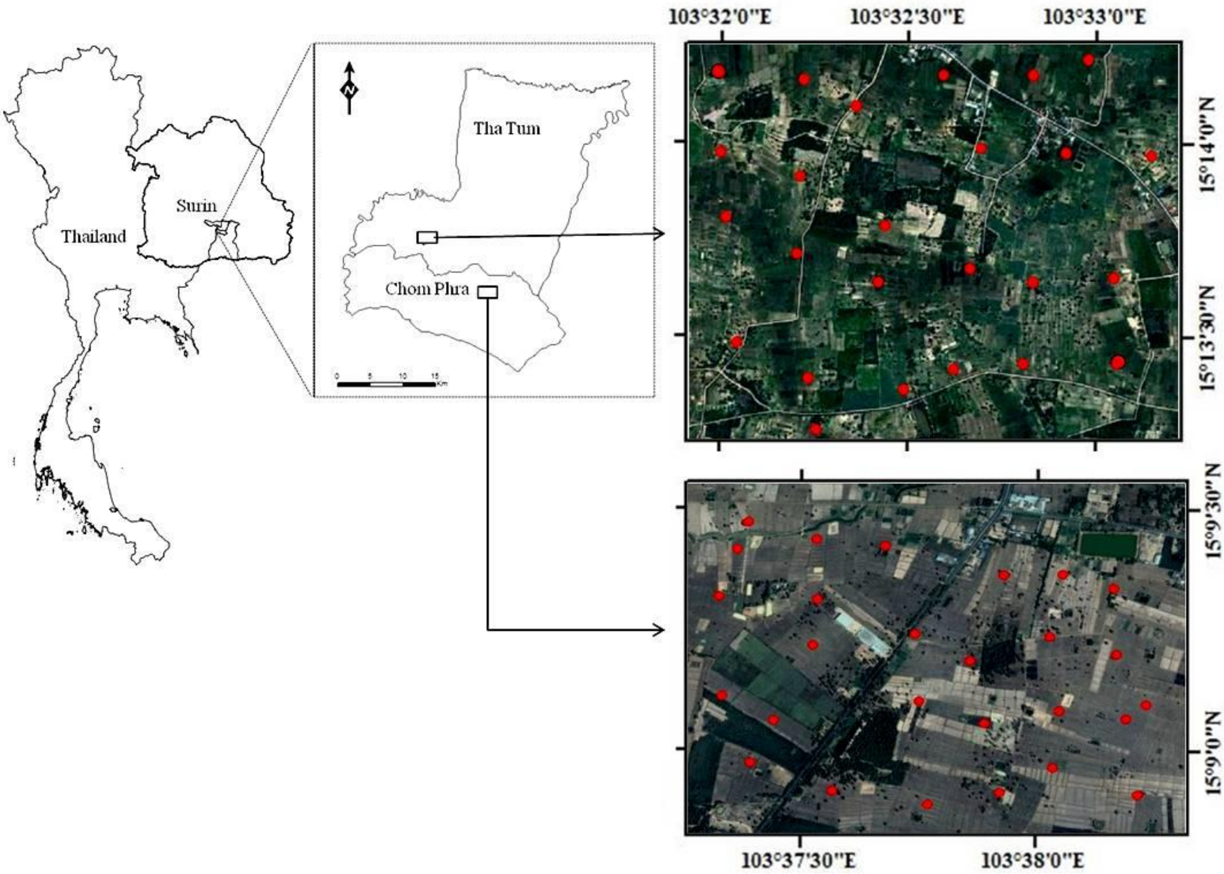

Fig.4.1 Location of Surin Province and 52 sampling sites. (Source: Google Earth Images©2015 CNES/Astrium, 10/19/2015).

Table 4.1 Monthly rainfall (mm) of the study area.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Tha Tum Meteorology Station													
2004-2013	20	5	33	92	168	166	212	252	263	118	16	3	1447
2011	0	10	21	30	114	262	226	270	298	302	5	0	1536
2012	80	2	60	49	280	53	110	326	178	27	11	0	1174
2013	0	0	13	114	119	145	171	292	356	64	2	20	1295
Surin Meteorology Station													
2004-2013	7	9	38	77	211	200	250	278	263	113	26	1	1473
2011	0	21	14	72	176	235	300	272	295	247	3	0	1635
2012	27	3	7	83	195	232	91	304	134	33	51	0	1159
2013	7	32	3	26	204	173	231	134	353	100	4	3	1270

4.2.2 Field measurements of relative elevation and soil water content

Field measurements were conducted in 25 plots in Tha Tum and 27 plots in Chom Phra, spread over approximately 500 ha at each site (Fig. 4.1). The relative elevation at each plot was measured by the static GPS surveying technique with a hand-held GNSS receiver and field controller (GRS-1 GG, TOPCON, Tokyo, Japan) and computer software (GNSS-Pro, TOPCON, Tokyo, Japan), where the lowest plot in both of the sites was fixed as 0 m of relative elevation. The field soil water contents at 20 cm depth were measured monthly from April to November in 2011–2013 by the Time Domain Reflectometry method using a soil-water sensor (HydroSense, CS620 with 20-cm probe, Campbell Scientific, Logan, USA).

4.2.3 Sampling and analyses

After harvest in 2011, composite soil samples were taken from 5 points in each site where field measurements were taken by the random sampling method at 0–20 cm depth. Soil samples were air-dried and passed through a 2-mm sieve. Soil pH was measured with a glass electrode using a soil to solution (H_2O, 1 M KCl) ratio of 1:1. Organic matter content was determined by the wet oxidation method (Walkley and Black, 1947). Available phosphorus (P) was determined by the Bray-II method (Bray and Kurtz, 1945). Available potassium (K) was extracted by ammonium acetate (Chapman, 1965) and measured with a flame photometer (Model 420 Sherwood Scientific, Cambridge, UK). Sieving was employed to measure the coarse and fine sand fractions, while the pipette method was used for silt and clay fractions (Gee and Bauder, 1986).

Undisturbed soil samples were collected to a 20-cm depth at the same time and site as the composite soil samples using a 100-mL core sampler. Soil water retention at 33 and 1,500 kPa (field capacity (FC) and permanent wilting point (PWP), respectively) were determined using a pressure plate apparatus (Dane and Hopmans, 2002). Hydraulic conductivity (HC) was measured using a constant head permeameter (Klute and Dirksen, 1986). Soil gravimetric water content (SWC) was calculated based on the sample dry weight and soil bulk density with core section volume.

The yield was determined for unhulled rice in 5 replicates of 1 m^2 of hand-harvested quadrats from each plot from the end of October to the middle of November in 2011–2013.

4.2.4 Climate data

Monthly and annual rainfall data during the three years of the experiment and the previous ten years were collected in adjacent stations from Tha Tum (representing the Tha Tum site) and Surin Meteorological Station (representing the Chom Phra site) to investigate the influence of climatic conditions on the rice yield (Table 4.1).

4.2.5 Statistics

Normality of soil and plant properties was tested by Shapiro Wilk's test. Analysis of variance (ANOVA) was applied to compare rice grain yield among the years. The t-test was used to compare measured values between the two sites. Spearman's correlation analysis was applied to evaluate relationships between the measured values because most of the data were not normally distributed. Differences were considered significant when P-values were lower than 0.05. All statistical analyses were carried out using the R statistical software program (R Development Core Team, 2009).

Spatial distribution maps of rice yield, elevation, and some soil physicochemical properties were produced based on geostatistical analysis consisting of variogram experiments, cross-validation, and the kriging method using ArcGIS software (Version 9.3).

4.3 Results

4.3.1 Rice yields, relative elevation, and soil physicochemical properties

The means of rice grain yield ranged from 1.8–2.7 t ha^{-1} and were not significantly different between years on the same site. The annual yield during the three years was also not different between the two sites. From both sites, the lowest rice yield of 0.4 t ha^{-1} occurred in 2012, and the highest yield of 2.4 t ha^{-1} occurred in 2011 (Table 4.2).

Elevations of both sites were within a similar range, although the mean value of elevation of Chom Phra was higher than that of Tha Tum (Table 4.2).

The soils from both sites were predominated by sandy texture, low nutrient contents (low pH and low available P, available K and organic matter contents), and low water-holding capacity (low SWC and AWC). Based on the data, soil-water properties and soil fertility status in Tha Tum and Chom Phra sites were similar, though sand content, available K, and pH were higher, and silt content and SWC were lower in Tha Tum than in Chom Phra (Table 4.2).

For all plots, AWC correlated with all the measured parameters except for organic matter content, available K, and pH (Table 4.3). The correlations were also found in each site, but AWC did not correlate with FC for Tha Tum and with bulk density, SWC, HC, and available P for Chom Phra. The soil particle size fractions correlated with bulk density, soil-water properties (SWC, HC, FC, PWP, and AWC), and soil chemical properties (pH, available P, and available K; Table 4.4, 4.5).

Table 4.2 Variation and significant differences in soil properties of Tha Tum and Chom Phra sites.

Variable[1]	Site	n	Mean	Minimum	Maximum	SD	*t*-value
Relative elevation (m)	Tha Tum	25	5.6	0.0	12.7	3.7	3.0**
	Chom Phra	27	8.7	2.7	15.0	3.7	
Yield 2011 (t ha^{-1})	Tha Tum	13	2.7	1.6	3.5	0.6	-1.4
	Chom Phra	8	2.1	0.9	3.2	0.7	
Yield 2012 (t ha^{-1})	Tha Tum	14	2.4	0.4	5.0	1.3	-1.3
	Chom Phra	18	1.8	0.3	3.5	1.0	
Yield 2013 (t ha^{-1})	Tha Tum	23	2.3	1.0	3.5	0.6	-0.5
	Chom Phra	25	2.2	1.2	4.5	0.8	
Sand content (%)	Tha Tum	25	78.5	66.1	83.7	4.1	-3.0**
	Chom Phra	27	73.6	55.7	82.7	7.0	
Silt content (%)	Tha Tum	25	15.5	10.1	21.7	3.4	3.3**
	Chom Phra	27	19.7	12.2	33.6	5.3	
Clay content (%)	Tha Tum	25	6.0	2.5	13.5	2.2	0.9
	Chom Phra	27	6.7	3.4	11.1	2.2	
Bulk density (g cm^{-3})	Tha Tum	25	1.5	1.3	1.6	0.1	0.1
	Chom Phra	27	1.5	1.4	1.7	0.1	
SWC (%)	Tha Tum	25	12.2	4.3	20.2	4.4	2.2*
	Chom Phra	27	14.6	7.2	23.1	4.0	
HC (%)	Tha Tum	25	2.0	0.0	7.1	1.8	-1.4
	Chom Phra	27	1.4	0.0	9.3	1.9	
FC	Tha Tum	25	9.3	6.2	13.9	1.8	1.5
	Chom Phra	27	10.4	5.9	16.2	2.7	
PWP	Tha Tum	25	3.3	1.9	6.7	0.9	1.6
	Chom Phra	27	3.8	2.1	5.5	0.9	
AWC (%)	Tha Tum	25	6.0	4.3	9.1	1.2	1.4
	Chom Phra	27	6.7	3.8	10.7	1.9	
Organic matter (%)	Tha Tum	25	0.8	0.5	1.1	0.2	0.3
	Chom Phra	27	0.8	0.6	1.2	0.1	
Available P (g kg^{-1})	Tha Tum	25	4.8	0.1	20.0	4.5	1.7
	Chom Phra	27	8.2	1.0	26.0	8.2	
Available K (g kg^{-1})	Tha Tum	25	15.4	7.0	37.0	7.1	-2.7*
	Chom Phra	27	11.2	7.0	17.0	2.4	
pH	Tha Tum	25	4.8	4.2	6.2	0.5	-3.6**
	Chom Phra	27	4.5	4.1	4.8	0.2	

*, ** significant at probability levels of 0.05, 0.01, respectively.
[1] SD: standard deviation, SWC: Soil water content, HC: Hydraulic conductivity, FC: Field capacity, PWP: Permanent wilting point, AWC: Available water capacity.

4.3.2 Relationship between rice yield and soil properties

Rice yields correlated with AWC, soil particle size fractions, and bulk density, but not with soil chemical properties such as pH, available P, and available K, except for available K for Chom Phra in 2012 (Table 4.4). The only parameter that showed a significant correlation with rice grain yield for all of the plots in all three study years was AWC. This relationship was observed in 2011 and 2012 at Tha Tum, but not at Chom Phra in all three study years. The relationship between rice yield and AWC can be seen in the maps drawn by the kriging method (Fig.4.2 and 4.3). For Tha Tum, the yields in 2011 and 2012 and AWC were high above and below the diagonal line from the northwest (top right) to southeast (bottom left).

Soil particle size fractions correlated with yield of both sites in 2011 and with a yield of Tha Tum in 2012 (negative for sand content and positive for silt and clay contents), but they were not correlated with yield in 2013 (Table 4.4). Soil bulk density correlated positively with the yield of all plots in 2011, with the yield of Tha Tum in 2012, and with the yield of Chom Phra in 2011 (Table 4.5). Relative elevation was negatively correlated with yield of all plots in 2011 and with yield of Tha Tum in 2012 but not with the yield of any year in Chom Phra (Table 4.4, 4.5).

4.3.3 Relationships between relative elevation and soil properties

Relative elevation was significantly negatively correlated with soil properties (i.e., bulk density, pH, and soil-water properties (AWC, SWC, FC, and PWP); Table 4.4, 4.5). It was also correlated with soil particle size fractions (negative with clay and silt contents, and positive with sand content); the correlations were stronger in Chom Phra than in Tha Tum. Correlations between relative elevation and particle size fractions were found for all plots, except for silt content (Table 4.3). The relationships between relative elevation, sand content, and AWC are found in Fig. 4.2. Sand content was high, and AWC was low at the high elevations in both sites.

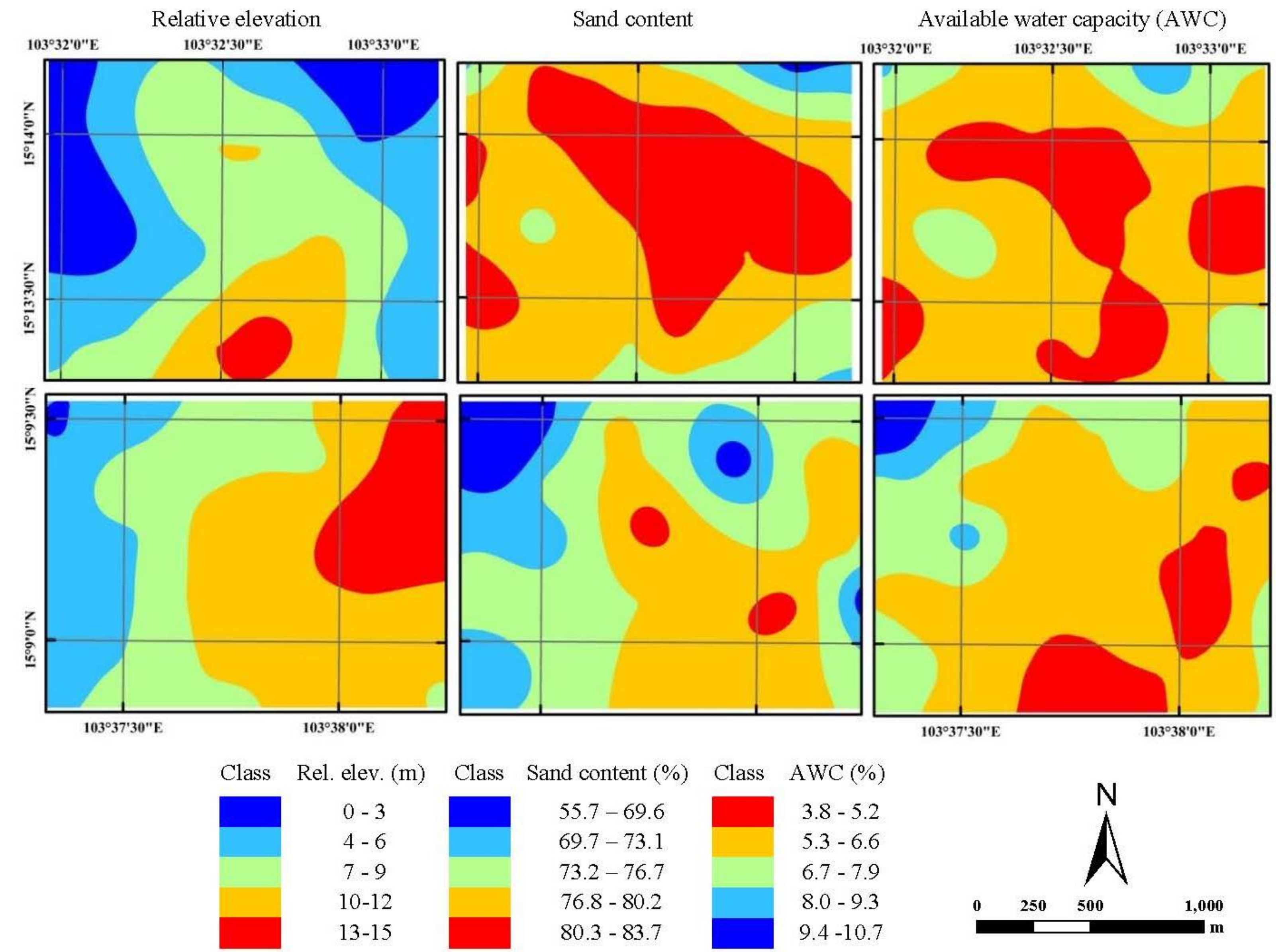

Fig. 4.2 Yield-controlling factor distribution maps of Tha Tum (above) and Chom Phra (below).

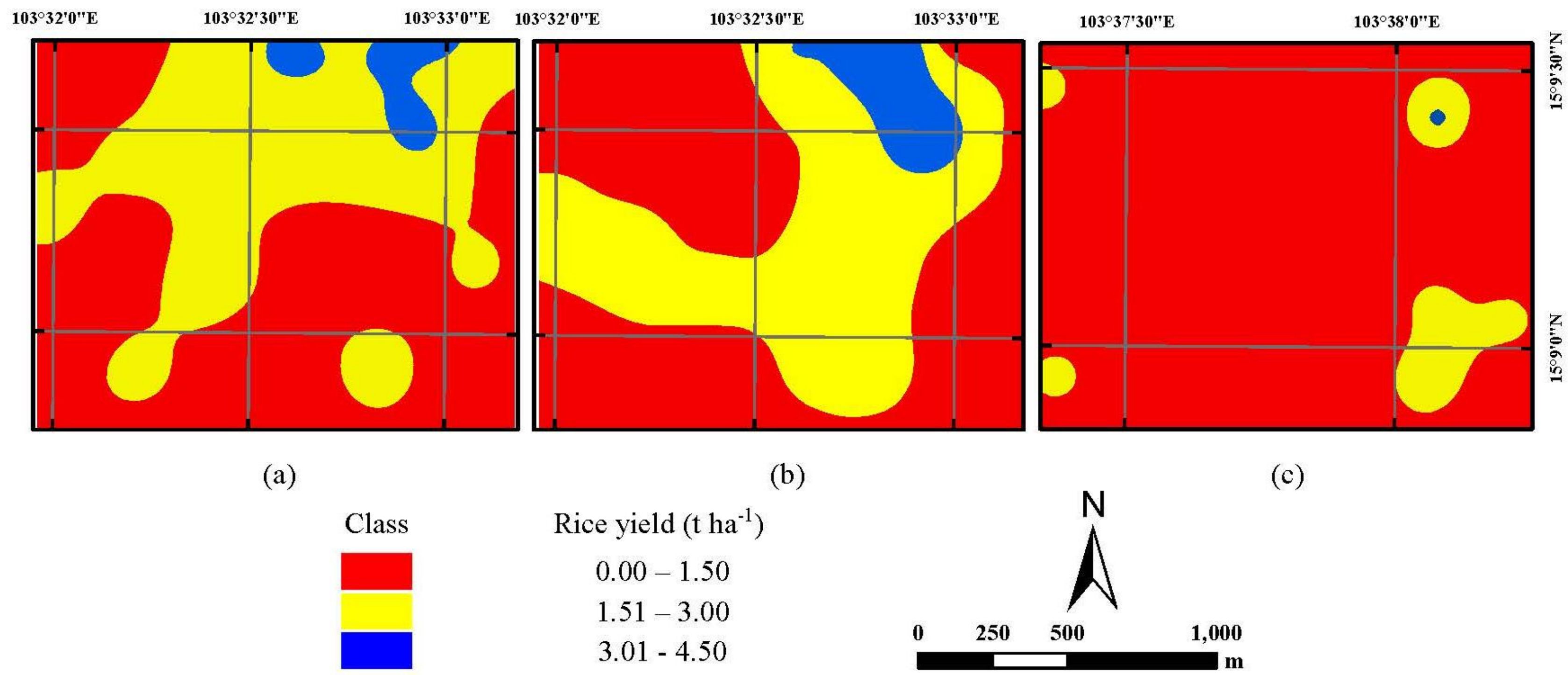

Fig. 4.3 Yield map in Tha Tum 2011 (a), 2012 (b), and yield map in Chom Phra 2011 (c).

Table 4.3 Spearman correlation coefficients between plant and soil properties at all plots.

Variable[1]	n	Rel. El.	Yield 2011	Yield 2012	Yield 2013	Clay	Silt	Sand	Bulk density	SWC	HC	FC	PWP	AWC	Organic matter	Avl. P	Avl. K
All																	
Rel. elevation	52																
Yield 2011	21	-0.39*															
Yield 2012	32	-0.28	0.66**														
Yield 2013	48	-0.09	0.35	0.49**													
Clay content	52	-0.27*	0.49*	0.15	0.11												
Silt content	52	-0.21	0.42*	0.17	0.10	0.93**											
Sand content	52	0.27*	-0.49*	-0.15	-0.11	-1.00**	-0.93**										
Bulk density	52	-0.24*	0.43*	0.14	-0.06	0.23*	0.20	-0.24*									
SWC	52	-0.26*	0.21	0.43**	0.08	0.28*	0.37**	-0.29*	0.47**								
HC	52	0.17	-0.36	-0.18	-0.03	-0.42**	-0.45**	0.42**	-0.64**	-0.66**							
FC	52	-0.33**	0.11	-0.17	0.01	0.52**	0.26*	-0.52**	0.27*	0.04	-0.14						
PWP	52	-0.51**	0.40*	0.18	0.17	0.73**	0.56**	0.73**	0.32*	0.31*	-0.26*	0.81**					
AWC	52	-0.53**	0.53**	0.38*	0.25*	0.74**	0.66**	-0.74**	0.28*	0.45**	-0.33**	0.57**	0.93**				
Organic matter	52	-0.04	0.05	0.16	0.07	-0.02	-0.09	0.02	-0.07	-0.07	0.07	0.08	-0.01	-0.07			
Available P	52	0.22	-0.23	-0.23	0.02	-0.20	-0.24*	0.20	-0.22	-0.15	0.23	-0.08	-0.20	-0.28*	0.22		
Available K	52	-0.08	0.17	0.28	0.11	-0.18	-0.27*	0.17	-0.10	-0.25*	0.29*	0.19	-0.01	-0.11	0.11	0.19	
pH	52	-0.35**	0.19	0.10	-0.04	0.02	-0.04	-0.02	0.23*	-0.01	-0.04	0.13	0.11	0.05	0.07	-0.46**	0.12

*, ** significant at probability levels of 0.05, 0.01, respectively.

[1] SWC: Soil water content, HC: Hydraulic conductivity, FC: Field capacity, PWP: Permanent wilting point, AWC: Available water capacity.

Table 4.4 Spearman correlation coefficients between plant and soil properties at Tha Tum site.

Variable[1]	n	Rel. El.	Yield 2011	Yield 2012	Yield 2013	Clay	Silt	Sand	Bulk density	SWC	HC	FC	PWP	AWC	Organic matter	Avl. P	Avl. K
Tha Tum																	
Rel. elevation	25																
Yield 2011	13	-0.47															
Yield 2012	14	-0.50*	0.76*														
Yield 2013	23	0.14	0.18	0.45													
Clay content	25	-0.44*	0.65**	0.47*	0.30												
Silt content	25	-0.41*	0.59*	0.51*	0.27	0.89**											
Sand content	25	0.44*	-0.65**	-0.47*	-0.30	-1.00**	-0.89**										
Bulk density	25	-0.24	0.18	0.50*	0.07	0.11	0.00	-0.11									
SWC	25	-0.42*	0.36	0.76**	0.19	0.08	0.19	-0.08	0.54**								
HC	25	0.32	-0.40	-0.59*	-0.17	-0.22	-0.30	0.22	-0.51**	-0.61**							
FC	25	-0.25	-0.07	-0.52*	-0.13	0.12	-0.23	-0.12	0.36*	-0.24	0.20						
PWP	25	-0.61**	0.38	0.38	0.16	0.54**	0.32	-0.54	0.53**	0.29	-0.12	0.63**					
AWC	25	-0.67**	0.71**	0.71**	0.22	0.68**	0.60**	-0.68**	0.47**	0.58**	-0.37*	0.22	0.85**				
Organic matter	25	-0.04	0.42	0.30	0.15	0.18	0.08	-0.18	0.14	-0.03	-0.04	0.23	0.17	0.08			
Available P	25	0.33	-0.31	-0.25	-0.20	-0.38*	-0.56**	0.38*	-0.17	-0.28	0.34*	0.17	-0.12	-0.35*	0.20		
Available K	25	0.12	0.06	-0.06	-0.24	-0.16	-0.33	0.16	-0.02	-0.39*	0.35*	0.38*	-0.03	-0.27	0.22	0.55**	
pH	25	-0.21	0.31	-0.04	0.00	0.29	0.36*	-0.29	0.20	0.06	-0.21	0.10	0.12	0.13	0.32	-0.45*	-0.19

*, ** significant at probability levels of 0.05, 0.01, respectively.

[1] SWC: Soil water content, HC: Hydraulic conductivity, FC: Field capacity, PWP: Permanent wilting point, AWC: Available water capacity.

Table 4.5 Spearman correlation coefficients between plant and soil properties at Chom Phra site.

Variable[1]	n	Rel. El.	Yield 2011	Yield 2012	Yield 2013	Clay	Silt	Sand	Bulk density	SWC	HC	FC	PWP	AWC	Organic matter	Avl. P	Avl. K
Chom Phra																	
Rel. elevation	27																
Yield 2011	8	-0.10															
Yield 2012	18	-0.08	0.29														
Yield 2013	25	-0.19	0.77*	0.53*													
Clay content	27	-0.57**	0.67*	0.13	0.12												
Silt content	27	-0.48**	0.69*	0.12	0.13	0.94**											
Sand content	27	0.57**	-0.67*	-0.14	-0.13	-1.00**	-0.94**										
Bulk density	27	-0.23	0.74*	0.06	-0.01	0.33*	0.33*	-0.34*									
SWC	27	-0.29	0.29	0.35	0.16	0.22	0.31	-0.23	0.46**								
HC	27	0.30	-0.76*	-0.11	-0.19	-0.36*	-0.41*	0.37*	-0.74**	-0.62**							
FC	27	-0.68**	0.31	0.13	0.14	0.75**	0.52**	-0.75**	0.21	0.13	-0.27						
PWP	27	-0.67**	0.43	0.13	0.24	0.84**	0.67**	-0.84**	0.19	0.24	-0.26	0.93**					
AWC	27	-0.63**	0.60	0.27	0.27	0.82**	0.71**	-0.82**	0.19	0.27	-0.25	0.83**	0.96**				
Organic matter	27	-0.23	-0.43	0.06	0.12	-0.27	-0.33*	0.27	-0.28	0.03	0.19	-0.11	-0.17	-0.20			
Available P	27	0.09	0.06	-0.13	0.18	-0.25	-0.18	0.25	-0.33*	-0.05	0.29	-0.39*	-0.32*	-0.29	0.17		
Available K	27	0.01	0.23	0.56**	0.25	0.05	0.00	-0.05	-0.20	0.24	0.00	0.22	0.20	0.24	-0.01	-0.01	
pH	27	-0.17	-0.21	0.05	-0.20	0.20	0.01	-0.20	0.35*	0.12	-0.19	0.50**	0.30	0.16	-0.13	-0.37*	0.26

*, ** significant at probability levels of 0.05, 0.01, respectively.

[1] SWC: Soil water content, HC: Hydraulic conductivity, FC: Field capacity, PWP: Permanent wilting point, AWC: Available water capacity.

4.4 Discussion

4.4.1 Rice yield and the effects of soil properties

During three experimental years, the cultivation conditions at Tha Tum and Chom Phra illustrated the variability typical for rainfed lowland rice environments in northeast Thailand. The lowest yield occurred in the driest year (2012), while the highest yield occurred in the wettest year (2011). Rice grain yield of 2.1 t ha^{-1} from both sites was in the range of average yield in northeast Thailand. Yield in this region is the lowest among all regions in Thailand because of three main constraints of the region—strong acidity, low nutrient levels, and low water holding capacity of soils (Prueksapong *et al*., 2015).

The only parameter correlated with rice grain yield for all of the plots in every study year was AWC. This indicated that AWC was the most important factor directly affecting the rice grain yield. The influence of available water on rice yield has been shown in field experiments and from normal to high rainfall assumptions in model estimation studies. From field experiments, Pantuwan *et al*. (2002) reported yield reductions of 19%–81% because of water limitations in northeast Thailand. Ouk *et al*. (2006) reported yield reductions of 12%–46% in Cambodia. From model estimations, yield reductions from water limitation were higher in Thailand (11%–58%) (Jongdee *et al*., 1997) than in Indonesia (0%–28%) (Boling *et al*., 2010), Cambodia (0%–22%) (Tsubo *et al*., 2009), and Laos (4%–12%) (Inthavong *et al*., 2014). In contrast, water limitation was less influential than a nutrient limitation on yield reductions reported in northeast Thailand, Indonesia (Boling *et al*., 2010; 2011), and Laos (Inthavong *et al*., 2014). The studies on nutrient limitation in northeast Thailand claimed that fertilizer response was poor (Ragland and Boonpuckdee, 1987), especially when compared with several other countries (Wade *et al*., 1999). The only soil chemical property that was correlated with yield was available K with Chom Phra yield in 2012, which is consistent with previous studies. The results indicated that rice yield strongly correlated positively with available K but not with available P (Liu *et al*., 2014; Mamun *et al*., 2015).

The correlation of soil particle size fractions with rice grain yield was found in specific sites and years; specifically, in both Tha Tum and Chom Phra sites in 2011, only in Tha Tum in 2012, and nowhere in 2013. Notably, the soil particle size fractions correlated with other yield-controlling properties, especially bulk density and soil-water properties, i.e., AWC, SWC, HC, or FC, as well as the yield. The soil particle size fractions would be indirect factors controlling yield following soil-water properties because the particle size fractions had a linear relationship with soil-water properties (Saxton and Rawls, 2006).

4.4.2 Relationship between rice yield-controlling factors

AWC correlated with other yield-controlling factors, i.e., soil particle size fractions, bulk density, SWC, HC, FC, and PWP. The correlations between AWC and soil particle size fractions were supported by a strong positive relationship between AWC and silt plus clay content, which indicated low water storage in high sand content fields (Prueksapong *et al*., 2015). A previous study by Saenya *et al*. (2015) in Sisaket Province in northeast Thailand reported that soil textures were the most critical factor for rapid water infiltration rate and soil moisture shortage risk, particularly in soils of loamy sand to sandy loam topsoil. In coarse soil texture-dominated areas, decreased water availability caused by fast infiltration rates reduces rice growth and production because of water stress. The relative elevation significantly correlated with all yield-controlling factors except for HC, i.e., soil particle size fractions, bulk density, SWC, FC, PWP, and AWC (Table 4.3-4.5). In northeast Thailand, the effects of topographical position on the undulating gentle slope are evident—even a few meters' difference (Homma *et al*., 2004) can determine whether an acceptable yield is gained or not (Haefele *et al*., 2006). In addition to drought in the growing season of this region, the high topographical position accelerates water scarcity, limiting rice yield (Homma *et al*., 2004). Slight differences in elevation can differentiate soil properties and hydrological conditions (Tsubo *et al*., 2006).

The elevation difference in topography would be a hidden yield-controlling factor by influencing the soil texture gradient (Eshett *et al*., 1989; Yamauchi, 1992) and then AWC.

In this study, higher elevations would have higher sand content (Boling *et al*., 2008; Haefele and Konboon, 2009; Prueksapong *et al*., 2015) and lower AWC than lower elevations. The paddy fields in high positions have low amounts of available water (Homma *et al*., 2004; Tsubo *et al*., 2006), and they generally experience high water stress (Haefele and Konboon, 2009) frequently in sandy soils with clay content less than 7% (Inthavong *et al*., 2011). The water stress concurrently reduces indigenous nutrient supplies (Haefele *et al*., 2008). The fields at higher elevations receive less water input from upper areas and have higher percolation rates, and thus lose standing water earlier than lower positions (Tsubo *et al*., 2006). Therefore, the sites at higher elevations have more risk of water limitation and yield reduction than those at lower elevation. This relationship was reported in Laos by Tsubo *et al*. (2006) and Inthavong *et al*. (2011), who investigated the variation in water availability and yield across a toposequence.

4.5 Conclusion

In this investigation of the factors controlling rice yield, correlations between the rice grain yield and soil physicochemical properties and elevation were analyzed in Surin Province, northeast Thailand. The results indicated that soil-water properties, especially AWC, were the most important yield-controlling factors, whereas the chemical status of soils was less important. AWC correlated with the soil particle size distributions. The rice fields at lower positions had higher clay and silt contents and thus had higher AWC than those at higher positions. Selective transportation of fine particles from high to low elevations might contribute to clay and silt distributions in the sites. To stabilize or increase rice yield in the region, the top priority should be water management at high elevations with sandy textured soils.

CHAPTER 5 General discussion and conclusion

5.1 Soil fertility status by soil/land classification inference

According to the analysis using 30,471 soil samples in Chapter 2, soil fertility status in Northeast Thailand was characterized by very strongly acidic (low pH), moderate available phosphorus (AP) levels, low organic matter content (OM), and low available potassium (AK) content. High coefficients of variation (CV) were observed for OM, AP, and AK (CV ≥ 35%) (Bahrami *et al*., 2019; Khan *et al*., 2021), while soil pH was moderately variable (CV = 15–34%). Among these properties, the highest variation was in AP, and the smallest variation was in pH (Cox *et al*., 2006; Liu *et al*., 2020; Li *et al*., 2021). The moderate pH and high OM variables could be attributed to pedogenic processes influenced by topographical position variations (Vasu *et al*., 2017).

The differences in the soil properties among the classification groups either by land use, landform, or soil order were significantly different at the 5% level, but the R^2 values were as low as 10%. One of the reasons could be attributable to an inherent limitation of soil mapping. According to Young (1973), soil maps have limitations for predicting soil properties accurately because of the following reasons: 1) More than half the total variability in soil properties, with respect to a large region, commonly occurs within areas as small as 1 hectare or even 10 m^2. Within areas or mapping units of this size, coefficients of variation for individual properties are 20–70%. 2) The purity of mapped soil series, that is, the percentage of the mapped area that actually belongs to the series indicated on the map, was formerly assumed to be about 85 % but actually is usually found to be only 50–65 %. 3) The accuracy with which a given soil property can be predicted from a soil map varies with map scale: the accuracy rises rapidly with an increase in scale from small to medium.

Auxiliary information such as soil/land classification categories of soil order, land use types, and landforms was used when it was thought relevant to a particular soil/land property. One reason why landform could explain the soil properties more strongly is probably that landform or topographical position may affect the particle size distribution of soils, which could correlate with many soil properties, including pH, OM, and AK, through redistribution of finer particles by soil erosion.

The relevance of the soil properties particle size and topographical position were investigated on the basis of the landform categories' mean difference (Table 2.3). Noteworthy that under the elevation range of 170 to 240 m amsl of northeast Thailand, the arable areas are mostly typical sandy soils, intense weathering, and high precipitation conditions. However, floodplains, landforms on the lowest topographical position, were excluded from consideration because at these landforms soil properties are not influenced only by topographical position but also by complex fluvial depositional systems.

The pH and AK of both denudation peneplains and alluvial plains had higher values in soils with fine, medium, and coarse particle size, respectively. In addition, all particle sizes in higher position landforms of denudation peneplains had higher pH and AK values than those in alluvial plains (Table 5.1). This indicated the equivalent influence of particle size and topographical position in relation to pH and AK. (Table 5.2). Soil pH differed with topographical position and correlated with fineness of particle size (Bai and Wang, 2011), according to the soil texture deviated by slope position. Moreover, landscape elevation contributed to soil pH (Salako *et al*., 2006). The AK content correlated with topographical position and differed with soil texture (Li *et al*., 2021). The potassium values varied with particle size distribution and weathering processes, while the K form occurrence was associated with landform and soil fraction (Sharma *et al*., 2006).

The OM and AP contents in denudation peneplains and alluvial plains were similar, with a trend that soils with finer particle sizes had higher OM and AP contents (Table 5.1). Thus, OM and AP contents were more strongly influenced by particle size than the topographical position (Table 5.2). In agreement with this finding, Spohn (2020) reported phosphorus content of the clay size fraction was on average 5.1 times more than that of the sand size fraction. Support of this result was obtained in Hefeng County, China, where it was reported topographical position was related to lower OM and AP content at higher topographical positions, while coarse particle size was related to the lowest OM and AP contents in sandy soil (Li *et al*., 2021).

Therefore, the explanation of soil properties, including pH, OM, AP, and AK, by landform with particle size classification would be improved by adding information on topological positions. The study results in relation to soil/land process and classifications of soil properties could be summarized as shown in Table 5.2.

Table 5.1 Landform categories mean differences and the partial regression coefficient of soil property prediction model.

	pH			OM			AP			AK		
1-FpBs	fg	0.020	****	d	0.021	****	bc	0.367	*	f	1.200	***
2-FpLv	efg	0.016	**	d	0.038	****	d	1.311	****	e	-	
3-AluC	a	-		a	-0.009	**	a	-		a	-1.557	****
4-AluM	b	-		b	-		a	-		b	-1.045	***
5-AluF	c	0.008	*	c	0.007	**	c	0.404	**	d	-	
6-DnC	cd	0.006	*	a	-0.012	****	c	-		c	-1.095	****
7-DnM	ef	0.010	***	b	-0.005	*	bc	-		d	-0.827	***
8-DnF	h	0.028	****	e	0.031	****	d	0.910	****	g	1.141	****
9-DnS	g	0.015	****	d	0.015	****	b	0.320	**	e	-	

Table 5.2 Soil properties related to soil/land processes and classifications.

Soil property	Classification inference effectiveness	Particle size and Topographical position relevant	Relate process
pH	landform > land use > soil order	particle size = topographical position	leaching
OM	landform > soil order > land use	particle size > topographical position	erosion, salinity
AP	land use > landform > soil order	particle size > topographical position	soil management
AK	landform > soil order > land use	particle size = topographical position	adsorption, fixation

5.2 Modification of soil/land classification

The soil/land classification should have a more significant influence on development plans than implied soil fertility status. A further consequence is crop yield estimation for each soil type. Soil responses to changes in land use are required. The final soil/land classification map should show the units of land which have a defined quantitative value for agricultural development. The land evaluation operation should indicate where alternative forms of land use or crops exist and provide soil-specific estimates of crop yields under a specified management level.

The soil/land classification limitations on inferring soil fertility status should be emphasized in the context of the sandy texture with low nutrient contents (low pH and low available P, available K, and organic matter contents) under alluvial systems and fluvial depositional systems in northeast Thailand.

The soil fertility status inference limitation may be overcome by alternative improvements as follows: 1) Soil/land classification could be modified. The taxonomic communication in soil maps emphasizes geomorphology-soil relationships, expressing how they typically occur in the field rather than providing agriculturally relevant soil property information. Most of the users do not understand the concept of soil series and prefer soil properties directly relevant to their needs. Therefore, modification for the simple soil classification information transfer should be introduced. 2) Stronger prediction models with more efficient methods could be developed to improve the prediction of the soil spatial distribution at the optimal study scale. 3) It is possible to provide soil analytical services for farm fields to monitor soil degradation and to conserve soil sustainability for agriculture. Because of the fact that soil properties have changed more quickly than survey capacity, very few places have up-to-date surveys. Therefore, actual nutrients in the soil today are very different from the nutrient data currently available.

5.3 Spatial variation of soil properties and factors controlling rice yield

The spatial variability of soil properties in paddy fields was reported in various scales of study (Yanai *et al.*, 2001; Vieira and Gonzalez, 2003; Moritsuka *et al.*, 2004; Vasu *et al.*, 2017). The spatial variability of soil properties on a regional scale (Brejda *et al.*, 2000; Couto *et al.*, 1997) were under the influence of topographic variables, such as elevation (He *et al.*, 2015), slope (Liu *et* *al*., 2013), and various soil forming factors; on field scale (Van Es *et al*. 1999; Mamun *et al*., 2015; Vasu *et al*., 2017) under the influence of land use activities; and on a single field scale (Earl *et al*., 2003; Godwin and Miller, 2003, Cox *et al*, 2005) under the influence of crop yield effects and soil performance (Yemefack *et al*., 2005). Spatial variation of soil properties has been reported in even within a small rice field (Dobermann *et al*., 1995; Moritsuka *et al*., 2004; Inthavong *et al*., 2011; Oo *et al*., 2013).

The spatial variation of soil properties relates to the topographical position, in terms of internal runoff and deposition processes (Homma *et al*. 2003, Dercon *et al*., 2006). The increase of water availability, soil fertility, and crop productivity was observed at the lower topographical position due to soil organic matter accumulation and clay deposits (Homma *et al*., 2003; Tsubo *et al*., 2007; Boling *et al*., 2008).

The spatial variation of soil properties in relation to rice yield, such as soil texture, pH, and organic matter content (Ahn *et al*., 2005) could explain more than 50% of yield variation (Dobermann, 1994; Casanova *et al*., 1999; Yanai *et al*., 2001). The specific influence of the topographical positions and soil texture seemed to indicate available water content in the fields, which is the most influential variable to the rice yield (Cox *et al*, 2006).

The factors controlling rice yield indicated that AWC was the most critical yield-controlling factor, whereas the chemical status of soils was less important. The topographical position is also a yield-controlling factor by influencing the soil texture gradient and then AWC. Therefore, AWC with topographical position and soil texture relation were the most useful to the yield predicting parameters. These results strongly suggest that, among soil information, landform and relating soil texture should be valued as yield-determining factors.

5.4 Conclusion

The soil properties in northeast Thailand, including pH, organic matter content (OM), available phosphorus (AP), and available potassium (AK), differed significantly (at the 5% level) between the different soil orders, land uses, and landform categories. In the regional soils, landform classification well-explained the pH, OM, and AK variability, and for AP, land use was the best parameter. Therefore, alternative recommendations are: (1) to modify the simple soil classification information transfer, (2) to develop stronger prediction models, and (3) to provide sequential soil analysis for farms.

This study clarified the relationship between the topographical position of soils and three main constraints for lowland rice production in paddy soils of northeast Thailand under the strong influence of sandy parent materials and tropical savanna climate. The constraints are first, the strong acidity of soils; second, the low nutrient level and associated soil properties, i.e., low TN, TC, CEC, low AP, and low AK; and third, the low water holding capacity of soils. All of these constraints were more serious at high topographical positions. The soils at high topographical positions indicated a risk for nutrient depletion and water deficiency, with more acidity under leaching conditions. In contrast, soils at low topographical positions showed the potential for salinity problems due to water movement in nutrient accumulation and leaching because of water stagnation and drainage.

The factor controlling yield in rainfed rice fields in undulating topography characteristic of northeast Thailand was available water capacity (AWC). The AWC was low in the soils with high sand content at high topographical positions. Chemical properties did not have significant effects on the yield. The priority for managing rice production systems to increase yields should be managing the water availability.

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