Impact of agricultural practices on the biogeochemical functioning of sandy salt-affected paddy soils in Northeastern Thailand

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Keywords: Soil salinity, land management, organic matter, paddy systems

Abstract

Most lowlands in Northeast Thailand are cultivated to rainfed rice. The main constraint for rice production is drought associated with sandy and acid soils that are also often saline. Efficient water management and organic matter (OM) inputs are low-cost solutions used by farmers to limit salinity effects and to enhance the physico-chemical properties of paddy soils where yield is very low. Field monitoring was conducted during the 2003 rainy season to explore the interactions between land management (i.e. water management and OM incorporation), salinity and soil function. Several parameters (Eh, pH, EC) were continuously measured inside and outside saline patches in two adjacent contrasting plots, differing in management (high management i.e. water management and OM addition vs low management no OM input limited water management). Soil solution was regularly sampled at three depths and analysed for Mn and Fe.

High reducing conditions appeared after flooding in all sites, but were limited inside the saline patch without OM addition. Anoxic processes lead to the reduction of Fe- and Mn-oxides, especially when OM was added. Oxide reduction led to the consumption of H+ and the greater the degree of Fe reduction, the larger the increase in pH. Where OM was not incorporated, high salinity prevented the establishment of the reduction processes and pH stabilised around 4. Even under high reduction conditions, Fe concentrations in the soil solution were below commonly observed toxic values. Moreover, amended plots had better rice production yield.

Water management and availability of organic carbon, which maintain saturation and control the extent of the reduction, are processes of major importance for pH regulation and rice production. Moreover, these practices were able to counteract the toxic effects that occurred in salt-affected paddy fields.

Introduction

Most lowlands in Northeastern Thailand are cultivated with rice, but among them, 8.5% have been classified as severely salt-affected (Arunin, 1984) due to the rising of the water table since land clearing. Water rises to the surface by capillary action and evaporates, so salts accumulate at the soil surface and a saline crust can be observed during the dry season. Therefore, salinity drastically affects soil fertility and rice productivity, already affected by the acidity of these sandy soils. Then, farmers focus their efforts on cultivating less affected soils, so the result is that the salt-affected soils become more damaged. However, in Isaan, efficient water management and organic matter addition or green manuring are low cost solutions used by farmers to supply nutrients to these poorly fertile soils.

In paddy soils, incorporating rice straw or green manure can be an useful way of adding organic matter and thus increasing carbon storage and providing nitrogen, phosphorus, potassium and other nutrients to soils (Vityakon et al., 2000). However, a poorly controlled incorporation of OM can be responsible of the appearance of strong reducing conditions that may have adverse effects on rice cropping, as for instance the production of sulphide and the subsequent formation of black roots (Gao et al., 2004) or organic

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acid toxicity (Saenjan, 1999). The addition of organic matter or the incorporation of crop residues increases the organic matter availability and thus the anaerobic bacterial activity. This can lead to a high transfer of electrons from organic matter to oxides, especially amorphous or poorly crystallised ones, leading to the reduction of both manganese and iron, and also to the establishment of strongly reducing conditions. Solubilisation of these elements is a function redox conditions driven by bacterial activity, organic matter availability, soil moisture and thus agricultural management. Moreover, reduction processes control the pH and the ionic composition of the soil solution, both acting on soil fertility (Ponnamperuma, 1976). Thus, Mn and Fe are key indicators for understanding the reduction processes and thus the biogeochemical functioning of rice paddy soils.

In order to quantify the impact of realistic low cost agricultural practices on the biogeochemical functioning of paddy fields in N.E. Thailand, we have studied the interactions between agricultural management (i.e. organic matter addition, water level control), salinity and redox processes, during the 2003 rainy season. Field measurements included pH, Eh, EC and major elements in the soil solution, with a particular focus on Fe dynamics.

Materials and methods

The field investigation was carried out in 2003, from July to November. Two rainfed lowland paddy fields of a rice cropped watershed in Isaan, close to Phra Yun in the Khon Kaen district (E 102º38′- N 16º22′) were selected, as representative of two types of farming practices: an intensively managed plot (L25 plot, 599 m^2) and a poorly managed one (L14, 718 m^2). The first plot was characterized by organic matter addition (buffalo, poultry and pig manure mixed with sawdust), of around 170 kg $plot^{-1}$ $year^{-1}$, corresponding to 2.4 t ha^{-1} $year^{-1}$ wet weight, and efficient water control with a high bund system that allows an almost continuous flooding. The second one did not receive any particular treatment, i.e. neither organic matter addition nor water management.

Saline patches were observed during the dry season inside each plot, and monitoring points were selected to reach the maximum contrast of salinity over a short distance (i.e. 8 meters). In each plot, one monitoring point was located inside an area were the production of rice was affected by high salt contents (soil conductivityobtained by EM38 higher than 250 $mS.m^{-1}$, labelled S for saline) while the other monitoring point was located in an area where rice yield was non affected by salinity (soil conductivity around 150 $mS.m^{-1}$, labelled NS for non saline).

Soils were sandy loam from the soil series Kula Ronghai (Natraqualf), which predominates in salt affected zones of Northeast Thailand lowlands. Main characteristics are summarised in Table 1.

The composition of flooding water, groundwater and soil solution was monitored during the entire rainy season. Flooding water was sampled close to each monitoring point and groundwater in piezometers. The free soil solution was sampled every week or every two days, inside and outside the saline patches, at 10, 25 and 45 cm depth in polypropylene pierced boxes

Table 1. Bulk soil analysis

		Salinity[a]		Organic matter		Exchangeable Cations[d]				Texture[e]			Bulk	Elemental analysis[g]			
Profile	Depth	Ec s.p.	pH	OC[b]	N[c]	Na^+	K^+	Ca^{2+}	Mg^{2+}	Sand	Silt	Clay	density[f]	Al	Mn	Fe	Fe_o[h]
	cm	$dS.m^{-1}$	(KCl)	$g.kg^{-1}$		$cmolc.kg^{-1}$					$g.kg^{-1}$		$g.kg^{-1}$				% Fe tot
L14-S	0-10	54.1	4.12	3.2	0.28	1.92	0.03	0.94	0.07	591	356	52	1.72	5.65	0.217	3.02	19.00
	10-20	15.6	3.98	1.8	0.16	0.97	0.03	0.71	0.07	623	305	72	1.84	8.33	0.289	6.71	12.00
	40-50	7.6	3.85	1.1	0.09	1.41	0.04	1.24	0.19	609	262	129	1.63	18.60	0.731	6.41	6.00
L14-NS	0-10	6.4	3.67	4.1	0.36	1.32	0.05	0.67	0.08	598	353	49	1.69	5.51	0.022	3.34	12.60
	10-20	2.7	3.76	1.6	0.14	0.97	0.04	0.88	0.12	622	324	54	1.81	6.98	0.025	5.01	10.50
	40-50	1.1	4.04	0.5	0.05	2.68	0.05	1.91	0.39	496	371	133	1.70	20.20	0.306	9.02	2.29
L25-S	0-10	27.1	3.85	4.7	0.41	3.09	0.15	0.92	0.13	627	311	63	1.61	6.83	0.000	3.59	21.30
	10-20	19.7	3.90	2.7	0.24	3.13	0.07	0.74	0.08	700	246	54	1.75	5.97	0.000	4.89	22.20
	40-50	30.0	4.15	0.9	0.08	1.06	0.03	0.54	0.08	728	196	76	1.62	8.68	0.000	4.14	5.60
L25-NS	0-10	12.9	4.28	3.8	0.33	0.53	0.15	0.95	0.10	679	259	62	1.55	5.89	0.046	3.50	18.30
	10-20	6.5	3.80	3.1	0.27	1.28	0.08	1.16	0.11	703	241	56	1.81	6.65	0.036	3.85	15.40
	40-50	2.9	3.71	1.0	0.09	1.76	0.05	1.34	0.28	612	236	152	1.62	26.90	0.014	7.83	3.25

a: Electrical conductivity of saturated paste, b: Organic C by Walkey and Black method, c: Kjeldahl method, d: Ammonium acetate method, e: Pipette method, f: 100 cm^3 cylinder method (average of 5 replications), g: acid attack (HF + $HClO_4$; HCl + HNO_3), h: Tamm extraction buried in soil, as described by Boivin et al. (2004). These devices allowed the soil solution to enter by free drainage and the sampling was carried out under a N2 atmosphere.

pH and EC were measured in the field as soon as possible after filtration of the soil solution, in order to prevent strong re-oxidation. Another aliquot was acidified for cation analysis by ICP-OES.

Eh was measured in situ during the entire cropping season, inside and outside the saline patches in the two plots, at 10 and 25 cm depth. In L25 plot, Eh was measured continuously every hour, whereas in L14, measurement was performed manually once a week.

Results

Flooding water did not vary in composition during the cropping period, except a slight increase in EC at the end of October, mainly due to increasing Na concentration (Table 2). The groundwater salinity was very high and the aquifer was not chemically homogenous (Table 2).

In the L25 plot, strong reducing conditions prevailed. In L25NS and L25S, Eh rapidly decreased after transplanting and stabilised around -200 to -250 mV at 10 cm depth. At 25 cm depth, Eh also decreased quickly in L25S, reaching -180 to -200 mV before increasing and stabilising at around -100 mV. In L25NS, this decrease was slower, and Eh stabilised at around -100 mV. Oxidation peaks occurred at different times, corresponding to rainfall events. Eh rapidly increased to oxidised values when plots were drained in November.

In L14NS, the Eh pattern was close to that observed in L25NS. In L14S, Eh was significantly higher than in L14NS, and higher at 25 cm than at 10 cm depth. Eh values were practically always above +100 mV, apart from an occasional rapid decrease to -45 mV at 10 cm depth.

In all locations except in L14S, EC increased with depth. Outside the saline patches, EC remained almost constant with time with slight fluctuations, around 6.4 ± 1.5 $dS.m^{-1}$, 10.7 ± 3.2 $dS.m^{-1}$ and 11.6 ± 0.8 $dS.m^{-1}$ in L25NS at 10, 25 and 45 cm depth, respectively, and around 3.5 ± 1.9 $dS.m^{-1}$, 8.1 ± 1.5 $dS.m^{-1}$ and 8.3 ± 0.6 $dS.m^{-1}$ in L14NS at 10, 25 and 45 cm depth, respectively. Electrical conductivity values and variations were larger inside the saline plots. In L14S, EC at 10 cm depth was higher than EC at 25 and 45 cm depth.

pH changes in the soil solution differed depending on the management practices and on the depth. After transplanting, pH at 10 cm depth in L25NS increased from 5 to 6.5 in a few days A similar increase, with a time lag, occurred at 25 cm (Figure 1). At 45 cm depth, pH remained low at 4.1 ± 0.5 during the entire cropping period. In L25S, pH at 10 cm depth showed the same trend as in L25NS, stabilising around 6.5. At 25 and 45 cm depth, pH remained very low, around 4.8 ± 0.5 and 3.8 ± 0.1, respectively (Figure 1). In L14NS, pH increased from 4.8 to 6.7 at 10 cm depth, much slower than in L25 and remained quite high until harvesting. At all other depths and also at 10 cm in L14S, pH remained constant around 4.

The main cation in the soil solution was Na, ranging from 14-80 $mmol.l^{-1}$ at 10 cm, 60-10 $mmol.l^{-1}$ at 25 cm and 50-135 $mmol.l^{-1}$ at 45 cm depth in L25NS and L14NS plots. Inside the saline patches, Na concentrations were significantly higher and more variable with time with most of the values ranging from 150 to 450 $mmol.l^{-1}$.

As for pH, Fe and Mn concentrations in the soil solution differed depending on the management practices and on the depth. Fe solubilisation was significantly higher in L25 than in L14 (Figure 2),

Table 2. Flooding water and groundwater analysis

		salinity		cation concentrations ($mmol.l^{-1}$)							
		pH	EC ($dS.m^{-1}$)	K	Al	Ca	Fe	Mg	Mn	Na	Si
L14S	flooding water	6.11 ± 0.71	1.41 ± 0.64	0.04 ± 0.02	0.14 ± 0.27	0.25 ± 0.15	0.03 ± 0.06	0.09 ± 0.05	0.01 ± 0.00	8.5 ± 2.6	0.32 ± 0.46
	groundwater	5.68 ± 1.77	26.0 ± 0.6	0.64 ± 0.08	0	5.5 ± 0.1	0	2.7 ± 0.1	0.04 ± 0.01	323 ± 38	0.30 ± 0.20
L14NS	flooding water	6.26 ± 0.49	1.2 ± 0.42	0.04 ± 0.03	0.22 ± 0.43	0.21 ± 0.07	0.05 ± 0.10	0.08 ± 0.02	0.01 ± 0.00	8.2 ± 2.0	0.48 ± 0.71
	groundwater	4.17 ± 1.61	7.94 ± 0.55	0.05 ± 0.02	0.03 ± 0.03	0.96 ± 0.15	0.60 ± 0.32	0.24 ± 0.03	0.09 ± 0.01	74 ± 3	0.31 ± 0.03
L25S	flooding water	5.84 ± 0.33	0.86 ± 0.46	0.03 ± 0.01	0.05 ± 0.08	0.17 ± 0.07	0.01 ± 0.02	0.10 ± 0.04	0.02 ± 0.01	4.9 ± 1.3	0.20 ± 0.15
	groundwater	3.63 ± 0.47	31.1 ± 0.8	0.28 ± 0.05	2.3 ± 0.1	6.5 ± 0.4	0	3.6 ± 0.2	0.80 ± 0.12	359 ± 55	0.32 ± 0.02
L25NS	flooding water	5.92 ± 0.49	0.81 ± 0.42	0.03 ± 0.01	0.08 ± 0.11	0.16 ± 0.07	0.02 ± 0.03	0.10 ± 0.04	0.02 ± 0.01	4.8 ± 1.4	0.24 ± 0.22
	groundwater	6.25 ± 0.74	23.0 ± 3.8	0.37 ± 0.02	0	4.7 ± 0.3	0	2.18 ± 0.15	0.10 ± 0.02	287 ± 34	0.61 ± 0.17

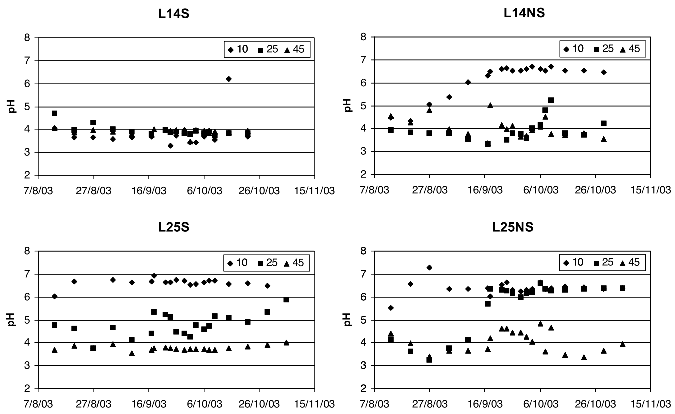

Figure 1. Changes in soil solution pH at 10, 25 and 45 cm depth, in the four monitoring points

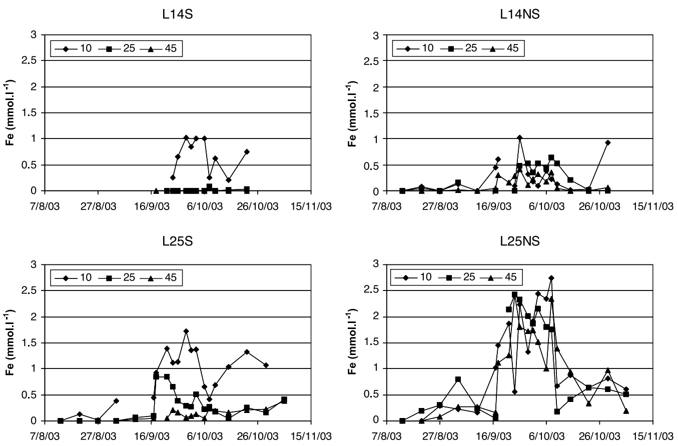

Figure 2. Fe content of the soil solution at 10, 25 and 45 cm depth, in the four sampling points

particularly outside the saline patch. Fe reduction increased with rice growth and Fe concentrations reached 2.74 and 2.5 mmol.l^{-1} in L25NS and 1.72 and 0.85 mmol.l^{-1} in L25S at 10 and 25 cm depth, respectively. At 45 cm depth, Fe solubilisation was also high in L25NS, with the same trend as at the other depths, while it remained low in L25S, less than 0.2 mmol.l^{-1}. After 55 days, Fe concentrations decreased dramatically until the rice harvesting. In L14, Fe reduction was low (Fe concentration 0 to around 1 mmol.l^{-1}), or even nil, inside the saline patch at all depths.

Discussion

Flooding leads to major chemical changes in the soil that affect element mobility. Within a few hours to days after submergence, O_2 is consumed by aerobes, which is reflected by the rapid decrease in Eh after flooding. Moreover, the controlled flooding limited, even decreased, the salinity in the top-soil layer, especially at 10 cm depth, i.e. in the root zone. The salt concentrations inside the saline patches decreased with flooding, mainly due to dilution.

The almost continuous submerged conditions induced anaerobic conditions, which were maintained during the cultural cycle. At 10 cm depth, i.e. in the rooted soil in well managed plot (L25NS and S) and also in L14 outside the saline patch, Eh reached very low values, lower than in deeper horizons, and topsoil remained highly reduced during almost the entire growth period.

Anaerobiosis leads to the establishment of reducing conditions, particularly strongly when organic matter is incorporated into the soils. Thus, other electron acceptors than O_2 are sequentially reduced: NO_3^-/N_2, Mn(III, IV)/Mn(II), Fe(III)/Fe(II), SO_4^{2-}/HS^-, and CO_2/CH_4 (Sposito, 1989), by facultative anaerobes followed by strictly anaerobes in order to oxidise organic matter (Ehrlich, 1996, Madigan et al., 2000). As a result, the concentration of reduced compounds like Fe^{2+} increases in the soil solution, and the changes in the soil solution composition are closely related to the metabolic activity of the microbial communities involved. Ferric iron is commonly the dominant electron acceptor in anoxic systems and may contribute considerably to organic matter biodegradation (Thamdrup, 2000, van Bodegom and Stams, 1999).

The reduction of oxidised compounds depends both on their availability and the presence of microbial communities in soils. Iron release increased with rice growth and was stimulated by organic matter addition, i.e. with high organic carbon availability, as observed by other authors (Tanji et al., 2003, van Asten et al., 2004). Both organic matter addition and high reducible Fe contents may increase the intensity of reduction. High concentrations of dissolved organic carbon, originating from the organic matter added, from root exudation and from the anaerobic biodegradation of root materials, were measured in L25, higher than in L14 at 10 and 25 cm depth (data not shown). These high dissolved organic carbon concentrations suggest there is no limitation in electron donors to sustain Fe reduction, particularly in the well-managed plot. Nevertheless, Fe release was highly limited under saline conditions. Salinity drastically affects microbial biomass and specific metabolic activities (Rietz and Haynes, 2003) and it can be argued that Fe reduction capabilities are also reduced. The number of active anaerobic iron-reducing bacteria is probably lower inside the saline patches and, even if organic substrates are added, their activity is probably strongly inhibited. Thus, by affecting the reducing activity inside the saline patches, salinity drastically affects the pH of the soil solution, even if organic matter is incorporated (see below).

In flooded anaerobic soils, Fe is highly available for plants and Fe toxicity may occur (Marschner, 1995; Becker and Asch, 2005). Even if lowland rice is adapted to such anaerobic conditions, Fe^{2+} can become toxic at high concentrations or when other nutrient deficiencies occur. Fe toxicity seems to appear when Fe concentration is high in the rhizosphere (Montas Ramirez et al., 2002) and when multiple deficiencies occur. In the four studied profiles, Fe concentrations were well below the concentration mentioned by Vizier (1978), so Fe toxicity seems not to be a major risk in these fields. Organic matter addition may also enhance sulfide toxicity resulting in black roots symptom (Tanji et al., 2003), but this can be counteracted by the precipitation of sulfide minerals like FeS when Fe^{2+} concentration is high (Gao et al., 2004). Even though we did not observe retarded plants having such symptoms, the conditions favouring both Fe solubilisation and sulfide accumulation need further investigations in amended plots especially if we want to propose alternative farming practices to farmers.

It is commonly observed that pH of submerged acid soils increases with time to fairly stable values close to neutrality (Ponnamperuma, 1976, Genon et al., 1994, Scott et al., 2003, Kirk et al., 2003, Kirk, 2004). pH greatly influences soil fertility as it controls several parameters like chemical equilibria and surface charges, microbial processes, plant absorption of nutrients, organic matter biodegradation, and also the availability of toxic substances (Sposito, 1989). The pH increase was quicker when organic carbon was highly available as in the L25 plot. Where organic matter was not added to soil, i.e. in low management plot, high salinity prevented high reduction in the top layer. Therefore, no pH increase occurred and pH remained unfavourable for rice growth. The two-stage pH vs time profile observed in paddy soils is mainly explained by the Fe systems. The initial pH rise is explained by the reduction of Fe oxides and the $Fe(OH)_3/Fe^{2+}$ couple. The further pH stabilisation around 6.5, when observed, may be explained by the formation of a mixed Fe(II)-Fe(III) hydroxide. Indeed, ion speciation computations revealed that the soil solutions were oversaturated with respect to an hydroxy-green rust in the intensely managed plot particularly (data not shown).

The alternation of oxic and anoxic conditions produce redoximorphic features, which were observed in the soil profile. Fe- and Mn oxide nodules were observed at 30-40 cm depth, particularly in non saline profiles. During the dry season, red coatings and iron sheaths could be observed around rice roots. They provide evidence of the biogeochemical redox processes occurring in the soil profile. Iron sheaths usually limit phosphorus availability for rice (Berthelin and de Giudici, 1993). The reduction process also may affect the CEC of the soil, especially because of the reduction of coatings that may neutralise negatively charged sites on clay minerals. Such poorly crystallised or amorphous Fe oxides, which represented a large proportion of iron in the studied soils, are preferentially reduced in hydromorphic soils (Munch and Ottow, 1980, Francis and Dodge, 1988). Moreover, structural Fe can also be reduced, thus increasing CEC (Stucki et al., 1987, Favre et al., 2002).

Conclusion

Intensive management of rainfed lowland rice soils in Northeastern Thailand has great impact on the biogeochemical functioning of these soils. It leads to the establishment of strong reducing conditions in the topsoil and to pH increase to near neutrality. Organic matter input seems to counteract salinity effects on soil chemistry and soil microbial activity. Moreover, the proportion of Fe released from the reductive dissolution of amorphous or poorly crystallized Fe oxides depends on such organic management. Thus, water management and availability of organic carbon, which maintain saturation and control the extent of the reduction, are processes of major importance for pH regulation and rice production. While strong reducing conditions appear to be favourable for pH, Fe toxicity could occur for sensitive rice cultivars as the Fe concentration in the root zone reaches high values. Repeated incorporation of organic matter could enhance the risk of Fe toxicity, particularly in such degraded and low buffered soils.

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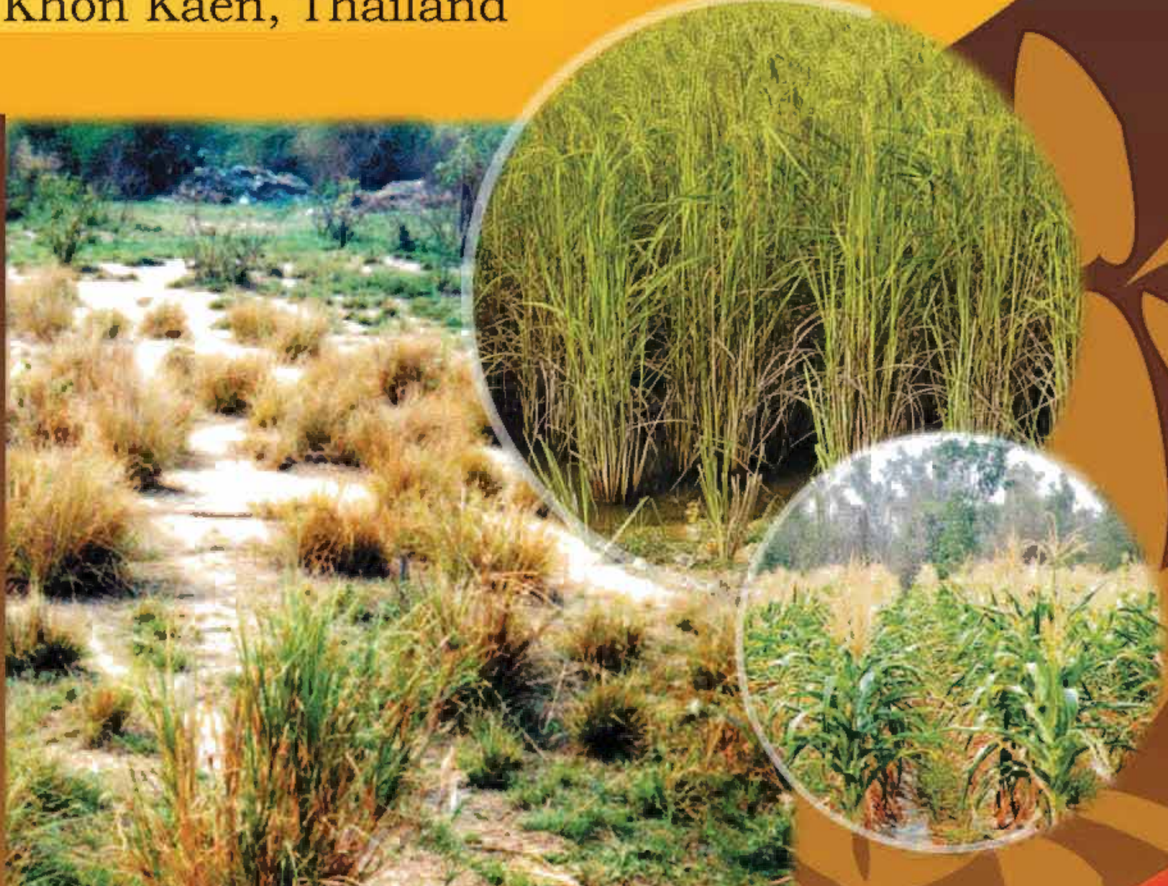

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