Toposequential Variation in Soil Fertility and Rice Productivity of Rainfed Lowland Paddy Fields in Mini-Watershed (Nong) in Northeast Thailand

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Abstract: Mini-watersheds called Nong in Thai are geographical components of rainfed lowland rice culture in Northeast Thailand, and constitute distinct units in understanding environmental constraints for low and unstable rainfed rice production there. The toposequential variation of soil fertility and its relation to rice productivity within mini-watersheds, was examined by phytometry of sampled soils and field measurements of rice growth and yield. The phytometry experiment with irrigated potted rice using soils sampled from various rice fields within each mini-watershed, revealed that soil fertility as evaluated by rice dry matter production showed a 5 times difference among the fields at most. The difference in the soil fertility was ascribed primarily to that in nitrogen (N) supply capacity, which itself had a strong correlation with soil organic carbon (SOC) content. Accordingly, the biomass production of pot-grown rice was proportional to SOC content, which suggested the usefulness of SOC as an index for soil fertility evaluation. The effect of clay on the soil fertility was much less than that of SOC. The actual rice yield in each field also showed quite large field-to-field variation, most of which was explained by the SOC content, rice growth duration and fertilizer application rate even though water availability also affected the yield. The yield positively correlated with growth duration and hence with earlier transplanting. Both SOC and clay contents of fields showed steep gradients with ascending field elevation within mini-watersheds, resulting in a marked toposequential distribution of rice yield. The toposequential distributions of SOC and clay contents imply that rice culture after deforestation accelerated soil erosion from upper to lower fields. The large toposequential gradient in soil fertility requires different resource and crop management for each toposequential position, in order to improve rice productivity of the mini-watershed as a whole.

Key words: Clay, Farmer's management, Northeast Thailand, Rainfed rice, Soil fertility, Soil organic carbon, Toposequence.

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the mini-watersheds. For this purpose, we collected soil samples from each field located at different toposequential positions in four mini-watersheds in Northeast Thailand. Fertility of the collected soils was firstly evaluated by phytometer experiment with potted rice as a test plant under irrigated condition, to identify soil factors associated with the production. Then, the toposequential variation of the phytometric soil fertility was investigated in the mini-watersheds. Finally, the effect of the variation of phytometric soil fertility on the rainfed rice production at each field in the mini-watersheds was analyzed in relation to the farmer’s crop management. This study discusses the strategy for improving rainfed rice production in the mini-watersheds, based on the results of field investigations.

Materials and Methods

1. Sampling of soils and rice plants

This study was done in a rainfed rice culture area about 25 km northwest from the center of Ubon Ratchathani City; the area extends along Se Bai River, a branch of Moon River. Four mini-watersheds (Wang O, Kha Khom, Hua Don and Mak Phrik) were selected for this study. Experimental fields were selected along a traverse line of each mini-watershed. Rainfed rice has been cultivated for about 50 years at Wang O and about 100 years at Kha Khom, Hua Don and Mak. Mini-watersheds at Wang O and Kha Khom open to rivers, and those of Hua Don and Mak Phrik are closed. The traverse line of the fields in the mini-watersheds at Wang O and Mak Phrik was from top to bottom, and that of those at Kha Khom and Hua Don extended from top on one side through bottom line to the top on the opposite side in the mini-watershed. The lines at Wang O, Kha Khom, Hua Don and Mak Phrik were 173 m, 700 m, 353 m and 257 m in length and 6.0 m, 1.6 m, 3.4 m and 2.6 m in the difference in field elevation, respectively. Cross sections on the traverse lines of the research fields are shown in Fig. 1. According to a soil map published by Department of Land Development, Thailand (Changprai et al., 1971; Kittayarak, 1971), soils in the respective mini-watersheds are classified as follows; Wang O to Khorat series (USDA Taxonomy: Ustoxic Dystropept); Kha Khom to Ubon series (Aquic Quartzipsamments) and Khorat series; Hua Don to Phimai series (Vertic Tropaquept) and Ubon series; and Mak Phrik to Roi Et series (Aeric Paleaquults).

Plow layer soils (20 cm in depth) were sampled from 5 different paddy fields along the traverse line in Wang O site and 7, 31 and 5 fields in Kha Khom, Hua Don and Mak Phrik, respectively, and subjected to phytometer experiment for evaluation of soil fertility. These fields belong to one farmer at Wang O, and six, five and one farmer at Kha Khom, Hua Don and Mak Phrik, respectively. Toposequential positions of the paddy fields were presented by the field elevation relative to the lowest paddy field in each mini-watershed (relative field elevation). Surface soils from 2 spots in secondary-grown woodland adjacent to Hua Don (Fig. 1) were also collected. The relative elevations of the spots were 3.9 and 4.0 m above the base of Hua Don mini-watershed. Soil was sampled after the first plowing in June 1998. Sampled soils were air-dried, cracked, and passed through 1-mm-mesh sieves to remove plant residues. Soil organic carbon (SOC) content was measured for each soil by Walkly and Black method (Walkly and Black, 1934), and soil texture by a pipette method. Rice biomass and paddy yields at maturity were measured in each field where soil was collected in 1998. Reaping was conducted on three replications in each field and each replication area was about 0.5 m². Farmers transplanted rice cultivar RD 6, a glutinous mutant of KDML 105, at all investigation fields from 25 June to 15 August. Since the cultivar matures almost on the same day regardless of the transplanting date, rice plants were harvested from 6 to 18 November at all fields. Amounts and application dates of chemical fertilizer in each field were recorded by observation and interview with the farmers. The combined chemical fertilizer of the 16–16–8% (N–P₂O₅–K₂O) type was used at all fields and the application rates varied from 0 to 32.5 g m⁻² (N–P₂O₅–K₂O: 0–0–0–5.2–5.2–2.6 g m⁻²) among the investigation fields. Precipitation data were collected at Ubon Rice Research Center, which was...


Table 1. Uptake of nitrogen (N) and recovery rate of fertilizer N under various fertilizer treatments in pot-grown rice.

| Fertilizer treatment | N uptake (g pot⁻¹) | N recovery rate |
|----------------------|-------------------|----------------|
| None                 | 0.24 ± 0.12       | a              |
| N                    | 0.42 ± 0.16       | 0.30 ± 0.12    |
| NP                   | 0.52 ± 0.19       | 0.47 ± 0.12    |
| NK                   | 0.47 ± 0.21       | 0.37 ± 0.16    |
| NPK                  | 0.30 ± 0.12       | b              |

Average ± standard deviation. n= 10. Values on a column followed by the same letter are not significantly different at 5% level.

Table 2. Coefficients of correlation among rice biomass, yield, soil organic carbon (SOC) and clay content measured at the farmer's field, and biomass production of irrigated and unfertilized pot-grown rice with soils sampled from each field.

| Farmers' fields | Pot-grown | Biomass | Yield | rice biomass | SOC | Clay |
|----------------|-----------|---------|-------|-------------|-----|------|
|                |           |         |       |             |     |      |
| Biomass        | 1         | 0.92**  | 1     | 0.51**      | 0.43** | 0.81** |
| Yield          | 0.96**    | 1       | 0.51**| 0.46**      | 0.81** | 0.97** |
| SOC            | 0.51**    | 0.46**  | 0.81**| 0.48**      | 0.97** |      |
| Clay           | 0.53**    | 0.54**  | 0.48**| 0.46**      | 0.97** |      |

*: significantly at 1% level.

Fig. 2. Correlation between dry matter production of rice and nitrogen (N) uptake at maturity in pot-growth experiment. Fertilizer: O None, N, ▲ NP, □ NK, ● NPK

located in the study area. The amount of precipitation in 1998 (1186 mm) was less than normal (1441 mm, average of 1988-1997) but not so rare (1214 mm in 1993 and 1114 mm in 1997).

2. Phytometry experiment

Soil fertility was evaluated by phytometry using rice. The 50 soil samples described above were put into 7.0 L pots 5.5 kg dry soils per pot, and rice was cultured without fertilizer application. In addition, soil samples from representative 10 fields in a Hua Don mini-watershed were also used for rice culture with different fertilizer application. N-P₂O₅-K₂O was applied as fertilizer at 0-0-0 (NF plot), 0.6-0-0 (N plot), 0.6-0.6-0 (NP plot), 0.6-0.6 (NK plot) and 0.6-0.6 (NPK plot). Three pots were used for each soil and each fertilizer level as replications. Three seedlings of rice cultivar KDML105 were transplanted onto each pot on 30 July 1998 and placed in an open space in Ubon Rice Research Center. Rice plants were grown under a well-watered condition until maturity on 13 November. Then plants were harvested and measured for dry weight and nitrogen (N) content. The N content was determined with ground plant samples by near infrared spectroscopic analysis (BRAN+LUEBBE, Infra Analyzer 500) equipped with IDAS software, calibrated by the Kjeldahl method.

Results

1. Variation in soil fertility measured by phytometry under well-watered conditions and the associated factors

Dry matter production of rice grown in pots without fertilizer application differed more than 5 times at most among soils from different fields. The dry matter production was almost proportional to plant N uptake irrespective of fertilizer application (Fig. 2). The physiological efficiency of nitrogen (N) for dry matter production under the unfertilized condition (173 g g⁻¹) was slightly higher than that under NPK fertilization (149 g g⁻¹) though not significantly. The N uptake of rice was significantly increased by N fertilization (P<0.05, Table 1). Under an N fertilized condition, application of phosphorus (P) fertilizer increased plant N uptake (P<0.05). The N uptake was also slightly increased by potassium (K) fertilizer application, but the effect was
insignificant. The fertilizer N recovery rate, which was calculated by dividing the difference in plant N uptake between the fertilized and unfertilized conditions by amount of applied N (0.6 g pot\(^{-1}\)), ranged from 0.30 g g\(^{-1}\) in the N plot to 0.48 in the NPK plot. The efficiency was not significantly affected either by SOC or clay contents. Thus, the results shows that rice biomass production in Northeast Thailand under well-watered conditions is most severely limited by N supply capacity of soil followed by P supply.

Soil organic carbon (SOC) content had a close correlation with the soil N supply capacity as measured by rice N uptake (r=0.81, P<0.01) and hence with the dry matter production (Fig. 3, r=0.83, P<0.01). The clay content, which was closely correlated with SOC content (r=0.67, P<0.01), had a comparatively smaller correlation with the dry matter production (Fig. 4, r=0.53, P<0.01). These results suggested that SOC content could be a useful index for evaluation of soil fertility under field conditions in Northeast Thailand.

2. Effect of soil fertility on rice productivity at each fields

Rice biomass production at the investigated fields ranged from 73 to 1265 g m\(^{-2}\) in 1998 and paddy yields from 0 to 387 g m\(^{-2}\), showing enormously large variations among the fields. The biomass production of pot-grown rice with soils sampled from each field under unfertilized and well-watered conditions, had a close relationship with the biomass (r=0.51, P<0.01) and yield at each field (Table 2; r=0.43, P<0.01). Rice biomass and yield at each field were also closely related to SOC content (Fig. 5). However, the coefficient of correlation between SOC and biomass production under field conditions was much less than those in the phytometry experiment, indicating that variation of water availability and farmer’s crop management also affected the growth and yield at the fields.

Table 3. Coefficients of correlation among rice biomass, paddy yield, growth duration, soil organic carbon (SOC) content, and application rate of nitrogen (N) fertilizer in each field in mini-watersheds.

| Biomass | Yield | Growth duration | SOC | N fertilizer |
|---------|-------|-----------------|-----|-------------|
|         |       |                 |     |             |
| Biomass | 1     | 0.92**          | 1   | 1           |
| Yield   |       | 0.75**          | 0.62** | 1          |
| SOC     | 0.51**| 0.40**          | 0.30 | 1           |
| N fertilizer | 0.35 | 0.51 | 0.14 | 0.05 | 1 |

*: ** : significantly at 1% and 1% level, respectively

Fig. 4. Relation between soil clay content and dry matter production at maturity in potted rice under unfertilized conditions. Symbols are the same as in Fig. 3.

Table 3 shows the coefficients of correlation among rice biomass, yield, growth duration, SOC content and the amount of N fertilizer applied at each fields. The rice growth duration, which differed more than one month among the fields depending on the transplanting date, had the closest correlation with either the rice biomass or yield. This suggests that the growth duration is quite important for rice production on such unfertile soils. The rate of N fertilizer application significantly differed with the farmer, but was independent of SOC content of the field. The amount of N fertilizer correlated with rice biomass and yield as well as SOC content did.

Multiple regression analysis on the factors of SOC content (g kg\(^{-1}\)), growth duration (GD, days) and the amount of N fertilizer (N, g m\(^{-2}\)) explained 71 % of the variation of rice biomass (RB, g m\(^{-2}\)) and 67% of that of yield (RY, g m\(^{-2}\)) at each field, as shown in the following regression equations:

\[
\text{RB} = 20.2 \times \text{SOC} + 49.0 \times N + 11.9 \times GD - 1022 \\
R^2 = 0.71
\]

(standardized: \(\text{RB}^* = 0.31 \times \text{SOC}^* + 0.26 \times N^* + 0.62 \times GD^*\))

\[
\text{RY} = 6.15 \times \text{SOC} + 27.6 \times N + 3.37 \times GD - 293 \\
R^2 = 0.67
\]

(standardized: \(\text{RY}^* = 0.27 \times \text{SOC}^* + 0.42 \times N^* + 0.51 \times GD^*\))

Agronomic efficiency of nitrogen (yield increase per
unit applied nitrogen) estimated from the multiple regression analysis was 27.6 g g⁻¹ and similar to those experimentally obtained in Northeast Thailand (Khunthasuvon et al., 1998; Ohnishi et al., 1999). The regression equations suggest that the differences in the rice biomass and yield between the SOC-richest field and the SOC-poorest field were 410 and 130 g m⁻², respectively, even when the transplanting date and fertilizer application rate were the same. This also indicates that SOC has a significant effect on rice productivity even under field conditions where water availability might have had some effects.

3. Toposequential variation of the soil fertility in mini-watersheds

Soil organic carbon (SOC) and clay content generally decreased with ascending relative elevation of the field in the mini-watersheds (Fig. 6 and 7). Soils in the upper fields had only 3 g kg⁻¹ SOC, which was about a half of that in the secondary woodland adjacent to Hua Don. In mini-watersheds in Hua Don and Kha Khom, SOC content in the lower paddies was evidently higher than that in the upper paddies, and in Hua Don it exceeded 10 g kg⁻¹. However, such an increase in SOC content in the lower fields was not observed at Wang O. The toposequential change of clay content was steeper than that of SOC content. The clay content almost reached a minimum, 0.04 g g⁻¹, at a 0.5 m relative elevation in all mini-watersheds. Although the difference in clay content between soils in upper paddies and the secondary woodland adjacent to the Hua Don mini-watershed was smaller than that in SOC content, the clay content in the woodland was 1.7 times as high as those at uppermost fields (2 to 3 m) in Hua Don. The change from forest to paddy field might have triggered the clay erosion from upper field to lower field.

The rice biomass production in the phytometry experiment was strongly affected by the toposequential distribution of SOC. Accordingly, the rice dry matter production determined by the phytometry experiment was closely and negatively correlated with the relative elevation of the field at Hua Don (Fig. 8; r = -0.72, P < 0.01). Similar correlations also existed between the relative field elevation and rice biomass (r = -0.70, P < 0.01) or yield (r = -0.75, P < 0.01) under field conditions at Hua Don.

Discussion

The results shown here revealed that there exist steep gradients in soil fertility along toposequence of rainfed paddy fields in three out of four mini-watersheds investigated in Northeast Thailand. It was also indicated that soil organic carbon (SOC) content is a good index of soil fertility in terms of nitrogen (N) supply capacity and rice productivity. Irrespective of fertilized or unfertilized conditions, the SOC content strongly correlated to rice production (Fig. 3). Although water availability is often emphasized as a major rice production constraint in
rainfed rice culture areas (Pushpavesa et al., 1986; Pantuwan et al., 2002), the phytometry experiment under well-watered conditions indicated that rice productivity can not be substantially improved by irrigation alone in the upper part of mini-watersheds where SOC content is extremely low. Thus, improvement of soil fertility is evidently one of the key technologies for improving rainfed rice productivity in Northeast Thailand.

SOC has many roles in rice production; nutrient supply and soil structure improvement (Hamblin 1985; Jenkinson, 1988). Since dry matter production in rice was severely restricted by nitrogen (N) uptake (Fig. 2; also Ohnishi et al., 1999), SOC was considered especially important as a source of N in unfertile soil there. Willett (1995) indicated that organic matter was also important for increasing cation exchange capacity (CEC), being more effective than clay in the case of sandy soils in Northeast Thailand. This supports the result of the present study.

Many investigators reported that soil fertility declined with the year after the change from forest to paddy fields in the tropics (Greenland and Lal, 1977; Oldeman et al., 1991). This was also recognized in this study; uppermost fields had lower soil fertility than the secondary woodland. It could not be judged from the data of this study whether the soil fertility is still declining or was sustained. However, the clay content almost reached a minimum in most fields except at the bottom of mini-watersheds and overflow of standing water across ridges of paddy fields was scarcely observed even under heavy rain in this study. This may indicate that the erosion of soil had probably terminated.

Even after soil erosion terminated, the SOC content may change dynamically with organic matter input and its decomposition. Most of the toposequential distribution of SOC content may be produced by the gradient of SOC decomposition rate, which is influenced by clay content and especially by soil moisture content in the dry season (Birch, 1958; Van Veen et al., 1985). Lower clay and soil moisture content at higher fields in mini-watersheds may have enhanced SOC decomposition.

Many investigators reported that rainfed rice productivity was improved by incorporation of organic matter to soil (Supapoj et al., 1998; Naklang et al., 1999). Under the present conditions where rice residue is the only source of field organic matter in Northeast Thailand except for a little fallow manure, the SOC distribution might also have been affected by rice yield for many years. Previous studies showed that SOC content was increased by rice straw incorporation (Chairoj et al., 1996; Naklang et al., 1999). Rice straw management after harvest is one of the key factors for sustainable production.

Although water availability must be taken into account, the results of this study indicate that a longer rice growth period with earlier transplanting and more N fertilizer application may improve rice yield. Quite low application of N fertilizer currently practiced (1.76 g m\(^{-2}\), average for all the investigated fields) will be improved in the near future (Pandy, 1998; Miyagawa et al., 1999). However, excess fertilizer application induces yield loss by lodging in the two popular cultivars, KDML 105 and RD 6, in Northeast Thailand (Ohnishi et al., 1999). The experimental maximum yield, around 400 g m\(^{-2}\), could be set for a temporal goal of yield improvement under current situations. Ohnishi et al. (1999), on the basis of N application rate in their genotype experiments, showed that semi-dwarf high yielding cultivars which had a shorter growth period than those cultivars hardly exceeded this yield level because of insufficient N uptake in a shorter period. Scraping soil nitrogen up by a long growth period is one strategy for increasing rice yield under such an extremely poor soil condition.

The most important suggestion from this study is the sustainable development of rainfed rice production in the mini-watershed by adapting crop and resource management along the toposequential distribution of soil fertility. This may include a conversion of rice cropping to green manure or forage cropping in the unfertile uppermost fields. Introduction of green manure or forage crops into upper fields, or feeding them to livestock can provide organic matter for the rest of the fields. The organic matter application may not only compensate the yield loss due to the land use change, but also improve the sustainability of rainfed rice production.

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