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Shoji, Koichi
Nakayama, Kazuaki
Kobayashi, Nobuya
Kawamura, Tsuneo
Horio, Hisashi

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Variability of Micro-elevation, Yield, and Protein Content Within a Transplanted Paddy Field

K. Shoji¹, K. Nakayama², N. Kobayashi³, T. Kawamura¹ and H. Horio^{1,3}

¹ Faculty of Agriculture, Kobe University, Kobe, 657-8501, Japan

² Graduate School of Natural Science and Technology, Kobe University, Kobe, 657-8501, Japan

³ Food Resource Education and Research Centre, Kobe University, Kasai-city, 675-2103, Japan

Correspondence: shojik@kobe-u.ac.jp

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Abstract

Due to the nature of waterlogged fields used for rice production, we hypothesized that micro-elevation (micro-relief, micro-topography, or differences in elevation) is an important factor for site-specific management within rice fields. A 0.5 ha transplanted and weed-free paddy field was selected as the observation site, where there was micro-elevation in a range of 100 mm within the field. Combine-monitored grain yield and the surveyed micro-elevation were compared at 96 locations in the field, and 60 hand-taken grain samples were analysed for protein content. Grain yield and protein content showed significant negative correlations with micro-elevation ($r = -0.50^{***}$ and -0.67^{***} , respectively), indicating that at lower elevations, grain yield increased gradually with protein content. Spatial variation in yield and protein content was attributed to availability of water and nutrient uptake at locations with different micro-elevation. Therefore, micro-elevation is expected to be one of the important factors for managing spatial variation in a small paddy field.

Introduction

Studies have been recently conducted on the variability of soil properties and yield in rice production systems, which may potentially lead to site-specific management of paddy fields. A suitable unit for “site-specific” management of rice fields may be individual fields surrounded by ridges within which water is retained. Ishida and Ando (1993a, 1993b) have examined spatial variability of chemical properties of soils of 159 paddy fields in a watershed in northern Japan, and classified the soil into ten groups in the region. They found that cation exchange capacity (CEC) and extractable Ca and Mg were major sources of variability. Becker and Johnson (1999) have concluded from observations at 64 sites in Côte d’Ivoire that water management was the most influential factor that explained variation in grain yield between fields. Casanova *et al.* (1999, 2002) have investigated soils, rice plants, and grain yields from over 30 direct-seeded paddy fields (0.5-3.0 ha) in eastern Spain. They related grain yield to topsoil CEC, which correlated with clay content, and to soil salinity, which was attributed to quality of ground water at various geographical location of each field near the ocean. Dobermann *et al.* (2002) have conducted comprehensive studies on field-specific nutrient management in Asian countries (fields of 0.3-4.0 ha), where potential nutrient supplies were measured and appropriate application rates of fertilizer were prescribed on a field-specific basis, resulting in general increases in grain yield and economic return.

Variability of soil properties or plant growth has been investigated also within rice fields. Marx *et al.* (1988) have investigated spatial variability of soil chemical

properties in three rice fields of over 10 ha each in Arkansas. They found that soil pH gradually decreased along the slope of the field toward the outlet, which was explained by the precipitation of calcium carbonate via transpiration of the irrigated water. Pettygrove *et al.* (1990) have investigated several forms of nitrogen in a 6.1 ha rice field in California, and concluded that inorganic nitrogen was spatially variable whereas mineralisable organic nitrogen was not. Dobermann (1994) has reported spatial variability of a direct-seeded (drilled) paddy field of 3.6 ha in Russia, concluding that micro-relief, soil pH, weed growth and seeding rates were major yield-determining factors. Dobermann *et al.* (1995a) have investigated the temporal and spatial variability of plant growth in two transplanted fields of 0.2 ha each in Philippines, and showed that short-distance variability was attributed mainly to non-uniform application of fertilizers. Dobermann *et al.* (1997) have then confirmed that short-distance variation was caused by irrigation water or land levelling, whilst long-range variation was by irrigation along gentle slopes. Yanai *et al.* (2000, 2001) have analysed the spatial variability of soil properties in a transplanted field of 0.5 ha in Japan, suggesting that a reasonable scale for site-specific management was about 20 to 50 m. Yanai *et al.* (2001) have carried out principal component analysis relating the extracted principal components to rice yield, showing that organic matter and inorganic minerals in the soil were major determinants of yield.

Despite these investigations on variability, application of site-specific management within paddy fields is still limited (Dobermann *et al.*, 2002). Other than some hand-operated tools such as an optical sensor to indirectly measure leaf area index (LAI) (Dobermann and Pampolino, 1995b), soil nutrient sensors, or chlorophyll meters, a limited number of engineering-based trials are presently in progress such as on machine-vision sensing of nitrogen content in plants (Suguri *et al.*, 2001) and on variable-rate application of fertilizer in paddy fields (Iida *et al.*, 2001; Umeda *et al.*, 2001).

In justifying site-specific management within a paddy field, approaches other than managing the nutrient status of soil as in upland cultivations should be considered. The flatness of a field is one of the most manageable factors in both modern and traditional rice farming at a given scale in the field. Differences in elevation, hereinafter referred to as “micro-elevation”, affect not only depth of water when the field is fully irrigated, but also the availability of water or the aeration of the soil when the field is drained. Dobermann (1994) has reported that weed populations, one of the major determinants of grain yield, were closely related to the variations in micro-elevation in a range of 150 mm within a field. Husson *et al.* (2000a, 2000b) have demonstrated that micro-elevation ranges of 300 mm caused changes in chemical soil properties and therefore affected plant growth and grain yield in sulphate soil environments of Vietnam. Micro-elevation within a field also affects the water and soil temperatures; specifically, their range within a day is reported to be greater at higher elevations (Nakamura and Shibusawa, 1981; Ohara *et al.*, 1986).

Observations at our transplanted rice fields have revealed variability of plant growth that appeared to be related to the micro-elevations within the field. Shoji *et al.* (2003) have confirmed from several samples in a paddy field that protein content of grain was higher at lower elevations. They have suggested that the protein content may also reflect variation in the maturity of the grain as evidenced by the percentage of filled spikelets and the grain weight. However, a clear relationship between micro-elevation and grain yield was not confirmed.

From a different aspect, protein content is one of the major taste-determining factors of rice. Lower levels of protein enhance its cookability and palatability hence providing competitiveness in the market, although the opposite objective is occasionally set for nutrition supply in some countries. In the context of site-specific

field management, protein mapping and its relation to grain yield have been studied for winter wheat (Reyns *et al.*, 2000). Their methods are not only useful for quality management in general, but also expected to indicate site-specific differences in the growth of the plant in paddy fields, since protein content and yield components are closely related (Shoji *et al.*, 2003; Matsuda *et al.*, 2000).

The objectives of this paper are to confirm the relationships between micro-elevation and grain yield or protein content of rice with a sufficient number of data sets at the field scale, and to determine whether micro-elevation may serve as an alternative indicator for site-specific management in paddy fields.

Materials and methods

Experimental field

In order to eliminate the effect of weed population and seeding rate, such as shown by Dobermann (1994), a mechanically transplanted field with complete weed control was used. The experimental paddy field was set up in 2001 at the Experimental Farm of the Faculty of Agriculture (currently Food Resource Education and Research Centre), Kobe University (134°52' E, 34°53' N, 53 m above sea level). On-site observations during the cropping period showed an average temperature of 24.0°C and a total precipitation of 532 mm. The soil was classified as “fine yellow soil” (Japanese soil taxonomy) with properties of heavy clay allowing little vertical infiltration of water. The area of the field was 100 m × 50 m which resulted from integration of nine small fields in 1969. The field has been uniformly managed ever since.

Crop residues and weeds were incorporated twice into the soil with a rotary tiller during the previous winter, and the field was irrigated and puddled twice with a rotary harrow 9 d and 6 d before transplanting. The second puddling was operated in several paths, as a local technique commonly practiced, so that the soil could be moved by the rear cover of the rotary harrow to roughly level the field. Rice seedlings (*Oryza sativa* L., cultivar “Dontokoi”, 24 d old) were transplanted on June 11 with a six-row transplanter at a row spacing and planting pitch of 0.30 m and 0.23 m, respectively. The effective planted area was 98 m × 48 m, with 12-row headlands placed at each longitudinal end. Slow-acting fertilizer (N: P₂O₅: K₂O = 63: 63: 63 kg ha⁻¹) was applied only once at transplanting. Chemical weed control was carried out one week before and after the transplanting. During the cropping period, weeds were manually removed occasionally.

The field was drained and dried between July 9 and 16, a common practice called “midseason drainage”, although the drainage was not total at low elevations in the middle of the field. Water thereafter was on average maintained at a lower level, and was not sufficiently re-supplied in that most of the areas except around the lower elevations were occasionally exposed. This common water-saving management at the latter stage was aimed at regulating the plant growth by restricting water and nutrient supply and at sustaining the viability of roots in a reduced soil environment. The average water requirement on sunny days was 7.2 and 13.5 mm d⁻¹ in depth, before and after the midseason drainage, respectively. The field was drained on September 14 until the crop was harvested to increase the trafficability for the combine.

Hand-sampling of grain and protein analysis

At the centres of 10 m × 8 m (approximately) grid, 16 hill-plants were hand-harvested from every 2 adjacent rows on October 2, obtaining a total of 60 samples. The grain was immediately threshed, naturally dried for a week, and husked to determine the yields of both fresh and husked grain. The moisture content of the grain was measured at both threshing and husking, and the grain yields were expressed

by adjusting the moisture content at 150 g kg^{-1} .

The surface of each grain was then ground and polished into easily cookable and edible form (“milled” or “whitened”) at the milling rate (white rice with respect to brown rice) of 0.9, and the protein content was analysed by NIR. The analyser (K-AS100N, Kubota Co. Ltd., Osaka, Japan), which was calibrated for different varieties of rice, was capable of measuring the protein content on a wet basis with a standard error of prediction (SEP) of 2.1 g kg^{-1} .

Yield mapping

A yield map was drawn to visually compare patterns of yield with micro-elevation, and to compensate for inevitable random errors associated with the hand-sampling of grain from the limited number of plants. A two-row head-feeding “*jidatsu*” combine (Fig. 1, Ee-4D, 8.8 kW, 0 to 0.6 m s^{-1} , Yanmar Co., Ltd., Osaka, Japan) was equipped with the yield monitor developed by Shoji *et al.* (2002), and was used to harvest the whole crop on October 3 and 4. The impact-based yield monitor was designed to compensate for the vibration of the combine and for the temporal drift of the output with time, having a root mean squared relative error of as low as 1.8 g kg^{-1} on the fresh grain weight basis. A delay time (Shoji *et al.*, 2000) of 11 seconds was employed to adjust the output of the monitor to the proper position on the map.

As a positioning device, a magnetic proximity switch was placed near the sprocket of the crawler on the right-hand side to detect the travelled distance (Shoji *et al.*, 2000). No other device (such as RTK-GPS) was employed for this specific purpose of the study, since the small, low-ground-pressure combine generated little slippage at the crawler on the drained field, and simply tracking down the transplanted rows provided a sufficiently precise recording of positions in the field.

Grain yields were calculated from the impulse received at the monitor from the grain at a grid resolution of $0.6 \text{ m} \times 1 \text{ m}$ to generate the original yield map. The 0.6 m width was equal to the swath of the two rows that the combine harvested in each path, whereas the 1 m in the travelling direction of the combine was adjusted to the resolution of the topographic map. The samples hand-taken at the 60 points were later added to the map.

Since a real-time grain moisture sensor was not mounted on the combine, the yield map was expressed on a fresh grain yield basis. However, the average moisture content calculated from the 60 hand-taken samples actually was $250 \pm 15 \text{ g kg}^{-1}$ in this case, and this reflects only $\pm 20 \text{ g kg}^{-1}$ of variation in the grain yield with the moisture content adjusted to 150 g kg^{-1} . Therefore, the fresh grain yield map can still express the trend of adjusted grain yield at an acceptable level of precision.

Topographic map

The micro-elevation was surveyed with an auto-level (vertical resolution of 5 mm) after the harvest at a grid resolution of $1 \text{ m} \times 1 \text{ m}$ to generate the topographic map of the field. Because of the low ground pressure from the crawlers of the combine (maximum of about 14 kPa), their prints were negligible in most part of the field where the combine travelled in the longitudinal directions. However, the headlands at each longitudinal end were slightly disturbed by the turns of the combine, and the topographic data there was used only as a reference.

Results

Micro-elevation

Figure 2 shows that the variation in micro-elevation was within a range of 100 mm . Lower elevations appeared around the edges of the field, where a heavy combine

Fig. 1.

harvester used until the previous year had turned and deformed the soil. There was also apparent unevenness of the surface in the middle of the field, where drainage was not complete and surface water was retained until late in the growing season before harvest.

There was a certain pattern in the unevenness of the surface. Semi-variograms of the micro-elevation in the north-south direction showed apparent periodicity [Fig. 3(a)]; one representing the section in the middle of the field (B-B') had a significantly higher peak ("sill") than the other. A total of 48 semi-variograms were analysed in this manner, and the frequency distribution of the "range" [Fig. 3(b)] was obtained. The distribution was then weighted by each "sill", resulting in that only the "range" of 14 m was distinctive. Therefore, the field had the most characteristic periodicity of 28 m in the north-south direction, as is apparent in Fig. 2 which shows three large depressions spaced at approximately equal intervals in the middle of the field. This periodicity was used to determine the size of the plot in the yield map associated with micro-elevation in the next section.

Yield

The yield map generated from the output of the yield monitor is shown in Fig. 4, where the manually reaped areas around the edges of the field were removed. High-yield regions were located around the three large depressions (Fig. 2), suggesting that grain yield was greater where elevation was lower. The short narrow band near the north-eastern edge of the field was, however, not related to micro-elevation, but to accidental fertilization during transplanting.

Fig. 4.

The relationship between grain yield and micro-elevation was investigated based upon the maps (Figs. 2 and 4), but with original micro-elevation and yield data grouped and averaged for plots of 7 m × 6 m. The length of 7 m in the north-south direction of the field was one quarter of the characteristic periodicity of 28 m discussed in the previous section, whereas the width of 6 m was a common multiple of the lateral resolution of the topographic map (1 m) and that of the yield map (0.6 m). A total of 96 data sets in the region of 84 m × 48 m was obtained where the combine travelled in north-south directions. On the other hand, the data in the headlands were not considered because of the incompatibility with the size of the plots, and because of the reduced reliability of the survey for the topographic map due to the disturbance of the surface induced by the turns of the combine.

Due to the lack of a moisture sensor for the fresh grain harvested with the combine, the moisture contents for the yield data were interpolated from the ones obtained from the hand-sampling surrounding each 7 m × 6 m plot, accepting that actual moisture content slightly decreases with time as sunny weather continued during the combine operation. The interpolation was simply weighted by the inverse of distance to each data point, as the plot size for the averaged yield was not compatible with the grid for the hand-sampling and no significant spatial dependence was found in the pre-measured moisture contents. The average monitored grain yields for each plot were then adjusted to a moisture content at 150 g kg⁻¹.

The hypothesis that higher yields were associated with lower elevation was statistically confirmed (Fig. 5). Grain yield seems to saturate at lower elevations, as Fig. 4 also indicated that the deepest region did not show the highest yield. The 60 hand-sampled grain yields also showed a similar correlation with micro-elevation ($r = -0.37^{**}$). In spite of the statistical significance, this decline in the correlation was caused primarily by the greater variability of sampling due to the limited number of hill-plants sampled at each location (Dobermann *et al.*, 1995a; Kusuda, 1990).

Fig. 5.

Protein content

Protein content was negatively correlated with micro-elevation (Fig. 6) *i.e.* it increased with relative depth of water, where micro-elevation alone explained 45% of the total variance of grain protein. Grain protein content evidently increased with grain yield (Fig. 7), indicating that the increase in grain yield resulted in the decline in grain quality in terms of palatability. However, no specific outlier in the relation was found, such as shown in a similar study on upland wheat production (Reyns *et al.* 2000).

Fig. 6.
Fig. 7.

Discussion

Yield monitoring on a combine demonstrated less fluctuation than sampling a small number of rice hill-plants for site-specific determination of grain yield. It was also significantly more time- and labour-saving than manually measuring the yield in plots (Lee *et al.* 1999; Yanai *et al.*, 2001), although direct validation of the accuracy of the yield map was not feasible in our case. Due to a larger number of samples and lower variability of the data, the relationship between micro-elevation and grain yield was statistically confirmed, whereas that is not the case with only 7 or 10 hand-sampled data sets of grain yield and micro-elevation in the field (Shoji *et al.*, 2003).

The size of the plots, within which grain yield was averaged for analysis, was comparable to that of Lee *et al.* (1999), where spatial variability of grain yield was observed when the yields were manually measured in plots of 6 m × 5 m size. Setting the length of the plots to 7 m was also advantageous in minimizing the fluctuation of the output of the yield sensor, which the grain was intermittently, not continuously, exposed to by the grain conveying units in the combine. The width of the plots (6 m), determined primarily by a compromise in terms of the resolution of the maps, was also considered appropriate, since the size of the depressions (Fig. 2) was almost equal in north-south and east-west directions.

The relationship between grain yield and micro-elevation (Fig. 5) indicated that, when linearly regressed, 25% of the total yield variance was explained by micro-elevation ($n=96$). In the 84 m × 24 m region in the middle of the field where micro-elevation varied most significantly, the R^2 was 0.31 ($n=48$). Conversely, even if the extreme data sets around the deepest depression (Fig. 2) were removed, which resulted in a micro-elevation range of only 50 mm, the R^2 was still 0.20 ($n=93$). These fits of regression are comparable to that of Yanai *et al.* (2001), where a R^2 of 0.43 ($n = 100$) was obtained for a multiple linear regression using three independent variables (*i.e.*, “organic matter”, “exchangeable bases”, and “soluble salts” factors), which were derived from principal component analysis of 12 chemical soil properties. Since Yanai *et al.* (2001) evaluated only soil properties before the growth period, part of their unexplained variance of yield could be attributable to micro-elevation. In a similar analysis conducted by Dobermann (1994) in a direct-drilled field, grain yield was mainly explained by soil pH, density of weeds, and seeding rate ($R^2=0.64$). However, he admitted that micro-elevation, plant germination, plant establishment, and weed growth were closely related. These are the factors that affected the variation in grain yield more evidently than in the transplanted and weed-uninfested field used in this study.

One of the criteria for the extent to which variation in micro-elevation should be managed is to seek the minimum range in micro-elevation that shows significant correlation to grain yield or protein content in each data set. Table 1 demonstrates that the range in micro-elevation in this field should be managed approximately within 20 mm for grain yield and 30 mm for protein content (5th column) to neutralize its

effect. These ranges are actually smaller than a typically recommended range of 50 mm upon land reclamation of a paddy field in Japan, although these numbers are based on different standards. It should be noted, however, that the ranges proposed here are simply derived from statistics, and for example, they could be even smaller if the variability of factors other than micro-elevation is smaller. Other criteria acceptable for marketing or profitability, such as coefficient of variation (Table 1, last column), therefore, should be also considered for real applications.

The significant effect of micro-elevation on grain yield and protein content is ascribed primarily to the intermittent supply of water after the midseason drainage. The tiller number per hill-plant, which is an essential yield component, actually increased more rapidly at higher elevations at the beginning, but the trend was reversed after the midseason drainage. In the latter period, it was observed that the lower the elevation, the more vigorous the vegetative growth as expressed by greater plant height, greater tiller number, and darker colour of leaves. Considering these observations and the fact that the increase in nitrogen fertilisation or uptake results in higher grain protein content (*e.g.* Perez *et al.*, 1996; Matsuda *et al.*, 1997), nitrogen uptake at lower elevations was greater than at higher elevations. With the intermittent supply of water, as the time of soil exposure to the air prolonged at higher elevations, so the water stress of the plants and the degree of denitrification and leaching from soil increased, which reduced the nitrogen uptake.

However, grain yield seems to reach the maximum limit at the lowest elevation (Fig. 5) despite the negative correlation discussed above. In the yield map (Fig. 4) where the yield data is not averaged in the 7 m × 6 m plots, there is obvious decline in grain yield at the extremely low elevation around the centre of the largest depression (Fig. 2). In that location, the leaves developed around the upper portion of the stem and spread in horizontal directions, which was evidently unsuitable for effective photosynthesis at the grain-filling period (*e.g.* Matsuba 2000), and the plants started to incline slightly at the root after heading. These phenomena are attributed to the incomplete midseason drainage that resulted in over-absorption of nitrogen and declined viability of roots in a reduced soil environment. This observation above and the negative relationship between micro-elevation and grain yield (Fig. 5) mostly agree with the well-known principles of water management for middle to late growth period. Accelerated drainage in a field of poor water permeability increases the percentage of filled grain and thus grain yield, whereas excessive or too early drainage results in shortage of water, thus hindering the grain filling process and decreasing grain yield (*e.g.* Maeda and Minami, 1978; Okuma *et al.*, 1980; Dingkuhn and Le Gal, 1996).

The periodicity in micro-elevation in the middle of the field (Fig. 2 and 3) is attributed to repeated traffic for years on the soil of declined bearing capacity due to poor drainage of water, especially at harvest, when a large-scale combine of high ground pressure had been operated. At least these periodical micro-elevations do not correspond at all to specific shape of original fields in our farm that used to have different elevations before being merged in 1969, and there are some other fields that show similar topographic trends where the drainage is not perfect. Subsequent rotary tillage during winter is also responsible; a rotary tiller directly mounted on the tractor without position control tends to penetrate deeper on soft soil at lower elevations and excavates the subsoil to aggravate small fluctuations in micro-elevation, which are eventually merged together to exhibit certain periodicity.

Better management of micro-elevation in such a field of poor water infiltration as used in this study, therefore, should be started with complete drainage before harvest, possibly by opening a couple of narrow open ditches in the middle of the field. In our experience, simply transporting the topsoil from higher to lower elevations after puddling has not been successful. During winter tillage, the vertical position of the

equipment should be controlled at least manually and approximately according to micro-elevation to form a less fluctuating boundary between topsoil and subsoil. The field then should be adequately dried to maintain the boundary before being filled with water.

Homogeneous water management is required throughout the field for adjusting yield and quality at an optimum level. Proper water management that controls nutrient uptake at desired growth stage is a key to pursue both greater grain yield and lower protein content without having such mutual compensation as shown in Fig. 7. If intra-field rather than inter-field site-specific management is in fact justified for rice cultivation, land levelling and water management are likely to become important components of site-specific management.

Conclusions

Grain yield and protein content of rice were measured in a weed-free transplanted paddy field, and were found to be related to the micro-elevation of the field. Both grain yield and protein content correlated negatively with micro-elevation, and 25% and 45%, respectively, of their total variance was explained by micro-elevation alone. Thus, the management of micro-elevation is likely to become one of the most essential factors for site-specific management of spatial variation within small paddy fields.

References

- Becker, M. and Johnson D.E. 1999. Rice yield and productivity gaps in irrigated systems of the forest zone of Côte d'Ivoire. *Field Crops Research* **60**, 201-208.
- Casanova, D., Goudriaan, J., Bouma, J. and Epema, G.F. 1999. Yield gap analysis in relation to soil properties in direct-seeded flooded rice. *Geoderma* **91**, 191-216.
- Casanova, D., Goudriaan, J., Catala Forner, M.M. and Withagen, J.C.M. 2002. Rice yield prediction from yield components and limiting factors. *European Journal of Agronomy* **17**, 41-61.
- Dingkuhn, M. and Le Gal, P-Y. 1996. Effect of drainage on yield and dry matter partitioning in irrigated rice. *Field Crops Research* **46**, 117-126.
- Dobermann, A. 1994. Factors causing field variation of direct-seeded flooded rice. *Geoderma* **62**, 125-150.
- Dobermann, A., Pampolino M.F. and Neue H.U. 1995a. Spatial and temporal variability of transplanted rice at the field scale. *Agronomy Journal* **87**, 712-720.
- Dobermann, A. and Pampolino M.F. 1995b. Indirect Leaf Area Index measurement as a tool for characterizing rice growth at the field scale. *Communications in Soil Science and Plant Analysis* **26**, 1507-1523.
- Dobermann, A., Goovaerts, P. and Neue, H.U. 1997. Scale-dependent correlations among soil properties in two tropical lowland rice fields. *Soil Science Society of America Journal* **61**, 1483-1496.
- Dobermann, A., Witt, C., Dawe, D., Abdulrachman, S., Gines, H.C., Nagarajan, R., Satawathananont, S., Son, T.T., Tan, P.S., Wang, G.H., Chien N.V., Thoa V.T.K., Phung, C.V., Stalin, P., Muthukrishnan, P., Ravi, V., Babu, M., Chatuporn, S., Sookthongsa, J., Sun, Q., Fu, R., Simbahan, G.C. and Adviento, M.A.A. 2002. Site-specific nutrient management for intensive rice cropping systems in Asia. *Field Crops Research* **74**, 37-66.
- Husson, O., Verburg, P.H., Phung, M.T. and Van Mensvoort, M.E.F. 2000a. Spatial variability of acid sulphate soils in the Plain of Reeds, Mekong Delta, Vietnam. *Geoderma* **97**, 1-19.
- Husson, O., Hanhart, K., Phung, M.T. and Bouma, J. 2000b. Water management for

- rice cultivation on acid sulphate soils in the Plain of Reeds, Vietnam. *Agricultural Water Management* **46**, 91-109.
- Iida, M., Umeda, M. and Radite, P. A. S. 2001. Variable Rate Fertilizer Applicator for Paddy Field. ASAE Paper No. 011115, American Society of Agricultural Engineers, St. Joseph, Michigan, U.S.A.
- Ishida, T. and Ando H. 1993a. Computer-assisted mapping of paddy-field soils. I. Production of closely spaced data from sparse data relating to soil chemical properties. *Soil Science and Plant Nutrition* **40**, 391-402.
- Ishida, T. and Ando H. 1993b. Computer-assisted mapping of paddy-field soils. II. Classification, mapping, and significance. *Soil Science and Plant Nutrition* **40**, 403-414.
- Kusuda, O. 1990. A basic study on field experiment and investigation method in rice plant II. Coefficient of variation and standard sample size in the survey of quantitative characters of mechanically transplanted rice (in Japanese with the summary in English). *Japanese Journal of Crop Science* **59**, 721-726.
- Lee, C.K., Iida, T., Umeda, M. and Kaho, T. 1999. Yield maps of grain and straw in Japanese paddy field (in Japanese with figures and the abstract in English). *Journal of Japanese Society of Agricultural Machinery* **61**(4), 133-140.
- Maeda, K. and Minami, M. 1978. Studies on physical and chemical properties and improvement of soil productivities in heavy clayey paddy fields III. Effect of improvement of drainage and irrigation water management on productivity of rice plants. *Bulletin of Hokkaido Prefectural Agricultural Experiment Station* **40**, 19-29.
- Marx, D.B., Gilmour, J.T., Scott, H.D. and Ferguson J.A. 1988. Effects of long-term water management in a humid region on spatial variability of soil chemical status. *Soil Science* **145**(3), 188-193.
- Matsuba, K. 2000. A new morphogenetic model on the most suitable leaf-internode unit and developmental stage for controlling plant type in rice cultivation (in Japanese with the abstract in English). *Japanese Journal of Crop Science* **69**, 293-305.
- Matsuda, H., Fujii, H., Shibata, Y., Kominami, C., Hasegawa, S., Oobuchi, K. and Andou, H. 1997. Effect of number of grains per amount of N heading and amount of N in grain on the protein content of milled rice (in Japanese with the summary in English). *Japanese Journal of Soil Science and Plant Nutrition*. **68**, 501-507.
- Matsuda, H., Fujii, H., Ando, H., Mori, S., Kominami C. and Shibata, Y. 2000. Protein content of milled rice as affected by number of grain per panicle (in Japanese). *Japanese Journal of Soil Science and Plant Nutrition*. **71**, 697-699.
- Nakamura, Y. and Shibusawa, S. 1981. Studies on the direct underground sowing machines in the submerged paddy field (V) – characteristics of water temperature and soil temperature at changing water depth – (in Japanese with the summary in English). *Bulletin of Ishikawa Prefecture College of Agriculture* **11**, 17-21.
- Ohara, Y., Otsuki, K., Takizawa, Y. And Maruyama, T. 1986. Variation of water temperature with rice growth and its estimation – Studies on water temperature and water management for paddy fields (II) – (in Japanese with figures and the abstract in English). *Transactions of the Japanese Society of Irrigation, Drainage and Reclamation Engineering* **123**, 33-40.
- Okuma, M., Chikura, S., Harada, K., Yano, M., Takefuji, K., Noguchi, H. and Yamamoto, T. 1980. Studies on the method of water management in the fully meliorated field – Effect of water level of sub-drainage canal and intermittent irrigation on the growth and yield of rice plant – (in Japanese). *Research Report of the Fukuoka Agricultural Experiment Station* **18**, 94-100.
- Perez, C. M., Juliano, B. O., Liboon, S. P., Alcantara, J. M. and Cassman, K. G. 1996. Effects of late nitrogen fertilizer application on head rice yield, protein content, and grain quality of rice. *Cereal Chemistry* **73**, 556-570.

- Pettygrove, G. S., Jiayou, D., Williams, J.F., Wick, C., Hafez, A.A.B. and de Boer, G. 1990. Variability of several forms of soil nitrogen in two rice fields. *Communications in Soil Science and Plant Analysis* **21**, 1843-1855.
- Reyns, P., Spaepen, P. and De Baerdemaeker, J. 2000. Site-specific relationship between grain quality and yield. *Precision Agriculture* **2**, 231-246.
- Shoji, K., Kawamura, T. and Horio, H. 2000. Yield mapping of transplanted and broadcast paddy field (in Japanese with figures and the abstract in English). *Journal of Japanese Society of Agricultural Machinery* **62**(2), 167-174.
- Shoji, K., Kawamura, T. and Horio, H. 2002. Impact-based grain yield sensor with compensation for vibration and drift. *Journal of Japanese Society of Agricultural Machinery* **64**(5), 108-115.
- Shoji, K., Tanimori, F., Nakayama, K., Kawamura, T. Kobayashi, N., and Horio, H. 2003. Variability of yield and quality of rice affected by fluctuation of elevation within a paddy field (in Japanese with the summary in English). *Japanese Journal of Farm Work Research* **38**, 73-78.
- Suguri, K., Iida, K., Umeda, M., Inamura, T. And Matsui, T. 2001. Estimation of nitrogen content using machine vision in a paddy field (in Japanese with figures and the abstract in English). *Journal of Japanese Society of Agricultural Machinery* **63**(3), 59-66.
- Umeda, M., Kaho, T., Iida, M. and Lee, C.K. 2001. Effect of variable rate fertilizing for paddy field. ASAE Paper No. 011111, American Society of Agricultural Engineers, St. Joseph, Michigan, U.S.A.
- Yanai, J., Lee, C.K., Umeda, M. and Kosaki, T. 2000. Spatial variability of soil chemical properties in a paddy field. *Soil Science and Plant Nutrition* **46**, 473-482.
- Yanai, J., Lee, C.K., Kaho, T., Iida, M., Matsui, T., Umeda, M. and Kosaki, T. 2001. Geostatistical analysis of soil chemical properties and rice yield in a paddy field and application to the analysis of yield-determining factors. *Soil Science and Plant Nutrition* **47**, 291-301.

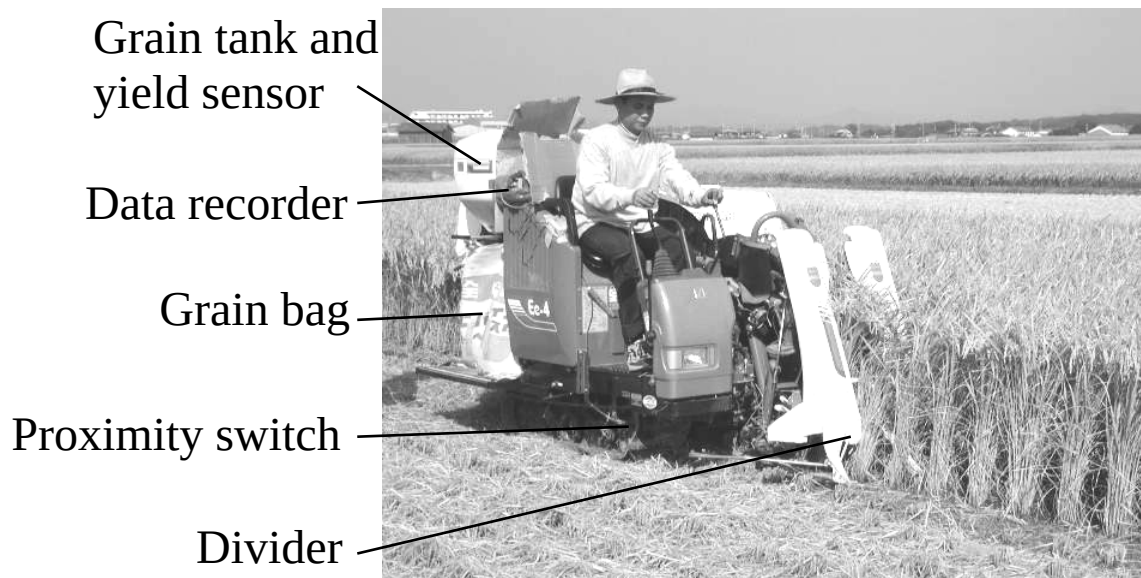


Fig. 1. Yield monitoring with a two-row head-feeding *jidatsu* combine.

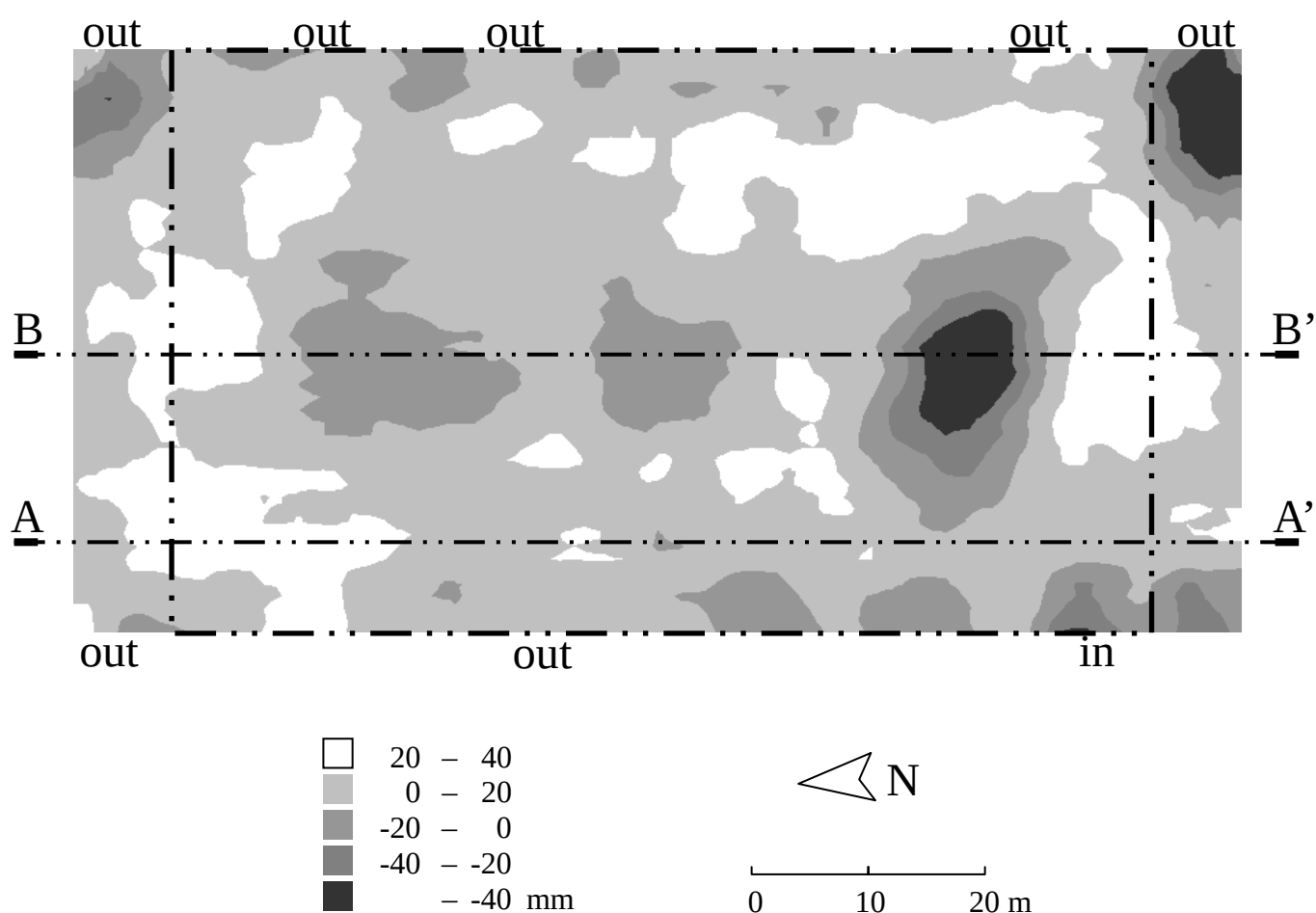


Fig. 2. Topographic map of the paddy field surveyed after harvest, with the field mean defined as zero of micro-elevation; “in”: water inlet; “out”: water outlets; AA’ and BB’: cross-sections noted in Fig. 3; boxed two-dot line: the region compared to the monitored yields.

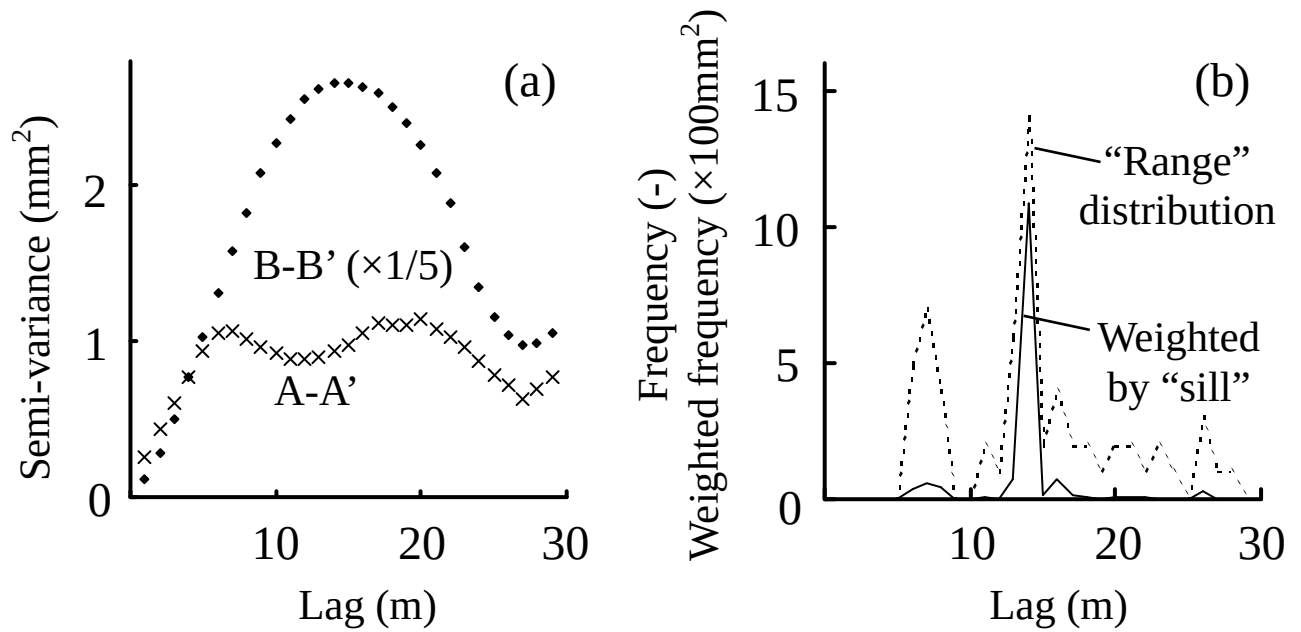


Fig. 3. Analysis of the micro-elevation in the longitudinal direction of the field: (a) semi-variograms in longitudinal cross-sections near the periphery (A-A') and in the middle (B-B') of the field denoted in Fig. 2; (b) dotted line: frequency distribution of the "range", or the lag where the first peak ("sill") of the semi-variance appeared; solid line: the "range" distribution weighted by the "sill".

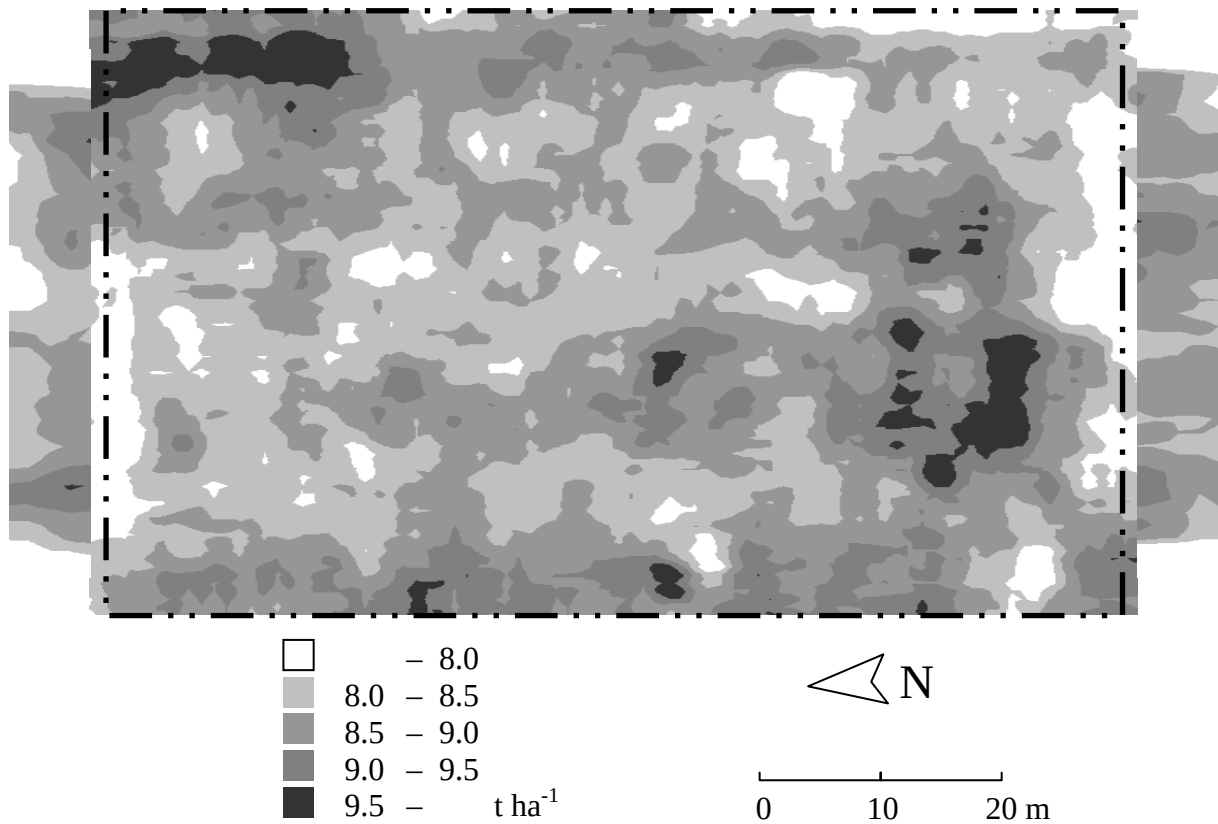


Fig. 4. Yield map of fresh grain calculated from the yield monitor mounted on the combine; boxed two-dot line: the region compared to micro-elevations.

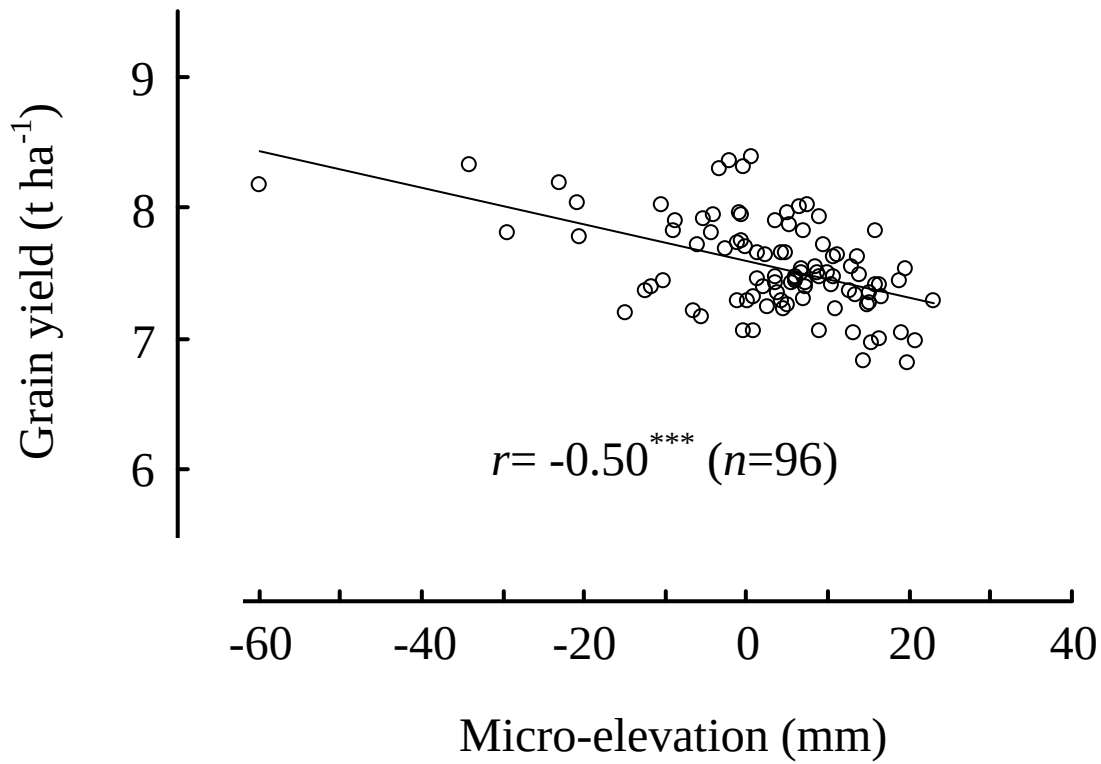


Fig. 5. Monitored grain yields (adjusted to a moisture content of 150 g kg⁻¹) and their relation to micro-elevation in the field with the zero point defined as the field mean, both averaged for 7 m × 6 m plots.

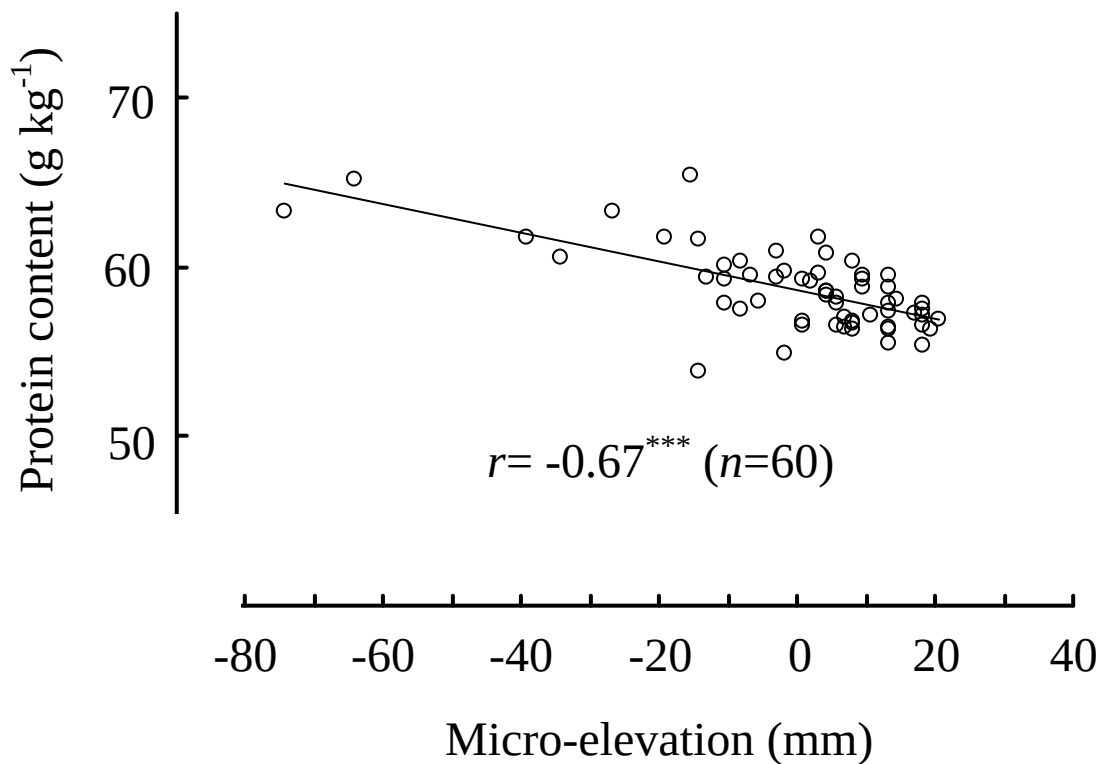


Fig. 6. Protein content of polished rice sampled at 60 locations and its relation to the micro-elevation of the field. The protein content is expressed at a grain moisture content of 150 g kg⁻¹.

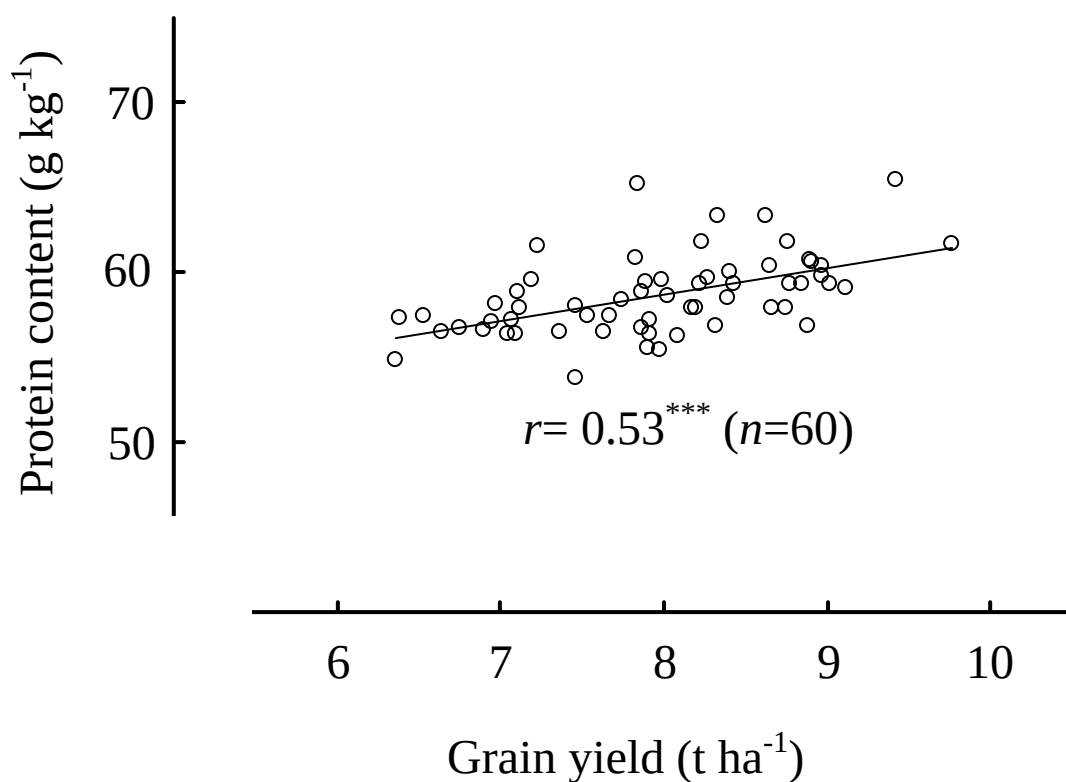


Fig. 7. Relation between grain yield and protein content (both adjusted to a moisture content of 150 g kg^{-1}) sampled at the 60 locations.

Table 1

Minimum range in micro-elevation within which significant correlations to grain yield and protein content are observed

<i>Attributes</i>	<i>Total samples</i>	<i>Size of grid or plot (m)</i>	<i>Significance level *</i>	<i>Minimum range (mm) ⁺</i>	<i>Extracted samples</i>	<i>Coefficient of variation</i>
Grain yield (monitored)	96	7×6	0.05	±7	50	0.042
			0.01	±11	67	0.047
Protein content (hand-sampled)	60	10×8	0.05	±14	42	0.027
			0.01	±17	47	0.035

* One-sided t-test, assuming that the correlations are negative

⁺ Upper and lower bounds of micro-elevation based on the field mean