The effect of yield–protein correlation on the optimal level of nitrogen fertilisation for wheat

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小麦の収量とタンパク質含有量の相関が最適窒素施肥量に及ぼす影響
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Introduction: The correlation between yield and protein content has long been studied in the wheat literature, as the issue has significant implications for producers’ fertilisation strategies as well as policymakers’ policy design of quality bonus schemes. These studies, however, are mostly confined to field experiments, with the majority of economic and modelling research failing to account explicitly for this type of correlation in their analysis. Thus, it is unknown how the optimal level of nitrogen fertilisation is affected by the underlying yield–protein correlation and, equivalently, to what degree misassumptions on the correlation distort the estimation of the optimal fertilisation strategy. Based on the results of the authors’ own field experiment, this study conducts a modelling analysis in which the optimal level of nitrogen application is derived repeatedly under different levels of the yield–protein correlation.

Materials and methods: The field experiment was carried out at the experimental field of the University of Tokyo (35°44’11”N, 139°32’20”E) between November 2010 and June 2011. Twenty-four plots of 24 m² each were assigned to 8 treatments by the split-split plot design with 3 replications. The treatments covered the full factorial combination of 2 sowing dates (2 Nov and 1 Dec) and 4 levels of nitrogen fertilisation (0, 80, 110 and 140 kg N ha⁻¹). Hard wheat cultivar Yumeshihou was sown by the direct drilling method, at the sowing rate of 80 kg ha⁻¹ and the row interval of 0.19 m. At the harvest between 15 and 23 June, the grain yield (t ha⁻¹) at 12.5 % moisture content was recorded. In addition, the grains from each plot were analysed by the Dumas method for their protein content (%) at 13.5 % moisture content.

From the yield and protein content data obtained from this experiment, two equations explaining the yield and the grain protein content were estimated using the ordinary least squares method (Table 1). The residual terms of these two equations were jointly tested for bivariate normality using the Shapiro-Wilk method. Next, the economically optimal level of nitrogen fertilisation was derived by the means of Monte Carlo experiments, whereby a combination of the yield and the protein content was drawn one million times under various levels of nitrogen fertilisation. These values were then converted to the expected profit per hectare of operation using the actual pricing structure of the Japanese wheat market (Table 2). This procedure was repeated 21 times under different assumptions on the yield–protein correlation, namely with \( \rho = -1, -0.9, \ldots, 1 \). Throughout these experiments, variances of the yield and the protein content were fixed at the level obtained from the field experiment data; only covariances were synthetically altered.

Results and discussion: The correlation efficient between the residual terms obtained from the field data was \(-0.21\), suggesting the presence of a modest level of the negative yield–protein correlation. The Shapiro-Wilk test did not reject the null hypothesis of bivariate normality \((W = 0.94; \rho = .28)\), and therefore the present specification of the two-equation system was justified. Different levels of the yield–protein correlation produced different solutions to the economic optimisation problem, with the optimal level of nitrogen fertilisation being considerably higher under a negative correlation (Fig. 1). This is because, under a negative correlation, there is less likelihood of nitrogen oversupply that would result in too high a protein content to receive a quality bonus, and producers can become more aggressive about targeting a higher yield with fertilisation. Overall, the importance of considering the yield–protein correlation has been verified, thereby warranting further investigations on the topic.
Table 1 Estimations of yield and protein content.

\[
y = 2.67 + 0.022 n + \varepsilon_1 (R^2 = .6498) \\
\text{(.33) \text{(0.0036)}} \\
p = 10.60 + 0.028 n + \varepsilon_2 (R^2 = .6180) \\
\text{(.42) \text{(0.004)}}
\]

\(y\): yield (t ha\(^{-1}\)), \(p\): protein content (%), \(n\): level of fertilisation (kgN ha\(^{-1}\)), \(\varepsilon_1\) and \(\varepsilon_2\): correlated residuals. The numbers in the parentheses below each equation are standard errors.

Table 2 Definition of expected profit per hectare.

\[
E\pi = \int \int_{\pi(a + b)} dy dp - \pi_n - \pi_o
\]

\(E\pi\): Expected profit per hectare of wheat operation, \(a\): portion of wheat price that is unrelated to the grain quality (58,340 JPY t\(^{-1}\)), \(b\): publicly funded quality bonus linked to the grain protein content (150,000 JPY t\(^{-1}\) for grains satisfying 11.5 < \(p\) < 14.0, zero otherwise), \(\pi_n\): the cost of nitrogen fertiliser (2,480 JPY kgN\(^{-1}\)), \(\pi_o\): all other costs incurred from wheat operation (292,980 JPY ha\(^{-1}\)).

Fig. 1 Expected profit per hectare under different levels of yield–protein correlation.