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Crop and soil specific N and P efficiency and productivity in Finland

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This paper estimates a stochastic production frontier based on experimental data of cereals production in Finland over the period 1977–1994. The estimates of the production frontier are used to analyze nitrogen and phosphorous productivity and efficiency differences between soils and crops. For this input specific efficiencies are calculated. The results can be used to recognize relations between fertilizer management and soil types as well as to learn where certain soil types and crop combinations require special attention to fertilization strategy. The combination of inputs as designed by the experiment shows significant inefficiencies for both N and P. The measures of mineral productivity and efficiency indicate that clay is the most mineral efficient and productive soil while silt and organic soils are the least efficient and productive soils. Furthermore, a positive correlation is found between mineral productivity and efficiency. The results indicate that substantial technical efficiency differences between different experiments prevail.

Key words: productivity, fertilization, wheat, barley, oats

Introduction

Mineral emissions from agriculture are claimed to contribute to a range of environmental problems that have arisen in the past decades. Examples of these problems are eutrophication of surface water, ozone depletion and pollution of natural areas (van der Bijl et al. 1999). In response, policy makers have shown an increasing interest in curbing mineral emissions from agriculture by introducing environmental legislation (e.g. the EU nitrate Directive (Europan Commission 1998)). Mineral policies in different countries may range from voluntary programs focusing on the training and schooling of farmers (e.g. Italy) to ‘simple’ fertilizer levies (Norway) and more complex systems of mineral surplus taxes (the Netherlands). In a system of mineral surplus taxes, farmers pay a levy on the surplus of minerals which is calculated as mineral input (e.g. through feed, fertilizers, seeds) minus mineral output (disposal through transporta-

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tion of manure, selling crops etc.). Several studies indicate that farmers can reduce mineral emissions by using mineral inputs in a more efficient way (e.g. Reinhard et al. 1999). However, the scope for the efficient use of minerals may be limited by natural conditions such as soil type and climate.

The vast economic literature on mineral emissions shows a strong bias towards studies aiming at analyzing policy instruments (see Hanley (1991) and Bäckman (1999) for an overview of studies focusing on policy instruments). These studies do not explain efficiency differences between farms, but focus on the effects of different policy measures on economic (e.g. income) and environmental variables (mineral use/ surplus). In one study, Reinhard et al. (1999) develop nitrogen efficiency indicators for a set of Dutch farms using a stochastic frontier function. The methodology in this report relies on that work. However, their sample of farms is taken from a region having approximately the same soil and climate throughout, and does not provide insight into the mineral efficiency and productivity of crops in different soil types. Moreover, their index of nitrogen efficiency is an aggregate measure at the level of the farm, i.e. it does not distinguish between crops. Johansson et al. (2004) use frontiers in a metamodelling of phosphorus and estimated cost functions. Oude Lansink et al. (2002) apply a non-parametric data envelopment analysis (DEA) on conventional and organic farms. That work includes input specific efficiencies and productivities of which one factor is land. This factor shows relatively high inefficiency but high productivity for conventional farms, but also shows low productivity and quite high efficiency for organic farms. This gives an indication that yields and fertilization are of importance when determining the frontier.

From actual farm data it is close to impossible to find the actual response of nutrients to yields because of low variation in nutrient inputs, high variation in output and variation in other management components. This study uses experimental data on five different soil types and three different crops in order to estimate a stochastic frontier in the sense of Meeusen and van den Broeck (1977) and Aigner et al. (1977). Battese (1992) also gives a survey of useful applications in agricultural economics. Two important dimensions can be distinguished in this study. The estimates of the stochastic production frontiers are used to generate efficiency indicators for nitrogen and phosphorus for different crops and soils. Further, a mineral productivity indicator is developed that reflects the environmental performance of different soil types relative to the best (most efficient) soil. A measure of mineral productivity for individual crops and soil types is useful because, in the absence of information of mineral leaching, it provides insight into the resource use of the production of different crops in different soils. Furthermore, the use of experimental data in the estimation of a stochastic production frontier allows for an assessment of the impact of local conditions on estimated efficiency ratios. This is because the experiments have all been designed such that the differences due to management should be excluded. The sites are located in different places, which may leave small differences in management despite the scientific design of the experiments. The experiment follows the common practice of fertilizing crops in Finland, where fertilizers and seeds are placed in separate rows in the soil. The machinery for this combines fertilizing and seeding into one activity. The actual practice is to give one application of fertilizers at sowing time and no further application during the growth period. It is also generally known that a P response in yield originates from plant available soluble P in soil and less from annual application, e.g. Saarela et al. (1995). The response of N, on the other hand, is based on the annual application of N. Additionally feasible measurements of plant available N in soils that could be used in the equations are still not developed for use in practical cultivation in Finland. Climatic effects such as temperature and precipitation are included as stochastic elements and separated from inefficiencies due to combinations of inputs or management.

The remainder of this paper is structured as follows. The following sections give a graphical demonstration of the mineral efficiency and productivity indicators that are developed in this paper. This is followed by a formal discussion in terms of the stochastic production frontier. Experimental data from Finland over the period 1977-1994 are the focus of the application, and the paper concludes with some comments.

Measurement of soil specific mineral efficiency

Input specific mineral efficiency is defined as the ratio of minimum feasible mineral use to the observed use of a mineral, conditional on observed levels of output and other inputs. The concept of mineral efficiency closely follows the idea of subvector efficiency, as discussed by Färe et al. (1994, p. 243, 250). The notion of soil specific mineral efficiency using a production frontier is illustrated in Figure 1. This figure shows the production frontiers of soils A and B, where soil B is a more productive soil type than soil A. At the observed input quantity on soil A (X_{Ai}), quantity Y_{Ai} is produced. However, at this observed input quantity, soil A has a maximum feasible output of Y_{Ai}^F. An output-oriented measure of technical efficiency (TE) is given by

$$TE = \frac{Y_{Ai}}{Y_{Ai}^F}. \tag{1}$$

N and P efficiency of mineral X is given here by the ratio of the minimum feasible to the observed use of N or P. The minimum feasible use of X on soil A at the observed output level is the quantity X_{Ai}^F. The mineral efficiency of soil A is therefore given by the soil specific efficiency measure:

$$E_A^S = \frac{X_{Ai}^F}{X_{Ai}}. \tag{2}$$

Next it is assumed that the quantity X_{Ai} is used on soil B to produce the same crop. Figure 1 shows that the minimum feasible use on soil A at the same output quantity as before (Y_{Ai}) is X_{Ai}^F, while for soil B it is X_{Bi}^F. Therefore, soil B uses mineral X more efficiently than soil A. This productivity difference between soil A and soil B is reflected by the ratio:

$$E_A^P = \frac{X_{Bi}^F}{X_{Ai}^F}. \tag{3}$$

The soil specific productivity measure reflects differences in natural circumstances due to soil type. In general, these factors are not directly under the control of farm managers, as opposed to factors that cause differences in the efficiency measure. Finally, an overall index of mineral efficiency for mineral X is

$$E_A^O = \frac{X_{Bi}^F}{X_{Ai}}. \tag{4}$$

where the relationship between E_A^O, E_A^P *and* E_A^S is given by

$$E_A^O = E_A^P \cdot E_A^S. \tag{5}$$

It should be noted that the overall efficiency is a hypothetical measure for the potential reduction of mineral use within a heterogeneous region rather than within an individual farm, since individual farms most often have a rather narrow range of soil types. The potential reduction could be achieved, assuming that a region would have the opportunity to allocate crop production to the most productive soils. Its more important to admit that, if there is inefficiency, there will in agriculture always be productivity and variability due to soil types, and to use this information in designing policy instruments.

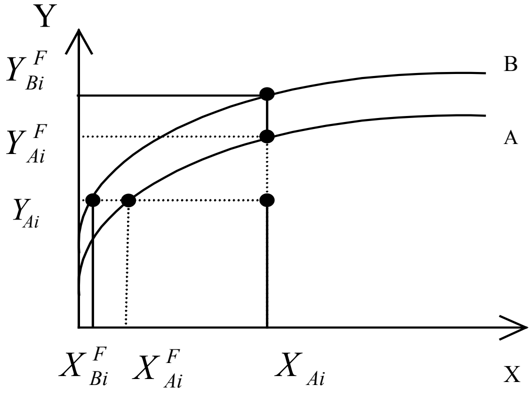

Fig. 1. Production frontier.

Soil specific mineral efficiency

Stochastic production frontier

The production of crops is affected by random elements such as different weather conditions and pest infestations. Therefore, modeling mineral efficiency in crops production requires an approach that accounts for stochastic elements. Following Aigner et al. (1977) and Meeusen and van den Broeck (1977), the stochastic production frontier used in this study relates quantities of the minerals nitrogen and phosphorus to the production of outputs and is given by

$$Y_i = f(N_i, P_i, t, D_i; \beta)\exp\{V_i - U_i\} \tag{6}$$

where the index *i* denotes individual observation and *t* denotes time. Furthermore, following the Frontier 4.1 application description Coelli (1994), for this application,

Y_i is yield per hectare
N_i represents the quantity of applied N fertilizer per hectare
P_i represents phosphorus in soil
β is a vector representing technology
D_i is a vector of soil dummies
V_i is a random error term, i.i.d. as $N(0, \sigma_v^2)$
U_i is a nonnegative error term representing technical inefficiency. U is i.i.d. as $N^+(\mu, \sigma_u^2)$; the distribution is either half-normal or truncated

The composite error $V_i - U_i$ term allows for the separation of variability (U) that can be influenced by the manager, from variability (V) that is out of reach of the manager. In our model, U is not a pure management effect, since the data are from field experiments which are designed to rule out the management factor. It is more clearly a result that comes from the design of the experiment, but that can be used as an interpretation of controlled actual situations since it reflects possible variability due to management. The production frontier is theoretically increasing but not necessarily concave in N and P[1]. Furthermore, it is assumed that N and P are strongly disposable, implying that it is possible to decrease either N or P without increasing P or N respectively, while keeping output constant. All other inputs are considered as constants. The output-oriented measure of technical efficiency is given by

$$TE = \frac{f(N_i, P_i, t, D_i; \beta)\exp\{-U_i\}}{f(N_i, P_i, t, D_i; \beta)} = \exp(-U_i) \tag{7}$$

where $0 < TE \leq 1$ with 1 indicating perfect technical efficiency and values close to zero low efficiency.

Empirical model

The Translog production frontier specification of equation (6) is given by

$$\begin{aligned} \ln Y_i = {} & \beta_0 + \beta_1 \ln N_i + \beta_2 \ln P_i + \beta_{11}(\ln N_i)^2 + \\ & \beta_{22}(\ln P_i)^2 + \beta_{12}\ln N_i \ln P_i + \beta_t T_i + \beta_{tt} T_i T_i + \\ & \beta_{1t} T_i \ln N_i + \beta_{2t} T_i \ln P_i + \sum_{j=1}^{n} \gamma_j D_{ij} + \lambda D_i + \\ & V_i - U_i \end{aligned} \tag{8}$$

where T represents a time trend and D_{ij} are soil specific dummy variables that take the value 1 if the j-th soil applies for observation i and zero otherwise. The time trend represents technological development, as in our case the development of varieties. The dummy variables have been constructed such that they take the soil with the highest productivity as the reference soil, i.e. all observations on the reference soil have $D_{ij} = 0$ for all j. The reference soil can be selected after preliminary calculations. All other variables are defined as before. Note that in the Translog specification of the production frontier in (8), cross terms of soil dummies and N and P have not been included. This is because there are not enough observations for each soil type and crop to do so. The Translog specification of the production frontier is sufficiently flexi-

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[1] This assumption is made here because this study uses experimental data with application levels of P and N that do not necessarily follow from profit-maximizing behavior. The production frontier might not be concave in the range of very small levels of P and N.

ble to allow for convex and concave regions of the production frontier. Calculating phosphorous (nitrogen) efficiency requires a solution of P^F for each observation, given the level of predicted output and the quantity of nitrogen (phosphorous). Following Reinhard et al. (1999), a solution for in our case P^F is found by inserting $U_i = V_i = 0$ into equation (8):

$$\beta_0 + \beta_1 \ln N_i + \beta_2 \ln P_i^F + \beta_{11}(\ln N_i)^2 + \beta_{22}(\ln P_i^F)^2 + \beta_{12}\ln N_i \ln P_i^F + \beta_t T_i + \beta_{tt} T_i T_i + \beta_{1t} T_i \ln N_i + \beta_{2t} T_i \ln P_i^F + \sum_{j=1}^{n} \gamma_{ij} D_{ij} + \lambda D_i - \ln \hat{Y}_i = 0 \qquad (9)$$

where $\ln \hat{Y}_i$ is obtained by inserting $V_i = 0$ into (8). Solving the second order polynomials gives the solution for observation i:

$$\ln P_i^F = \frac{-\beta_2 - \beta_{12}\ln N_i - \beta_{2t} T_i \pm \sqrt{(\beta_2 + \beta_{12}\ln N_i + \beta_{2t} T_i)^2 - 4\beta_{22} c}}{2\beta_{22}} \qquad (10)$$

where

$$c = \beta_0 + \beta_1 \ln N_i + \beta_{11}(\ln N_i)^2 + \beta_t T_i + \beta_{tt} T_i T_i + \beta_{1t} T_i \ln N_i + \sum_{j=1}^{n} \gamma_{ij} D_{ij} + \lambda D_i - \ln \hat{Y}_i. \qquad (11)$$

The positive root is used for the input specific efficiencies. If the observation is both input specific and technically efficient then there is only one solution and one root where U = 0.

Calculation of N and P efficiency indexes also requires a solution for N and P for the reference soil, i.e. the soil with the highest productivity. These values, N_i^{FR} and P_i^{FR} respectively are found by using equations (10) and respective for P_i^{FR}, together with (11) and respective for P, while leaving out the term $\sum_{j=1}^{n} \gamma_{ij} D_{ij} + \lambda D_i$ in the equation for c.

Data and estimation

Data have been obtained from a data set of fertilizer field trials from 24 experiments at 14 different locations in Finland over the period 1977–1994. The experiments have originally been designed to measure the short and long term effects of different phosphorous application levels on yields of different cereals in different soils. Three crops and five soil types are distinguished. The crops included in the analysis are barley, oats and wheat. The number of observations is 550 for barley, 240 for oats and 180 for wheat. The soil types in the data set are fine sand, clay, loam, silt and organic soil. Organic soils are included only for wheat. Including organic soils in barley and oats gave a production frontier that was decreasing in inputs over a large part of the domain. For barley a separate dummy was included for northern plots (north of 62°N), since these plots are characterized by less favorable weather conditions, resulting in substantially lower yields[2]. This regional dummy represents a productivity difference that is not related to the soil.

The experiments distinguish five different rates of phosphorous application, each at a range of N fertilizer application levels. The range of N applications in our sample for grains is 40–138 kg ha^{-1}, with no zero observations. Phosphorous is applied in steps of 15 kg ha^{-1} from 0–60 kg ha^{-1}. The data set also includes the level of phosphorous in the soil. According to Saarela et al. (2004) there is a rather high mean P pool of approximately 850 kg ha^{-1} in the cultivated soils for the beginning years 1977–1981, but the level of plant available P is rather low. The P level in the soil is measured every third year before the beginning of the crop season. Missing data on the P level in the soil in intermediate years are imputed by regressing a time trend on the P level in the soil for each individual experiment (24 regressions in total).

All yields and inputs are measured in kg ha^{-1} (see Table 1); the P level in the soil is measured in mg l^{-1}. The P fertilizer that was applied in the field trials was in the form of 9% super phosphate until 1987 and as 20% super double phosphate thereafter. A more detailed description of the data, includ-

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[2] It was also found that the production frontier became downward sloping over a particular domain if the regional dummy was not included.

Table 1. Description of the data.

Crop	No. of observations	Yield		N application (kg ha^{-1})	P application (kg ha^{-1})	Plant available P in soil (mg l^{-1})
		Average	Std. Dev.	Average	Average	Average
Barley	755	3270	1130	68	30	7.6
Wheat	180	3190	1110	91	30	5.2
Oats	325	3880	1090	65	30	5.8

ing the results of the field trials, can be found in Saarela et al. (1995) and in Saarela et al. (2003).

The stochastic production frontier in (8) is estimated with maximum likelihood using the FRONTIER 4.1 package (Coelli 1994).

Results

The stochastic Translog production frontier has been estimated for barley, oats and wheat. The truncated distribution for U was accepted for wheat and oats, but for barley a half normal distribution was used. Parameter estimates and t-values can be found in the appendix (Table A.1 to A.3). Approximately 42% of the parameters of the production frontier of barley are significant at the critical 5% level. For oats and wheat the percentage of significant parameters is 85% and 71%, respectively. The many insignificant variables for barley can give an indication of missing information or omitted variable. The results for wheat and oats are more reliable. Although the individual variables are insignificant, the model specification used is the most favorable since Cobb-Douglas or a model with constant returns to scale is tested against the translog specification (Table A.4). The relative productivity of different soils has been modeled using dummy variables, where the most productive soils represent the reference soils. For all crops, clay was found to be the reference soil. The negative values of the parameters associated with the soil dummies of the other soils indicate lower productivity. It can be seen that most parameters associated with the soil dummies are significant at the critical 5% level.

The results in the appendix (Table A.4) show that the Cobb-Douglas specification is rejected at the 5% level against a translog specification for all crops. This implies that a flexible functional form such as the translog specification is more appropriate than the Cobb-Douglas for this data set. The hypothesis of constant returns to scale in a Translog specification is also rejected at the critical 5% level for oats and wheat and at the 10% level for barley. The hypothesis of the nonexistence of inefficiency is also rejected for all the crops. This means that the inefficiency terms (U_i) are not insignificant. A test for the significance of soil productivity differences is separately performed by a t-test on the difference between the coefficients associated with the soil-dummies. This is because some of the variables were not significant. The results of the test for soil productivity differences are found in Table 2 and show that clay, loam, silt, sand and organic soils are significantly different from each other for wheat. Silt is significantly different from clay, loam and sand for all crops. Clay is also significantly different in terms of productivity from loam for wheat but not for barley and oats.

Technical and input specific efficiencies are found in Table 3. Soil specific efficiency for Nitrogen and Phosphorous (E^S) are consistent with equation (2). Soil specific productivity indices (E^P) are calculated by equation (3). The overall efficiencies E^O are calculated by multiplying E^S by E^P. The frontier values required for the efficiencies are calculated using equations (10)–(11) and respectively for P.

The results in Table 3 show that the technical efficiencies are, on average quite similar for different crops, with average values for different crops in the range 0.69–0.77. The efficiency differences

Table 2. Soil productivity differences (t-values in parentheses).

	Loam	Silt	Sand	Organic
Barley				
Clay	–0.08	–0.38*	–0.20*	–
	(–1.01)	(–5.02)	(–2.30)	
Loam		0.30*	0.12*	–
		(7.25)	(2.46)	
Silt			–0.18*	–
			(–3.75)	
Oats				
Clay	–0.03	–0.36*	–0.04	–
	(–0.44)	(–6.85)	(–0.80)	
Loam		0.33*	0.02	–
		(10.91)	(0.54)	
Silt			–0.32*	–
			(–7.34)	
Wheat				
Clay	–0.46*	–0.84*	–0.08*	–1.18*
	(–12.04)	(–31.49)	(–3.71)	(–52.34)
Loam		–0.39*	0.37*	–0.72*
		(–11.15)	(11.47)	(–27.42)
Silt			0.76*	–0.34*
			(19.73)	(–11.92)
Sand				–1.10*
				(–51.94)

* Significant at 5%.

between different experiments are prominent although the data are designed to exclude management as a source of inefficiency, i.e. all experiments use the same application rates, and the same soil tillage and pest management techniques. Moreover, the soil types are accounted for in the estimation procedure by including soil specific dummies. The implication is that efficiency differences between experiments must be attributed to local variations in climate and pest occurrence. However, some differences between soil types still remain. Another implication is that efficiency differences between farmers that are found in studies using farm level data may also be largely attributable to local variations that are out of the control of the farm managers or to errors in the specification of the production frontier and measurement errors in the data.

Table 3 also shows that input specific efficiencies for N and P (E^S) are smaller than the input specific soil productivities (E^P). Moreover, it can be seen that silt soils have a lower productivity for P and N than clay, loam and sand. The organic soils are characterized by a high natural N content, which may explain their low N efficiency for wheat. It can also be seen that the overall input specific efficiencies are very low in some instances (e.g. for P on silt and organic soils). However, it is important to note that the input specific efficiencies reflect the possibility to reduce the use of one specific input, while keeping yield and the use of other inputs constant. If the isoquant is flat over a large range (indicating low substitution possibilities) then very low efficiencies may arise. Therefore, the low overall P efficiencies for barley and oats on silt, and wheat on silt, loam and organic soils, are an indication of small substitution possibilities between inputs.

A comparison of input specific efficiency and soil productivity between crops in Table 3 shows that oats and wheat have a higher productivity and efficiency for N, whereas barley and oats have a higher productivity and efficiency for P. The low productivity indices for P and N on the sand and silt soils that are found in this study might indicate that these soils are more vulnerable to mineral

Table 3. Technical efficiency and mineral specific efficiency and productivity at the sample mean.

			Nitrogen			Phosphorus		
Crop	Soil type	TE	E^S	E^P	E^O	E^S	E^P	E^O
Barley	Clay*	0.71	0.58	1.00	0.58	0.52	1.00	0.52
	Loam	0.70	0.30	0.51	0.15	0.40	0.77	0.31
	Silt	0.66	0.05	0.08	0.00	0.20	0.38	0.08
	Sand	0.72	0.14	0.23	0.03	0.29	0.57	0.17
	Average	0.69	0.14	0.14	0.02	0.29	0.46	0.14
Oats	Clay*	0.84	0.75	1.00	0.75	0.54	1.00	0.54
	Loam	0.78	0.91	0.88	0.80	0.90	0.74	0.67
	Silt	0.72	0.89	0.45	0.41	0.68	0.29	0.20
	Sand	0.76	0.65	0.84	0.55	1.00	0.74	0.74
	Average	0.77	0.84	0.78	0.65	0.83	0.65	0.55
Wheat	Clay*	0.72	0.57	1.00	0.57	0.61	1.00	0.61
	Loam	0.73	0.86	0.70	0.60	0.17	0.27	0.03
	Silt	0.70	0.50	0.67	0.32	0.78	0.10	0.08
	Sand	0.93	0.84	0.87	0.73	0.03	0.80	0.02
	Organic	0.92	0.76	0.52	0.39	0.15	0.07	0.01
	Average	0.74	0.66	0.86	0.55	0.46	0.67	0.36

TE= technical efficiency, E^S= soil specific efficiency, E^P= soil productivity index, E^O= overall input specific efficiency
*Reference soil

leaching as well. If the government aims at protecting the groundwater, then it might discourage excess fertilization of these soils, rather than of clay and loam where fertilization and P level variations are less important.

Discussion

This paper has estimated a stochastic production frontier based on experimental data of cereals production in Finland over the period 1977–1994. The estimates of the production frontier are used to analyze nitrogen and phosphorous productivity and efficiency differences between soils for wheat, barley and oats.

The measures of mineral productivity and efficiency indicate that clay is the most mineral efficient and productive soil; silt and organic soils are the least efficient and productive soils. Furthermore, a positive correlation is found between mineral productivity and efficiency.

Substantial (Table 3) technical efficiency differences between different experiments prevail. This is surprising since the management factor should be excluded and since the soil type has been accounted for in the production frontier specification. The technical efficiency differences between experiments cannot be attributed to management factors, but should be attributed to different local conditions (e.g. water supplies, climate) or other factors such as misspecification and errors in the measurement of the data. Farm level data are more frequently used in efficiency studies, and the results in this paper indicate that management factors as a source of efficiency differences in farm level studies may confound with differences in local conditions (soil type, climate) between farms and other factors.

The data used in this paper allow for making an assessment of the efficiency and productivity of mineral use on different soils. However, from an environmental point of view, mineral leaching and losses are more important, and the results are to be interpreted with caution because of the inherent flexibility of the production frontier and the normally high variability in yields of cereals. Nevertheless, future research should make an attempt to determine the efficiency of different soils in terms of leaching, which could be achieved by specifying mineral leaching as an external output and by estimating output distance functions for different crops (see Färe et al. 1993).

Conclusions

The results indicate that substantial technical efficiency differences between different experiments prevail, despite the use of experimental data that exclude the management factor. This result implies that results found in efficiency studies using farm level data are likely confounding management factors with differences in local conditions (soil type, climate) between farms. In the experimental design, however, the domain needs to be large enough to show the optimal intensities. A high variability in yields is problematic when using flexible functional forms such as the translog specification.

The productivity differences between different soils need to be accepted. There exists inefficiencies particular to certain soils. This has implications on the importance of accurate fertilization management. The management involves soil sampling and P and N fertilization. For soils that are sensitive to nutrient inefficiency, the soil sampling needs to be more frequent than for soils with higher efficiency. In cereal production a sampling interval of 10 years gives rather good information that can be utilized. Particular to clay and partly to loam, the excess use of P fertilizer is of less importance than for soils that have higher inefficiency and lower productivity, as long as soils are not saturated with P. Another implication from the results is the importance of pesticides and liming in the utilization of nutrients. In our analysis unexplained yield variability shows up as inefficiency in input specific efficiencies. The importance of pesticide use for nutrient efficiencies requires still more attention.

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Appendix 1

Table A1. Parameter estimates for barley.

Parameter	Coefficient estimate	Standard error	T-value
β_0	6.21	5.56	1.12
β_1	0.486	2.67	0.18
β_2	0.545	0.34	1.59
β_3	–0.017	0.32	–0.05
β_4	–0.128	0.02	–6.19
β_5	0.045	0.07	0.60
β_6	0.145	0.06	2.49
β_7	0.002	0.00	3.16
β_8	–0.044	0.01	–3.36
β_9	–0.002	0.01	–0.48
γ_1	–0.083	0.08	–1.01
γ_2	–0.383	0.08	–5.02
γ_3	–0.200	0.09	–2.30
λ_1	–0.050	0.03	–1.60

λ represents local dummy

Table A2. Parameter estimates for oats.

Parameter	Coefficient estimate	Standard error	T-value
β_0	5.77	0.91	6.32
β_1	1.85	0.46	4.06
β_2	–0.45	0.29	–1.56
β_3	0.19	0.08	2.45
β_4	–0.29	0.06	–4.61
β_5	–0.10	0.03	–3.55
β_6	–0.24	0.05	–4.54
β_7	0.05	0.01	3.86
β_8	0.02	0.01	3.17
β_9	0.00	0.00	–0.26
γ_1	–0.03	0.06	–0.44
γ_2	–0.36	0.05	–6.85
γ_3	–0.04	0.06	–0.80

Table A3. Parameter estimates for wheat.

Parameter Wheat	Coefficient estimate	Standard error	T-value
β_0	–19.20	0.99	–19.44
β_1	14.77	0.57	25.77
β_2	–2.62	0.74	–3.51
β_3	0.63	0.18	3.54
β_4	–1.92	0.10	–18.97
β_5	–0.10	0.02	–4.91
β_6	–0.07	0.10	–0.71
β_7	0.01	0.02	0.60
β_8	0.01	0.01	2.22
β_9	0.00	0.00	0.72
γ_1	–0.46	0.06	–8.02
γ_2	–0.84	0.05	–16.59
γ_3	–0.08	0.12	–0.69
γ_4	–1.18	0.05	–24.73

Appendix 1

Table A4. Results of tests on the Cobb-Douglas specification, constant returns to scale and inefficiency.

Specification	H_0	Test value	Critical Value	Outcome
Cobb-Douglas				
Barley	$\beta_1 + \beta_2 = 1$, $\beta_{ij} = 0$, $\beta_{it} = 0$	Likelihood ratio = 371	$\chi^2 = 16$ at α 0.025	H_0 rejected
Oats	$\beta_1 + \beta_2 = 1$, $\beta_{ij} = 0$, $\beta_{it} = 0$	Likelihood ratio = 66.5	$\chi^2 = 16$ at α 0.025	H_0 rejected
Wheat	$\beta_1 + \beta_2 = 1$, $\beta_{ij} = 0$, $\beta_{it} = 0$	Likelihood ratio = 80.3	$\chi^2 = 16$ at α 0.025	H_0 rejected
Constant returns to scale				
Barley	$\beta_1 + \beta_2 = 1$, $\beta_{12} + \beta_{11} = 0$, $\beta_{12} + \beta_{22} = 0$, $\beta_{1t} + \beta_{2t} = 0$	Likelihood ratio = 9.83	$\chi^2 = 11.14$ at α 0.025, 9.49 at α 0.05	H_0 rejected at α 0.05
Oats	$\beta_1 + \beta_2 = 1$, $\beta_{12} + \beta_{11} = 0$, $\beta_{12} + \beta_{22} = 0$, $\beta_{1t} + \beta_{2t} = 0$	Likelihood ratio = 30.4	$\chi^2 = 11.14$ at α 0.025,	H_0 rejected
Wheat	$\beta_1 + \beta_2 = 1$, $\beta_{12} + \beta_{11} = 0$, $\beta_{12} + \beta_{22} = 0$, $\beta_{1t} + \beta_{2t} = 0$	Likelihood ratio = 82.5	$\chi^2 = 11.14$ at α 0.025	H_0 rejected
No inefficiency				
Barley	$^*\eta = 0, \Rightarrow \sigma^2_u = 0$	Likelihood ratio = 104	$\chi^2 = 5.02$ at α 0.025,	H_0 rejected
Oats	$^*\eta = 0, \Rightarrow \sigma^2_u = 0$	Likelihood ratio = 109	$\chi^2 = 5.02$ at α 0.025,	H_0 rejected
Wheat	$^*\eta = 0, \Rightarrow \sigma^2_u = 0$	Likelihood ratio = 102	$\chi^2 = 5.02$ at α 0.025,	H_0 rejected

$$^*\eta = \frac{\sigma^2_u}{\sigma^2_u + \sigma^2_v}$$

Appendix 1

Table A5. Correlation between inputs, time and efficiencies for wheat.

				Nitrogen			Phosphorus			
	TE	*N*	*Psoil*	E^S	E^P	E^O	E^S	E^P	E^O	*t*
TE	1.00									
N	0.00	1.00								
Psoil	0.13	0.26	1.00							
t	0.03	0.34	0.29	–0.08	0.02	–0.07	0.09	–0.03	–0.02	1.00
Nitrogen										
E^S	0.10	–0.77	0.39	1.00						
E^P	–0.15	0.42	0.12	–0.40	1.00					
E^O	0.02	–0.55	0.54	0.84	0.14	1.00				
Phosphorus										
E^S	–0.12	0.59	–0.55	–0.92	0.39	–0.78	1.00			
E^P	–0.10	0.35	0.15	–0.31	0.97	0.19	0.29	1.00		
E^O	–0.09	0.50	–0.49	–0.81	0.62	–0.58	0.86	0.61	1.00	