European Review of Agricultural Economics Vol **36 (1)** (2009) pp. 53–77
doi:10.1093/erae/jbp003
Advance Access Publication 18 March 2009

The effects of EU agricultural policy changes on farmers' risk attitudes

Phoebe Koundouri

DIEES, Athens University of Economics and Business, Greece

Marita Laukkanen and Sami Myyrä

Agrifood Research Finland, Helsinki, Finland

Céline Nauges

LERNA-INRA, Toulouse School of Economics, France

Received November 2007; final version received January 2009*

Summary

This analysis utilises a model of production under risk estimated on Finnish farm-level data to measure farmers' risk attitudes in a changing policy environment. We find evidence of heterogeneous risk preferences among farmers, as well as notable changes over time in farmers' degree of risk aversion. This result is due to the increase in the non-random part of farm income generated by the policy change after Finland's European Union accession. The analysis confirms the assertion that agricultural policies that are decoupled from production do affect input use and crop mix through their effect on farmers' risk attitudes.

Keywords: Common Agricultural Policy, risk preferences, decoupled payments, Finland

JEL classification: C33, D81, Q12, Q18

1. Introduction

One key mechanism through which agricultural support policies, even decoupled ones, may influence production decisions is their effect on farmers' risk aversion (see Hennessy, 1998, and USDA, 2004, for a comprehensive discussion).[1] By increasing wealth, decoupled payments may change farmers' risk aversion if tolerance for risk varies with wealth, which in turn

*Review coordinated by Paolo Sckokai

1 Decoupled payments are fixed-income transfers that do not depend on the farmer's production choices, output levels or market conditions.

may affect production through two channels: (i) the choice of output mix and (ii) the input decisions where the level of input use affects output variability.[2] Compared with a less risk-averse farmer, a more risk-averse farmer would plant less land to a riskier crop and use less of an input that increases output variability.

A number of recent empirical articles analysing the impact of decoupled farm programmes on production and land allocation decisions have confirmed the role of such risk effects. Sckokai and Antón (2005) studied the impact on land allocation and yields of the area-based payments and output price support provided by the European Union (EU) through its Common Agricultural Policy (CAP), using farm-level panel data from five European countries. They estimated a system of reduced-form equations and accounted for farmers' risk aversion by incorporating moments of the output price distribution and the initial wealth of farmers in the explanatory variables, following the approach developed in Chavas and Holt (1990). Goodwin and Mishra (2006) used US farm-level data to analyse the production effects of direct farm payments. They estimated reduced-form equations describing land allocated to corn, soyabeans and wheat. Farmers' risk preferences were represented by a proxy variable, the ratio of expenditures on insurance to total farm expenses. Sckokai and Moro (2006) were, to our knowledge, the first authors to build a structural model, which explicitly considers farmers' risk attitudes when assessing the impact of the CAP on arable crop production. They used the so-called 'certainty equivalent' representation of the utility function and assumed constant relative risk aversion preferences, which are a class of DARA preferences. Using a sample of Italian specialised arable crop farms, equations for outputs, inputs and acreages allocated to different crops were estimated simultaneously, and an estimate of the risk-aversion parameter was derived for three typical farm sizes. They find evidence that the total impact of the effects related to risk is important in the CAP arable crop regime.

The previous empirical literature assessing the risk-related production impacts of decoupled farm payments has thus either settled for including a proxy for risk preferences as an explanatory variable (Sckokai and Antón, 2005; Goodwin and Mishra, 2006) or, where risk preferences have been explicitly modelled, presupposed that farmers' risk behaviour is consistent with a specific class of risk preferences (Sckokai and Moro, 2006). This article estimates the effect of agricultural payments on risk attitudes, production and land allocation without making a priori assumptions on the form of risk preferences. The risk preference function is estimated simultaneously with the production technology and land allocation equations. The estimable risk preference function is flexible enough to allow for different types of risk attitudes, e.g. increasing, constant or decreasing absolute

2 Several empirical studies have shown farmers' risk preferences to be consistent with decreasing absolute risk aversion (DARA) (see, e.g., Saha *et al.*, 1994; Chavas and Holt, 1996), so one would expect direct payments to reduce farmers' risk aversion.

risk aversion. Furthermore, we can evaluate how risk aversion changes across farms and over time. This latter property is particularly interesting for the purpose of assessing the impact of past or future policy changes on farmers' risk attitudes and the associated effect on production and land allocation decisions. The technique used is due to Kumbhakar and Tveterås (2003), which we extend to account for the choice of the output mix by farmers. The approach is not restricted to the choice of a specific utility function and the implied risk preference function.

This analysis utilises a data set of Finnish grain farmers covering the 1992–2003 period. The data encompass years both before and after Finland's accession in the EU and the implementation of the CAP, which replaced agricultural price supports with area payments. The application is interesting in that it is the first paper, to the best of our knowledge, that investigates how farmers' risk attitudes have changed with policy changes in general, and with CAP regulation in particular.[3]

This article is structured as follows. Section 2 provides background information on grain production in Finland. A description of the data follows in Section 3. Section 4 presents the theoretical model of grain production under risk and Section 5 discusses the empirical model specification, estimation procedure and results. Moreover, the last part of Section 5 undertakes a policy simulation: the estimated production technology and risk preference function are used to assess the impact of agricultural subsidies on optimal land allocation and input levels. The concluding section summarises the insights gained on the risk-related effects of decoupled agricultural policies.

2. Environmental and policy context for grain production in Finland

Finland's northern location between the 60th and 70th latitudes makes the climatic conditions relatively harsh for agriculture, although the Gulf Stream raises temperatures 3–4°C above those normally observed in similar latitudes. The thermal growing season ranges from an average of 180 days a year in the south to 100 days in the north. From time to time, frost occurs in the middle of the summer in all parts of the country. Grain production is concentrated in southern Finland, with wheat and barley being the main crops produced.

3 The effects of EU accession on farming have been studied in several articles but from a different viewpoint than the one considered in this article. Mora and San Juan (2004) addressed the impact of the CAP on the evolution of agricultural product specialisation in Spain. Georganta (1997) studied the effect of the CAP by simulating the possible effects of relaxing the existing interventional policy on total factor productivity in Greece. Wier *et al.* (2002) analysed the impact of the Agenda 2000 reform on agriculture and environment in Denmark. Niemi (2005) examined the static welfare effects of Finland's accession in the EU using a partial equilibrium framework and derived the changes in consumer and producer surplus and budgetary transfers that followed from the integration in the EU. See also Demekas *et al.* (1988) for a survey of studies that have examined the costs and benefits of the CAP for the EU as a whole, as well as the effects of the CAP on world markets.

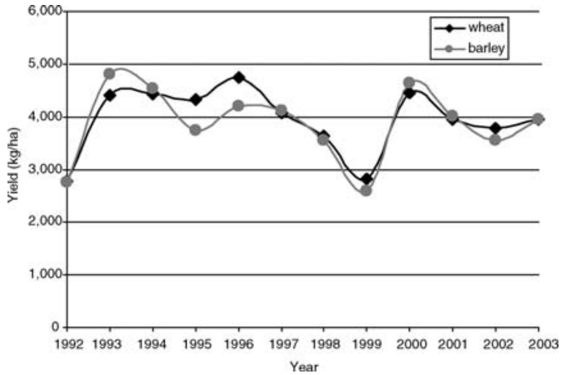

Figure 1. Average per hectare yield of wheat and barley in the study sample.

Average cereal yields reach only about half of the levels observed in southern European countries, and yield fluctuations are notable (Figure 1).

Finland joined the EU in January 1995. The membership and the application of the CAP radically changed the economic operating environment of agricultural producers, in particular in terms of income support. Prior to the EU membership, incomes were steered through price policy, where target prices for agricultural products were set in biannual negotiations between producer organisations and the government. Until 1995, target prices were applied to all the grains grown in the country – wheat, barley, rye and oats. In the CAP, the corner stone of support is instead formed by direct area and headage payments, although the CAP also includes instruments which aim at maintaining the prices of agricultural products above world market prices: public intervention precludes prices from falling below a set minimum price, and import duties are levied to raise the prices of imported products to the EU price level. From 1995 till 2004, wheat, barley and rye were included in the CAP price intervention programme, whereas oats no longer received price support. Since 2004, only wheat and barley have been subjected to the price support policies. Policy reforms in 1992 and 1999 brought the CAP cereal intervention prices closer to the world market prices. The cut in intervention prices was compensated for through direct area-based subsidies paid from both national funds and the agricultural budget of the EU. When Finland joined the EU in 1995, the average grain price in Finland fell by 57 per cent (Table A1), which brought Finnish producer prices to the level of the EU prices. The price of inputs also fell in 1995, but less markedly.

Because of the relatively low yields, the role of support in grain production is more pronounced in Finland than in other EU countries. Direct support payments currently make up 45 per cent of the total return of agriculture when, prior to the EU accession, their share was less than 20 per cent (Niemi and

Ahlstedt, 2005). Table A1 reports the subsidy levels for the main cereals, wheat and barley.[4]

The impact of the changes in agricultural support, brought along by the application of the CAP, on grain farmers' risk attitudes is ambiguous a priori. On the one hand, if it is assumed that farmers exhibit DARA, the overall decrease in farm income should lead to higher risk aversion. On the other hand, the effect of the decrease in overall expected income could have been offset by the increase in the non-random part of income owing to the introduction of the CAP. In general, CAP regulation has had a strong impact on Finnish farmers' income, farm structure and crop mix (Niemi and Ahlstedt, 2005), which may be at least in part explained by changes in risk attitudes. However, how farmers' risk attitudes have changed over time after Finland's EU accession remains an open question that we try to address in this article.

3. Data

The data used in this study have been obtained mainly from farm profitability bookkeeping records collected annually by MTT Agrifood Research Finland. The records are collected following EU accounting guidelines and provide the Finnish set of data for the European Commission's Farm Accountancy Data Network (FADN). They include annual farm-level information on acreage allocated to each crop, crop yields, total variable costs and expenditures on fertilisers and plant protection, working hours and capital asset values for approximately 900 farms from all over Finland, out of a total of approximately 44,000 farms.[5] The bookkeeping data are used, for example, in negotiations on agricultural support between Finland and the EU and are representative of farming in Finland except for farm size, which is larger than the national average (Niemi and Ahlstedt, 2005).

The sample used in the analysis covers farms in Finland's main crop production region, the provinces of Varsinais-Suomi, Kymenlaakso and Itä-Uusimaa, in the years 1992–2003. The region produces approximately 40 per cent of Finland's grain production. Farms that grow both wheat and barley, the two principal crops in Finland, and devote more than 65 per cent of their total land (owned plus leased) to the cultivation of grains were included in the sample.[6] The farm-level bookkeeping data were

4 Subsidies shown in Table A1 are the total per-hectare subsidies received by the farmers in our sample for each type of crop. They include subsidies from the EU (through the CAP) as well as national subsidies set by the Finnish government. All farmers in our sample belong to the same EU support region and thus there is only temporal and no cross-sectional variation in the crop-specific subsidies.

5 The sample is a rotating panel random sample. The rotating speed is on average 5–10 per cent per year but changes yearly.

6 We selected those farms that are involved primarily in crop production and which grow both wheat and barley. We believe that the set of selected farms is still representative since farmers growing both crops represent 90 per cent of the sample. As will be discussed later, working on the sub-sample of farmers who grow both wheat and barley implies that our optimisation problem has no corner solution.

Table 1. Descriptive statistics (443 observations)

Variable	1992–2003	1992–1994 (pre-CAP)	1995–2003 (CAP)
Total farm size (ha)	66	50	69
Share of grain area planted with barley, (per cent)	46	59	44
Share of grain area planted with wheat (per cent)	38	30	39
Yield of barley[a] (kg/ha)	3,873	4,240	3,785
Yield of wheat[b] (kg/ha)	3,975	4,051	3,963
Total value of grain production (€/year/ha)	473	553	460
Total variable costs for crop production[c] (€/year/ha)	244	309	233
Working hours in crop production (hours/year/ha)	23	29	22
Cost for plant protection (€/year/ha)	47	34	49
Cost for fertilisers (€/year/ha)	116	122	115
Start of the growing season (number of days since 1 January)	144	143	144

[a]Data on yields are missing for some farms.
[b]Includes spring wheat and winter wheat.
[c]Does not include labour costs.

complemented with weather data for each province from the Finnish Meteorological Institute; grain, fertiliser and plant protection price indices from Statistics Finland; labour prices from the Information Center of the Ministry of Agriculture; and grain prices and area subsidies from MTT Agrifood Research annual publication *Finnish Agriculture and Rural Industries*. The data set used in the analysis is an unbalanced panel of 100 farmers over the 1992–2003 period and includes a total of 443 observations.

Table 1 reports descriptive statistics for the key variables. We report averages over the entire sample period, as well as averages for the pre-CAP period 1992–1994 and for the CAP period 1995–2003. Average farm size and the share of area devoted to each crop have changed over the years. The average farm size was 69 ha after 1995 and 50 ha in the pre-EU period.[7] On average, during the 1992–2003 period, wheat and barley represent 84 per cent of the total area planted with grain in the sample.[8] The rest of the cultivated area is shared equally between rye and oats. Following the entry into the EU, the share of total grain area devoted to wheat has

7 The change in the economic environment of farmers could have induced the exit of the least profitable farmers, or have led to some consolidation in the agricultural sector. We are unable to control for entry/exit of farmers per se over the period. However, by going through the data, we checked that almost all farmers who were surveyed between 1992 and 1995 remained in the sample in the later years as well.

8 Wheat includes both winter wheat and spring wheat. The data do not allow considering them as distinct crops.

increased, from 30 per cent before 1995 to 39 per cent after 1995, whereas cultivation of barley has decreased from 59 per cent before 1995 to 44 per cent after 1995. The shift from barley cultivation towards wheat cultivation may have been caused by the per hectare payments for wheat exceeding those for barley from 1997 onwards (Table A1). Farmers may also have been controlling the level of output risk through crop choice.

Average yield per hectare has decreased after 1995 for both wheat (−2 per cent) and barley (−11 per cent). The switch from price support to area-based subsidies has provided incentives to increase the area cultivated where possible, and production has become more extensive on average. The lower output prices have at the same time reduced investments in land improvement measures, such as liming (Niemi and Ahlstedt, 2005).[9] The sample averages also confirm the decrease in the total value of grain production after Finland had to comply with the CAP requirements (Table 1).

4. A model of grain production under risk

Farmers may face several types of risk but, in general, producers of field crops are found to be more concerned about yield and price variability than about other categories of risk (USDA, 2004).[10] As for Finland, Liu and Pietola (2005) showed that yield volatility is large and dominates price volatility in the hedging decisions of Finnish wheat producers. One may argue that, after Finland entered the EU and cereals price support was replaced by area payments, the role of price volatility in explaining revenue variability for wheat and barley producers should have strengthened.[11] However, using analysis of variance to decompose the observed variability in wheat and barley revenues to effects due to yield, price and acreage variability, one can show that yield variability still largely dominates during the CAP period: between 1995 and 2003, yield explained 80 per cent of the variation in annual wheat revenues, price 18 per cent and acreage 2 per cent. For barley, the corresponding figures were 96, 2 and 2 per cent. The joint consideration of output price uncertainty and production uncertainty is rather difficult and has been done only in the context of multiplicative production risk (Moschini and Hennessy, 2001) or in a mean-variance framework (Coyle, 1999).[12] Thus, we choose to focus on production risk, which is clearly the dominant source of risk in our case.

9 Unfortunately, land quality will not be controlled for in the empirical model since this variable is not part of the FADN data.

10 Other categories of risk may include income/financial risk or institutional risk (changes in laws and regulation).

11 Output prices decreased significantly at the time Finland entered the EU, but the fall in prices was completely anticipated by producers at the time cereal production decisions for 1995 were made: negotiations on the conditions of Finland's EU membership, including agricultural support, had started already in 1993, and the decision to join the union was taken in a national referendum held on 16 October 1994.

12 See also Isik (2002) for the development of an analytical model simultaneously considering production and price uncertainty. Our specification also relies on the underlying assumption that the farmers in our sample are technically efficient.

Cereal farmers in our sample produce two main crops, barley and wheat, which we focus on in the following analysis. As is often the case with agricultural data sets, input data are not available by crop. Given the data limitations, we cannot identify the parameters of crop-specific production functions. Instead, we specify a single-equation joint production function,[13] which summarises the relationship among aggregate outputs and aggregate inputs.[14] In order to account for heterogeneity in crop mix across farms, we control for the land allocated to each of the two crops in the production function.

The usual way of accounting for production risk is to assume a Just–Pope (1978, 1979) form for the technology:

$$y = f(x, A; z) + g(x, A)e, \tag{1}$$

where in our case y represents aggregate grain production, $f(x, A; z)$ is the mean production function and $g(x, A)$ the production risk function. Vector x includes three variable inputs, namely fertiliser, labour (which corresponds to total working hours in crop production, including both hired labour and family labour) and plant protection, as well as one fixed capital input (defined as the total value of fixed assets on the farm). Vector A represents land allocations (for wheat and barley) that enter both the mean function and the risk function. Vector z includes exogenous variables which control for heterogeneity across farms and which are assumed to enter the mean production function only. The random term e represents a weather shock that may affect output, exogenous to farmer's action, with $E(e) = 0$ and $V(e) = 1$ (Just and Pope, 1978, 1979). The risk function $g(x, A)$ is flexible with respect to the impact of inputs on risk (i.e. each input can either have no effect, decrease or increase production risk).

By assumption, farmers maximise the expected utility of profit under the constraint that the total land is fixed. The farmer's optimisation programme is written as follows:

$$\begin{aligned} &\operatorname*{Max}_{x,A}\left\{E\left[U(\pi) : A_b + A_w = \overline{A}\right]\right\} \\ &= \operatorname*{Max}_{x,A}\left\{E\left[U(p(f(x, A; z) + g(x, A)e) - w'x + s'A) : A_b + A_w = \overline{A}\right]\right\}, \end{aligned} \tag{2}$$

where $A = \{A_b, A_w\}$ denotes land allocations to barley and wheat, $\bar{A}$ the total area in barley and wheat production, p the grain price, w the vector

13 The single-equation approach has been used widely to circumvent the problem of estimating production functions in the absence of activity-specific input data (see, e.g., Christensen *et al.*, 1973; Hasenkamp, 1976; Vincent *et al.*, 1980). A perhaps more widely used alternative to the single-equation specification would be the duality approach to estimating production functions with aggregate input data (see, e.g., Hasenkamp, 1976; Chambers and Just, 1989; De Borger, 1992; Sckokai and Moro, 1996; Oude Lansink and Peerlings, 1997). However, this approach also has its shortcomings (see, e.g., Lence and Miller, 1998, for a discussion) and is ill suited for joint estimation of production functions and risk preferences.

14 Aggregate output corresponds to the total value of production of wheat and barley (measured in constant year 2000 euros).

of variable input prices, and $s = \{s_b, s_w\}$ the per-hectare subsidies to barley and wheat.

Differentiating the Lagrangian with respect to the J variable inputs yields the following first-order conditions (FOC):

$$\frac{\partial f}{\partial x_j} = \frac{w_j}{p} - \theta(\cdot)\frac{\partial g}{\partial x_j}, \quad j = 1, \ldots, J. \tag{3}$$

The optimal land allocations satisfy

$$\frac{\partial f}{\partial A_b} + \frac{s_b}{p} + \theta(\cdot)\frac{\partial g}{\partial A_b} = \frac{\lambda}{pE(U')} = \frac{\partial f}{\partial A_w} + \frac{s_w}{p} + \theta(\cdot)\frac{\partial g}{\partial A_w}. \tag{4}$$

Function $\theta\,(x, A, z, s, p)$ in equations (3) and (4) is the risk preference function. It is defined as $\theta\,(x, A, z, s, p) = E(U'e)/E(U')$, where U' is the marginal utility of profit. Variable λ is the shadow price associated with the land constraint. Condition (4) holds when areas allocated to wheat and barley are both strictly positive, which is the case in the sample studied.[15]

Under the assumption that $U(\pi)$ is continuous and differentiable, $U'(\pi)$ can be approximated at $e = 0$ by a second-order polynomial. Thus, the function θ takes the following form:

$$\theta(x, A, z, s, p) = \frac{-\mathrm{AR}\sigma_\pi + 0.5\mathrm{DR}\sigma_\pi^2\gamma}{1 + 0.5\mathrm{DR}\sigma_\pi^2}, \tag{5}$$

where $\mathrm{AR} = -U''(\pi)/U'(\pi)$ is the Arrow–Pratt measure of absolute risk aversion, $\mathrm{DR} = U'''(\pi)/U'(\pi)$ a measure of downside risk aversion, $\sigma_\pi^2 = \mathrm{var}[\pi] = p^2[g(x, A)]^2$ and $\gamma = E(e^3)$ the measure of the degree of asymmetry (skewness) in the distribution of e (see Proposition 1 in Kumbhakar and Tveterås, 2003).

In order to estimate the risk function, a parametric form of AR is needed. Kumbhakar and Tveterås propose specifying AR as a flexible function of expected profit μ_π as follows: $\mathrm{AR} = \sum_{q=0}^{Q} \delta_q \mu_\pi^q$, where q is the order of the polynomial, δ_q are parameters to be estimated, and expected profit is computed as $\mu_\pi = E[p(f(x, A; z) + g(x, A)e) - w'x + s'A] = pf(x, A, z) - w'x + s'A$. Given AR, downside risk aversion can be derived using the relationship $\mathrm{DR} = -\partial\mathrm{AR}/\partial\mu_\pi + \mathrm{AR}^2$.

Identification of the full set of parameters in the model is obtained through the simultaneous estimation of the production function [equation (1)] and the optimality conditions for input choices [equation (3)] and land allocations [equation (4)]. The underlying assumption of the AR equation is that the parameters of the relationship between risk aversion

15 If either wheat or barley is not grown every year by all grain farmers (i.e. when land allocations to one of these crops is equal to zero), the problem has corner solutions. The modelling of corner solutions in this setting is outside the scope of this paper and is left for future research.

and expected profit (the δ_qs) are constant across farmers and across time. But, because risk aversion varies as a function of expected profit (μ_π), the approach yields an estimate of the absolute risk aversion AR for each farmer and each year covered by the sample. Also, the sign of the derivative of the AR function with respect to expected profit μ_π will indicate whether risk preferences exhibit decreasing absolute risk aversion (the derivative is negative), constant absolute risk aversion (the derivative is equal to 0) or increasing absolute risk aversion (the derivative is positive).

5. Empirical application

5.1. Specification of the production function

To estimate the model developed in Section 4, we have to assume parametric forms of the mean production function $f(x, A; z)$ and the production risk function $g(x, A)$. In this context, it is not necessary to specify an exact functional form for the utility function, although a parametric form of the AR function implicitly implies some form of the underlying utility function. We assume a form that is quadratic in $(x, A; z)$ to represent the mean output function. Vector x gathers variable and fixed inputs (fertilisers, labour, plant protection and capital) and vector A contains the land allocations to barley and wheat, A_b and A_w. In our model, variable inputs correspond to total expenditures for fertilisers and plant protection (measured in constant year 2000 euros, using the corresponding price index deflator in Table A1), whereas labour is measured in hours and land allocations in hectares.

The variables in z are a time trend variable t ($t = 1, \ldots, 12$), which provides a measure of technical change over the period, and the variable START, which indicates the starting date of the growing season (measured as a number of days from 1 January).[16] The start of the growing season is defined by the Finnish Meteorological Institute as the first day each year where (i) snow cover has disappeared from open places; (ii) once snow cover has disappeared, the mean daily temperature has remained above +5°C (the temperature at which soil is sufficiently thawed for root activity to begin) for five days. The variable START is used here as a proxy for the time of sowing, the actual sowing time being unobserved.[17] Hence, a higher value of the

16 Additional variables related to climatic conditions, such as efficient temperature and rainfall during the growing season, were included in preliminary estimations. However, they were excluded from the final version of the estimated model in order to avoid collinearity with the START variable and to keep the set of unknown parameters at a reasonable size. Moreover, information on farmer's own characteristics (age, education, etc.) was excluded from the estimated model owing to a large number of missing observations.

17 Finland is at the very edge of climatic conditions suitable for grain production – the climate is comparable with that in Alaska. In addition to challenges posed by the low temperatures, spring droughts are prevalent in June, which is the critical time for the yield formation of grains. This means that the time of sowing is critical for yield – the highest yields are obtained when weather conditions permit early sowing (Larpes, 1979).

START variable indicates a later time of sowing and is thus expected to have a negative impact on yield. The START variable is location-specific.[18]

For the representative farmer and for each year, the mean production function is specified as follows:

$$\begin{aligned} f(x, A; z) = & \sum_k \alpha_k x_k + \sum_l \alpha_l A_l + \alpha_t t + \alpha_s \text{START} \\ & + \frac{1}{2}\left(\sum_k \sum_{k'} \alpha_{kk'} x_k x_{k'} + \sum_l \sum_{l'} \alpha_{ll'} A_l A_{l'} + \alpha_{tt} t^2 + \alpha_{ss} \text{START}^2\right) \\ & + \sum_k \sum_l \rho_{kl} x_k A_l + \sum_k \lambda_k x_k t + \sum_k \eta_k x_k \text{START} \\ & + \sum_l \lambda_l A_l t + \sum_l \eta_l A_l \text{START} + \xi_{ts} t \text{START}, \end{aligned} \quad (6)$$

where k, k' = fertilisers (F), labour (L), plant protection (P), capital (K) and l, l' = barley (b) and wheat (w).

We assume a Cobb–Douglas function to represent the risk function. The functional form used in the estimation incorporates the set of inputs as well as land allocations to barley and wheat:

$$g(x, A) = x_F^{\beta_F} x_L^{\beta_L} x_P^{\beta_P} x_K^{\beta_K} A_b^{\beta_b} A_w^{\beta_w} \quad (7)$$

where the βs are unknown parameters to be estimated. Using equations (6) and (7), the first-order conditions for variable inputs choices and land allocation can be derived analytically as described in equations (3) and (4).

5.2. Estimation procedure and specification tests

The full system, which encompasses the production function [equation (1)], the FOC for input choices [equation (3)] and the FOC for land allocation [equation (4)], is estimated through full information maximum likelihood (FIML). All variables have been rescaled, i.e. divided by their mean. To control for any correlation between farmers' unobserved heterogeneity and explanatory factors, we use Mundlak's approach, which models the correlation of unobserved heterogeneity with regressors (Mundlak, 1978). The underlying assumption of Mundlak's approach is that the correlation between farm-specific heterogeneity (i.e. farm-specific unobserved error terms) and the explanatory variables can be modelled as a linear function of the group means of the explanatory variables (i.e. the individual mean of each explanatory variable, computed for each farmer over all time periods). The error term of this auxiliary regression is then assumed to be orthogonal

18 Because a farmer would typically wait beyond the beginning of the growing season to sow, we treat the START variable as known *ex ante*.

to the explanatory variables. A likelihood-ratio (LR) test confirmed the superiority of this specification over the specification without any control for farm's unobserved heterogeneity.

A full description of all equations and identities used in the FIML estimation is presented in the appendix. Absolute risk aversion AR is specified as a second-order polynomial approximation of expected profit μ_π. Under the assumption of multivariate normality of the error terms, FIML provides consistent parameter estimates.[19]

Using an LR test, the quadratic form for the mean production function was found to outperform the less flexible Cobb–Douglas functional form. As for the risk function, convergence could not be achieved when $g(\cdot)$ was specified as a quadratic function. This is likely to be due to the high number of parameters to be estimated when both $f(.)$ and $g(.)$ are assumed to be quadratic.[20]

Finally, monotonicity and concavity of the production function were tested at each point in the sample. The variable inputs, namely fertilisers, labour and plant protection, were found to have a positive marginal product for 99, 98 and 97 per cent of the observations, respectively. The second-order partial derivative was found negative (i.e. decreasing marginal product) for all the three inputs.

5.3. Results and discussion

Table A2 displays the full set of FIML estimation results.[21] We first discuss results concerning farmers' risk attitudes. To obtain an insight into the risk attitudes and the differences therein, we computed the predicted values of the absolute risk aversion (AR) and downside risk aversion (DR) functions for each farm and for each year. The predicted values of AR and DR are measures of risk aversion that are easier to interpret than the predicted value of the risk preference function θ, since the magnitude of the latter is affected by output variance, skewness, absolute risk aversion and downside risk aversion. In the case of AR, a positive value indicates risk aversion, and the larger the positive value of AR, the stronger the aversion to risk. Downside risk aversion means that when there is a choice between two output distributions with the same mean and variance, the output distribution which is less skewed to the left is preferred (see, e.g., Kumbhakar and Tveterås, 2003). The intuition behind this is that farmers are willing to pay a premium in order to avoid particularly bad outcomes. Another easy-to-interpret measure of risk aversion is the relative risk premium

19 The Bera–John test did not reject the null of multivariate normality at the 10 per cent level of significance (Bera and John, 1983).

20 The mean production function $f(.)$ contains 89 unknown parameters (44 parameters for all quadratic terms in inputs, trend and the START variable, 44 parameters for the mean explanatory factors to control for farm's unobserved heterogeneity, and the constant term). The risk function $g(\cdot)$ contains six unknown parameters if assumed as Cobb–Douglas and 27 parameters if assumed as quadratic.

21 The 44 estimated coefficients of the group means of the explanatory variables are not shown but are available from the authors upon request.

Table 2. Predicted risk aversion (AR), downside risk aversion (DR) and relative risk premium (RRP) for each year (computed at the sample mean in each year)

Year	Predicted risk aversion (AR)	Standard error	Predicted downside risk aversion (DR)	Standard error	Relative risk premium (RRP)	Standard error
1992	0.222***	0.0417	−0.034	0.0285	0.45***	0.1184
1993	0.247***	0.0438	−0.011	0.0259	0.39***	0.0967
1994	0.246***	0.0437	−0.013	0.0260	0.31***	0.0763
1995	0.183***	0.0590	0.133***	0.0314	0.02***	0.0061
1996	−0.025	0.0452	0.158***	0.0235	−0.01*	0.0036
1997	0.003	0.0465	0.151***	0.0229	0.00	0.0030
1998	−0.086**	0.0436	0.178***	0.0269	0.00	0.0026
1999	−0.152***	0.0566	0.133***	0.0288	−0.02***	0.0056
2000	−0.884***	0.1317	1.075***	0.2799	−0.02***	0.0017
2001	−0.509***	0.0761	0.502***	0.1123	−0.01***	0.0014
2002	−0.826***	0.1227	0.969***	0.2482	−0.01***	0.0015
2003	−0.900***	0.1343	1.106***	0.2894	−0.01***	0.0015

*, **, ***Significance at the 10, 5 and 1 per cent level, respectively.

(RRP), which measures the share of profit that the farmer is willing to forego in order to avoid production risk.[22] Values of AR, DR and RRP, computed at the sample mean in each year from 1992 to 2003, are reported in Table 2.

The results indicate that farmers' risk attitudes have changed considerably over the study period. The changes seem to be affected by EU accession. First, during the three pre-CAP years 1992–1994, the predicted mean values of AR are positive and almost constant (ranging from 0.222 to 0.247), whereas in the accession year 1995, the predicted AR falls considerably (to 0.183). The positive predicted values imply that Finnish crop farmers in our sample were, on average, risk averse throughout the pre-CAP period and the accession year. For 1996 and 1997, the predicted mean AR values are zero, which implies no cost of risk for the farmers. Finally, during the post-CAP period of 1998–2003, the mean value of AR in our sample becomes negative with declining trend (ranging from −0.086 in 1998 to −0.900 in 2003). Relative risk premium has decreased from up to 45 per cent of expected profit before 1995 to −1 to −2 per cent of expected profit after 1995. This implies that the cost of risk for the farmers in our sample has become, on average, negative. It is also worth noticing that in 1999–2000, coinciding with the 1999 CAP reform, we observe another considerable decline in the predicted value of AR. As far as the mean DR values are concerned, they are practically zero during the pre-CAP period, but become positive and

22 The relative risk premium is approximated as follows: $\sigma_\pi^2 \mathrm{AR}/2\,\mu_\pi - \sigma_\pi^3 E(e^3)\mathrm{DR}/6\,\mu_\pi$ (Antle, 1987).

Table 3. Predicted mean risk aversion (AR) for different farm sizes (computed at the sample mean for each size class)

	Small farms (9–33 ha)	Small to medium farms (34–45 ha)	Medium to large farms (46–63 ha)	Large farms (64–167 ha)
AR	0.320***	0.223***	−0.240***	−1.476***
Standard error	0.0609	0.0619	0.0478	0.2293

significant, with an increasing trend, after EU accession. Again, we observe a marked increase in the absolute mean value of DR from 1999 to 2000, which can be attributed to the 1999 CAP refom. The intuition behind positive and increasing mean DR values is that farmers are more willing to adopt production practices with possibly disastrous effects.

Entering the EU, Finland replaced earlier target prices with substantially lower intervention prices, and direct area payments became the corner stone of agricultural support. The 1999 reform further reduced the intervention prices and increased the cereal area payments. Furthermore, the study region was included among the EU less-favoured areas, which further increased the amount of the area payments granted to farmers. Thus, both policy changes substantially increased the proportion of farm income that is non-random. The marked change in farmers' willingness to take risk can be explained by the increase in the non-random income being large enough to make the cost of risk negative for the average farmer, i.e. risky behaviour becoming preferable (compared with risk averse behaviour) in terms of its effect on expected utility.

Predicted risk aversion was found to be significantly and negatively correlated with farm size (as measured by the total area planted with grains in the farm): the correlation coefficient was −0.45. To further examine the relationship between farm size and risk aversion, we computed the predicted risk aversion for four farm size classes (Table 3). The size classes were constructed so that each class includes the same number of observations, and predicted AR was then computed at the sample mean for each size class. The results display important differences owing to farm size. The predicted AR values range from 0.320 in the class of small farms (farms with less than 33 ha planted with grains) to −1.476 in the class of large farms (farms with more than 64 ha planted with grains). Thus, small farms turn out to be the most risk averse. The finding is parallel to those of other studies. Sckokai and Moro (2006) found marked differences in the estimated relative risk aversion coefficients among farm size classes. Here, medium and large farms are most willing to take risk, to the point of exhibiting risk-loving behaviour. This finding is possibly due to their ability to hedge against risk through the substantial non-random income brought along by the EU area payments.

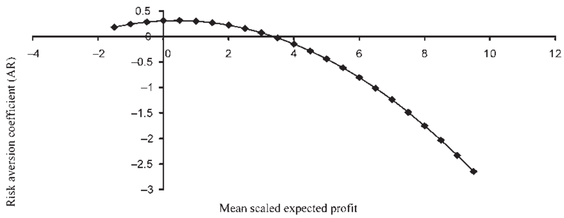

Figure 2. Estimated AR risk function.

As discussed earlier, the Kumbhakar and Tveterås' approach also allows testing for some important properties of farmers' risk attitudes, in particular whether risk aversion increases or decreases with wealth or income. The AR function is shown in Figure 2 as a function of the (mean-scaled) expected profit. In our sample, we find evidence that the average farmer exhibits DARA. That is, the derivative of the AR function with respect to expected profit μ_π is negative at the sample mean.[23] This result is in line with several empirical studies on farmers' risk preferences (see, e.g., Chavas and Holt, 1996; Saha *et al.*, 1994). The differences in the farmers' risk aversion due to farm size class also seem reasonable in the light of the average farmer exhibiting DARA, in particular, as the increased wealth provided by the CAP area payments is directly linked to farm size.

Our estimates also provide information on the production function and the risk function. The elasticities of grain output with respect to the three inputs are as follows: 0.77 for fertilisers, 0.60 for labour and 0.50 for plant protection. Note, however, that the magnitude of the technology parameters should be interpreted with caution since we estimate a single-equation joint production function which summarises the relationship among aggregate outputs and aggregate inputs. Technical change, which is computed by taking the derivative of the mean production function with respect to the variable t, is found to be negative at the sample mean (estimated at − 0.04, significant at the 15 per cent level). The estimate of technical change may be biased by a decrease in production efficiency owing to bringing less productive lands into cereal production, given the incentives provided by the area-based payments. This trend can be seen both in Finnish agriculture as a whole (Niemi and Ahlstedt 2005) and in our sample, where the average farm size has increased by 38 per cent from the pre-CAP period 1992–1994 to the CAP period 1995–2003. Unfortunately, data limitations do not allow us to control for land quality.

Finally, the estimates of the production risk function show that all the three variable inputs (fertilisers, labour and plant protection) are risk-decreasing. The results are in line with a priori expectations. We are concerned with production risk due to weather and other environmental conditions. Both drought

23 In our sample, the average mean-scaled expected profit is 5.26. The AR function reaches its maximum value (is equal to 0) when the mean-scaled expected profit is equal to 0.40 (3.37). For any expected profit lower (higher) than 3.37, the farmer is risk-averse (risk loving).

and the leaching of nutrients due to excessive rain decrease plant growth's ability to take in nutrients. High fertiliser application rate provides plants with more nutrients, which alleviates yield losses associated with adverse weather conditions. Plant protection limits the effect of plant diseases, pests and weeds on cultivated plants. An increase in labour input allows a farmer to conduct field works such as seeding and harvesting with care, as well as to adequately attend to plant growth, which enables, for example, early detection of pests. The results support conventional agronomic wisdom. Increasing the scale of production through larger acreage tends to increase risk. The effect is larger for wheat than for barley, as one would expect, given that wheat requires a longer growing season than barley and is thus more sensitive to adverse weather conditions.

5.4. Policy simulation

We used the estimated production technology and risk preference function to assess the impact of agricultural subsidies on optimal land allocation and input levels. Specifically, we considered the effects of (i) area payments of the kind in place in Finland in 2003, and (ii) a single farm payment such as the one introduced in the whole EU after the 2003 reform. The 2003 area subsidies for wheat and barley in the study region were €628 and €532 per hectare (MTT, 2004), and the 2006 single farm payment was €246.60 per hectare (MTT, 2007). The optimal levels of the decision variables for the case of no subsidies and for the subsidy schemes (i) and (ii) were obtained by calculating θ using equation (A8) and the estimated parameters, and then solving the first-order conditions (A2)–(A4) and the optimal land allocation equation (A5), with the error terms set to zero.[24] The exogenous variables were set at their 2003 means. Producers were assumed to have perfect foresight regarding output price. As our model is concerned with aggregate grain production, the output price was set equal to the weighted average of wheat and barley prices in 2003. The area subsidies s_b and s_w in equation (A5) equal zero for the case of no subsidies as well as for the scheme with the single farm payment. Both the single farm payment and the crop-specific area subsidies, however, affect the value of θ appearing in equations (A2)–(A5), through the value of expected profit.

Table 4 presents the changes in the optimal input levels and land allocation induced by the two subsidy schemes, relative to the levels chosen without subsidies, for the average grain farm in southern Finland. The table shows that direct farm payments do have production effects. Both the crop-specific area payments and the single farm payment affect the optimal input mix only through their impact on farmers' risk attitudes. The changes in the optimal input mix display a decrease in the level of fertiliser applied but an increase in the levels of labour and plant protection. As

24 For a risk neutral agent, the value of θ is zero for each policy alternative considered, and the input mix and land allocation thus do not change.

Table 4. Simulated impact of direct farm payments on input use, land allocation and production for the average farm (per cent change relative to the absence of subsidies)

Policy	Fertilisation	Labour	Plant protection	Share of land in wheat	Share of land in barley	Production
Area subsidies	−5.02	1.39	108.91	−1.41	1,441.00	−2.96
Single farm payment	−2.04	0.73	56.78	−0.22	219.77	−1.63

one would expect, the impact of the crop-specific area payments is larger than that of the single farm payment. For both subsidy schemes, fertilisation and labour choices are only slightly different from those without subsidies. The level of plant protection instead is 56 per cent higher with the single farm payment than without subsidies, and 109 per cent higher with the area subsidies. Note that while ceteris paribus a less risk averse agent would use less of a risk-decreasing input, we reported changes in the optimal levels of all the inputs. The FIML results indicate that each input increases average production and decreases production risk. In the light of these findings, it is not surprising that both subsidy schemes have a small negative impact on expected aggregate production: as producers become less risk averse, the optimal input mix allows for more risk but slightly decreases average production.

The effect on land in barley production is the largest in terms of a per cent change. Recall that both acreage in wheat and acreage in barley were found to be risk-increasing. However, as land in production is fixed, increasing the acreage of one crop requires decreasing that of the other. Both the price and the area payment for wheat exceed those for barley, and most land is allocated to wheat in all the scenarios considered. The direct farm payments increase producers' willingness to take risk. Owing to its small acreage share, the marginal impact on risk of increasing acreage in barley is greater than that of acreage in wheat, which results in shifting some land from wheat to barley production.

The CAP reform replacing area subsidies with a single farm payment appears to halve the impact of farm payments on input use and aggregate production when risk effects are accounted for. The distortionary impact of the farm payments is the largest on plant protection, whereas impacts on fertilisation, labour and production are small. Interestingly, by reducing the fertilisation levels, the direct farm payments work in the same direction as the Finnish agri-environmental support, whose main objective is to reduce nutrient runoff from agricultural land. The increase in plant protection will potentially lead to increased runoffs of plant protectants and thus offset the environmental benefit.

6. Concluding remarks

In this paper, we propose a technique which allows simultaneous estimation of production technology, risk attitudes and land allocation decisions, under production risk and a changing policy environment. Our approach, which is an extension of Kumbhakar and Tveterås (2003), does not imply any specific form of farmer's risk preferences and allows estimating year- and farm-specific predictions of risk attitudes. We apply this technique to data for 100 cereal farms in Finland over the 1992–2003 period.

Our results show that there is heterogeneity in risk attitudes across farmers and across years. Risk aversion has changed markedly during the study period: the cost of risk for the mean grain farmer is positive (but decreasing) until the EU accession year, whereas it becomes negative (and decreasing) after the accession. Overall our results confirm the assertion that decoupled agricultural support policies, through their effect on income, affect farmers' risk attitudes, which in turn affect production through choice of crop mix and input use (Hennessy, 1998; Sckokai and Antón, 2005; Goodwin and Mishra, 2006; Sckokai and Moro, 2006). A policy simulation based on the old CAP area subsidies and the new single farm payment illustrates the effect of direct payments on input mix and production. Although the effect on production as well as on fertilisation and labour was small, the policies markedly increased the use of plant protectants.

Our analysis indicates that farmers' risk attitudes vary by farm and by year. Thus, studies evaluating the impact of agricultural policies should be careful when drawing policy conclusions on the basis of a single measure of risk attitudes, constant over time and across farms. When farmers are not risk neutral, many agricultural support programmes alter optimal input levels even for supposedly decoupled programmes (Hennessy, 1998), and the magnitude of such impacts will be affected by the degree of risk aversion or risk loving. Predictions for the implications of agricultural policies may be flawed if the impacts on risk attitudes, as well as their interactions with producer decisions, are not adequately taken into account.

Although these results are interesting, our work carries a number of important caveats. As it is well known, the stochastic specification of the production function proposed by Just and Pope (1978) allows inputs to be either risk-increasing or risk-decreasing. However, whereas the Just and Pope technology does not restrict the effects of inputs on the output variance to be related to the mean, Antle (1983, 1987) has shown that the Just and Pope specification restricts the effects of inputs on higher order moments (skewness, kurtosis, etc.). To address this issue, Antle (1983, 1987) has proposed a moment-based approach, which amounted to a set of general conditions under which standard econometric techniques can be used to identify agricultural technology and estimate risk-attitude parameters of a population of producers. Using this flexible method of moments, Antle and Goodger (1984) and Groom *et al.* (2008) have found that the marginal effects of inputs on the third moment of profit had a significant effect on the optimal decisions of their respective case studies. Although we cannot preclude this possibility for our case study, modelling the third moment of the output distribution as a function of inputs would imply a different framework than the one we use, away from the Just and Pope formulation. This is certainly a caveat of our analysis and an aspect of our work that could inspire further research.

A second caveat of our empirical analysis is that, owing to the unavailability of crop-specific *input* data (which is typical in production-side analyses of agriculture), we estimated a single production function, with aggregate output as the dependent variable. As a consequence, the impact of production risk on different crops is slightly restricted, since it appears only through the effect of land allocation on aggregate output. Moreover, the underlying assumption of our parametric AR function is that risk aversion is a function of expected profit and that the parameters of the relationship between risk aversion and expected profit (the δs) are constant across farmers and across time. Non-parametric techniques for the measurement of farm-specific risk aversion could be investigated in future research.

Finally, in this paper, we focus on production risk and do not take into account output price risk. As argued by Isik (2002), results from studies that focus on one of the two sources of uncertainty may not hold if both output price and production uncertainty are present. In fact, these uncertainties may have opposite impacts on the input use. Developing a framework for simultaneously estimating risk preferences, production technology and land allocation, under both production and output price uncertainty, is a potential extension of our model that could be done along the lines of Kumbhakar (2001). However, it is worth noticing that the multi-step estimation procedure of Kumbhakar (2001) is less efficient than the one we propose in our paper. Thus, an extension of our model going in this direction would have a relevant methodological interest.

Acknowledgements

We would like to thank the Business Accounting team at Agrifood Research Finland for providing us with the data. We also thank Kyösti Pietola, Jyrki Niemi and seminar participants at Agrifood Research Finland, Athens University of Economics and Business and Australian Bureau of Agricultural and Resource Economics for helpful comments. Finally, we are grateful to Editor Paolo Sckokai and three anonymous referees for insightful remarks and suggestions.

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Appendix

Table A1. Prices and subsidies for barley and wheat, and price indices for fertilisers, labour and plant protection (2000 = 100)

Year	Price of barley[a] (€/kg)	Price of wheat[a] (€/kg)	Area subsidy for barley[a] (€/ha)	Area subsidy for wheat[a] (€/ha)	Fertilisers price index[b]	Labour price index[b]	Plant protection price index[b]
1992	0.284	0.362	0	0	150.90	86.35	147.30
1993	0.280	0.361	0	0	149.60	88.65	151.00
1994	0.271	0.355	0	0	127.10	88.65	150.60
1995	0.124	0.144	364	364	106.10	88.65	113.60
1996	0.127	0.150	396	396	105.60	90.95	111.60
1997	0.126	0.145	404	429	103.90	93.24	106.70
1998	0.125	0.137	412	524	100.80	95.41	104.40
1999	0.123	0.135	406	464	98.20	97.70	102.00
2000	0.117	0.131	507	589	100.00	100.00	100.00
2001	0.113	0.128	507	600	108.30	102.30	96.40
2002	0.100	0.130	529	627	106.10	110.81	94.40
2003	0.101	0.113	532	628	105.10	116.22	90.00

[a]Finnish Agriculture and Rural Industries 1994–2004, MTT Agrifood Research Finland.
[b]Statistics Finland, Annual Agricultural Price Indices (2000 = 100).

Table A2. FIML estimation results (443 observations)

Parameter	Variable	Estimated coefficient	Standard error	p-Value
Mean production function				
	Constant	−14.087	54.913	0.798
α_F	Fertilisers	0.214	0.407	0.600
α_L	Labour	1.777***	0.684	0.010
α_P	Plant protection	0.825	0.520	0.113
α_K	Capital	−1.608	2.336	0.492
α_w	Land allocated to wheat	−0.954	1.061	0.369
α_b	Land allocated to barley	−0.754	0.927	0.416
α_t	Time trend	0.387	0.302	0.201
α_s	Starting date of growing season	0.105	0.268	0.695
α_{FF}	Fertilisers × fertilisers	−0.416***	0.069	0.000
α_{LL}	Labour × labour	−0.552***	0.106	0.000

(*Continued on next page*)

Table A2. (*continued*)

Parameter	Variable	Estimated coefficient	Standard error	*p*-Value
α_{KK}	Capital × capital	0.357	0.541	0.509
α_{PP}	Plant protection × plant protection	−0.565***	0.061	0.000
α_{FL}	Fertilisers × labour	−0.099*	0.058	0.090
α_{FP}	Fertilisers × plant protection	−0.106**	0.043	0.015
α_{FK}	Fertilisers × capital	0.172*	0.090	0.055
α_{LP}	Labour × plant protection	−0.024	0.049	0.621
α_{LK}	Labour × capital	−0.089	0.099	0.369
α_{PK}	Plant protection × capital	0.294***	0.078	0.000
α_{ww}	Land to wheat × land to wheat	−0.008	0.092	0.932
α_{bb}	Land to barley × land to barley	−0.133**	0.060	0.028
α_{wb}	Land to wheat × land to barley	−0.175***	0.058	0.003
α_{tt}	Time trend × time trend	−0.022***	0.007	0.004
α_{ss}	Starting date × starting date	−0.001	0.002	0.726
ρ_{Fw}	Fertilisers × land to wheat	0.336***	0.032	0.000
ρ_{Fb}	Fertilisers × land to barley	−0.026***	0.007	0.000
ρ_{Lw}	Labour × land to wheat	0.449***	0.061	0.000
ρ_{Lb}	Labour × land to barley	−0.034***	0.013	0.007
ρ_{Pw}	Plant protection × land to wheat	0.356***	0.045	0.000
ρ_{Pb}	Plant protection × land to barley	−0.034***	0.008	0.000
ρ_{Kw}	Capital × land to wheat	−0.833***	0.152	0.000
ρ_{Kb}	Capital × land to barley	0.277*	0.165	0.094
λ_F	Fertilisers × time trend	0.032***	0.008	0.000
λ_L	Labour × time trend	0.056***	0.013	0.000
λ_P	Plant protection × time trend	0.033***	0.009	0.001
λ_K	Capital × time trend	−0.054	0.035	0.129
η_F	fertilisers × starting date	0.005*	0.003	0.061
η_L	Labour × starting date	−0.006	0.004	0.146
η_P	Plant protection × starting date	0.000	0.003	0.992
η_K	Capital × starting date	0.000	0.015	0.982
λ_w	Land to wheat × trend	−0.046**	0.021	0.025
λ_b	Land to barley × trend	−0.004	0.015	0.802
η_w	Land to wheat × starting date	0.006	0.007	0.439
η_b	Land to barley × starting date	0.005	0.006	0.440
ξ_{ts}	Time trend × starting date	−0.002	0.002	0.331
Output risk function				
β_F	Fertilisers	−0.017***	0.004	0.000
β_L	Labour	−0.209***	0.037	0.000
β_P	Plant protection	−0.052***	0.009	0.000
β_K	Capital	−0.042	0.057	0.466
β_w	Land to wheat	0.311***	0.034	0.000
β_b	Land to barley	0.004***	0.001	0.000
AR function				
δ_0		0.309***	0.056	0.000

(*Continued on next page*)

Table A2. (*continued*)

Parameter	Variable	Estimated coefficient	Standard error	*p*-Value
δ_1		0.029*	0.016	0.065
δ_2		−0.036***	0.007	0.000
γ[a]		−1.645***	0.153	0.000

[a]The parameter γ measures the degree of skewness in the distribution of the random term in the production function (e).
*, **, ***Significance at the 10, 5 and 1 per cent level, respectively.

A3. Specification of the estimated system

The full system combines five equations: the production technology [equation (A1)], the first-order conditions for the three variable inputs [equations (A2–A4)] and the first-order condition for land allocation [equation (A5)].

$$\frac{y}{g(x,A)} = \frac{f(x,A,z)}{g(x,A)} + e \tag{A1}$$

$$\begin{aligned}&\alpha_k + \alpha_{kk}x_k + \sum_{k' \neq k} \alpha_{kk'}x_{k'} + \sum_{l} \rho_{kl}A_l + \lambda_k t + \eta_k \mathrm{START}\\ &-\frac{w_k}{p} + \theta(\cdot)\frac{g(\cdot)}{x_k}\beta_k = u_k \quad \text{for } k = \mathrm{F, L, P}\end{aligned} \tag{A2)−(A4}$$

$$\begin{aligned}&\alpha_{\mathrm{b}} + \alpha_{\mathrm{bb}}A_{\mathrm{b}} + \sum_{k} \rho_{k\mathrm{b}}x_k + \lambda_{\mathrm{b}}t + \eta_{\mathrm{b}}\mathrm{START} + \frac{s_{\mathrm{b}}}{p} + \theta\frac{g(\cdot)}{A_{\mathrm{b}}}\beta_{\mathrm{b}} -\\ &\alpha_{\mathrm{w}} - \alpha_{\mathrm{ww}}A_{\mathrm{w}} - \sum_{k} \rho_{k\mathrm{w}}x_k - \lambda_{\mathrm{w}}t - \eta_{\mathrm{w}}\mathrm{START} - \frac{s_{\mathrm{w}}}{p} - \theta\frac{g(\cdot)}{A_{\mathrm{w}}}\beta_{\mathrm{w}} = u_{\mathrm{s}},\end{aligned} \tag{A5}$$

where e, u_{F}, u_{L}, u_{P} and u_{S} are the error terms appended to each equation.

In addition, the FIML estimation is based on the following identities:

$$\begin{aligned} f(x, A, z) = & \sum_k \alpha_k x_k + \sum_l \alpha_l A_l + \alpha_t t + \alpha_s \text{START} \\ & + \frac{1}{2}\left(\sum_k \sum_{k'} \alpha_{kk'} x_k x_{k'} + \sum_l \sum_{l'} \alpha_{ll'} A_l A_{l'} + \alpha_{tt} t^2 + \alpha_{ss} \text{START}^2 \right) \\ & + \sum_k \sum_l \rho_{kl} x_k A_l + \sum_k \lambda_k x_k t + \sum_k \eta_k x_k \text{START} \\ & + \sum_l \lambda_l A_l t + \sum_l \eta_l A_l \text{START} + \xi_{ts} t \text{START} + \nu, \end{aligned} \tag{A6}$$

where ν represents farmers' unobserved heterogeneity. Following Mundlak (1978), we model ν as a linear function of the group means of the whole set of explanatory variables (i.e. the individual mean of each explanatory variable, computed for each farmer over all time periods), whereas the remaining component (or error term of this auxiliary regression) is assumed to be negligible.

$$g(x, A) = x_F^{\beta_F} x_L^{\beta_L} x_P^{\beta_P} x_K^{\beta_K} A_b^{\beta_b} A_w^{\beta_w} \tag{A7}$$

$$\theta = \frac{-AR\sigma_\pi + 0.5\text{DR}\sigma_\pi^2 \gamma}{1 + 0.5\text{DR}\sigma_\pi^2} \tag{A8}$$

$$\text{AR} = \delta_0 + \delta_1 \mu_\pi + \delta_2 \mu_\pi^2 \tag{A9}$$

$$\text{DR} = -\frac{\partial AR}{\partial \mu_\pi} + \text{AR}^2 \tag{A10}$$

$$\mu_\pi = pf(x, A, z) - w'x + \sum\nolimits_l s_l A_l \tag{A11}$$

$$A_b + A_w = \overline{A}. \tag{A12}$$

Corresponding author: Céline Nauges, LERNA-INRA, Toulouse School of Economics, Manufacture des Tabacs, 21 Allée de Brienne, 31000 Toulouse, France. E-mail: cnauges@toulouse.inra.fr