Economic modelling of agricultural production: past advances and new challenges

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Abstract – *This paper is a methodological review focusing on the major advances in modelling issues in agricultural production economics that have been made over recent decades. Issues include the role of markets and international trade, structural and dynamic aspects of production, environmental impacts of production decisions and risk issues. We describe the main scientific developments and their implications for policy design and evaluation for each topic. We also provide a short conclusion on emerging issues, data and modelling requirements and perspectives for future research.*

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JEL Classification : Q12, Q15, Q17

1. Introduction

The economic analysis of agricultural production has benefitted from considerable advances over the past decades (see, *e.g.* Chavas, Chambers and Pope, 2010 for a recent survey), and a comprehensive survey of the major contributions to this field is outside the scope of the present paper. We therefore restrict our attention to a selection of topics: the modelling of markets and trade, structural and dynamic aspects of production, environmental impacts of production decisions, and risk issues. It is important to mention that the paper reflects a fairly personal (and therefore necessarily partial) view from each co-author on the major advances in the field, in terms of methodology or issues addressed, as well as future challenges and possible solutions.

Since the objective is to provide agricultural economists with a retrospective analysis of a selection of research work, the contents of the present paper draw upon a bibliographical analysis over the past 30 years. This analysis is used to provide leading models, methods and empirical applications as examples of European contributions regarding modelling of agricultural markets and international trade, structural and dynamic aspects, environmental impacts, and production and land-use decisions. We follow the description of each topic with a short conclusion on emerging issues, data and modelling requirements, and perspectives for future research.

We should point out that our review is primarily a methodological one, focusing on advances in modelling issues rather than empirical results obtained with these methods. Furthermore, wherever possible, we have tried to illustrate the review by selecting European contributions to the literature in agricultural economics. It is likely that both the academic and research system, and the specificity of European agricultural and environmental policies, can help us understand some differences with research from non-European agricultural economists.

2. Economics of production for modelling agricultural markets and trade

Over the last 30 years, economic models of agricultural markets have proliferated thanks to the growing availability of databases on an international level and the rapid development of scientific computing and software. Accordingly, models became increasingly rich, with more products, technologies, activities, factors, regions and more sophisticated specifications of production, demand and international trade. The development of these models was mostly motivated by the need for decision-makers to follow agricultural economic issues. Thirty years ago, the design of many models was guided by the multilateral trade negotiations of the Uruguay Round. More recently, the price spikes induced by the global “food crisis” of the late 2000s revived the issue of world food security. Many economic models were then used to assess the long-term sustainability of existing systems and of alternative policy *scenarii*. The dramatic development of the world biofuel markets has also generated a major debate, with economic models mostly used to assess land-use changes induced by this new policy-supported demand for energy. These policy objectives have obviously orientated the design and specifications of agricultural market models.

As expected, these numerous models have generated both converging and conflicting results. Many executive reports have disseminated results to policy-makers and stakeholders, as well as scientific syntheses that identify methodological progress and remaining gaps (*e.g.* Hertel, 1990; von Tongeren *et al.*, 2001; Robinson *et al.,* 2014 to name a few). In this section, we review the main evolutions of the agricultural supply components in market models. It has long been customary to distinguish between Partial Equilibrium (PE) and Computable General Equilibrium (CGE) models. The first CGE models to include agricultural markets explicitly were implemented in the 1980s and were, at the time, considered promising economic tools allowing the “farm problem” to be better addressed (Gardner, 1992) because they explicitly represented farm primary factors (land, labour and capital). The distinction between PE and CGE models is still partly used today but it appears less relevant, as some projects have coupled both types of models, and farm primary factors are increasingly incorporated in PE models. The main difference between PE and CGE models is that the former assume demand to be independent from changes in production plans, whereas in CGE models, such changes have a feedback effect on demand through income. Instead of this PE/CGE distinction, we prefer to structure our review in light of the main methodological recommendations formulated nearly 30 years ago to improve the representation of agricultural supply in market models. The recommendations made by various economic modellers were collected in Goldin and Knudsen (1990) and can be grouped into three main areas: technological representation, dynamics and statistical validation.

Technology

Thirty years ago, the specifications of technological constraints faced by farmers, including the substitution patterns between the different inputs/factors, were rightly considered as essential model components (see McKitrick, 1998). Such specifications partly determine the international cost competitiveness of the various agricultural sectors in different regions and their response to price shocks. However, these specifications were constrained by both the product/factor dimensions of the models and the use of simple functional forms (such as the Cobb Douglas or the Constant Elasticity of Substitution, CES). Significant progress has been made in this area in both PE and CGE models over the last thirty years. The models' product and factor dimensions have considerably increased with the fine distinction of energy, chemical, and animal feed products and the different land qualities that exist across regions. More recently, the specific role of water and associated technologies (rain-fed *vs.* irrigated farming) are introduced in the models, hence improving their usefulness. The complex interactions between crop and livestock farming, through on-farm production and consumption of animal feed and organic fertilizer, are also better taken into account. This greater product/factor disaggregation adds value to the efforts to develop more flexible representations of technological relationships. In CGE models, complex CES nesting structure or more flexible and globally regular forms have been implemented to represent the substitution possibilities among inputs/factors in production activities and their mobility across outputs. However these improvements resulting from the development of dual theories of producers/consumers do not ease the direct interpretation of parameters in agronomical/zootechnical terms. By contrast, structural PE models mostly retain their original, mathematical-programming approach, facilitating multidisciplinary research. However, these structural PE models have also slightly departed from a pure primal approach by relying on the principles of Positive Mathematical Programming (PMP). They often add dual cost functions in order to replicate perfectly the economic observations and to smooth production responses.

Dynamics

Thirty years ago, market models were either static or with lagged/recursive dynamics. All economic modellers recognized that these simplifying assumptions needed to be improved as it was widely believed (and supported by limited econometric evidence) that the long-term consequences could be considerably different from the short-term ones. A truly dynamic model can thus better capture the adaptation possibilities of the farm sector, for instance, to policy or price shocks. It also allows for a better consideration of the transition path from one steady state to another. While some efforts have been made in this area, most models remain of comparative static nature or feature simple dynamics. For instance, few structural market models (either PE/CGE) currently take into account the dynamic of livestock production (between calf/heifer/cows for instance) that may lead to some interesting features such as negative short-term supply price elasticities (Rosen, 1994). Technical change is mostly exogenous and investment decisions (in physical capital or in land allocation to deal with agronomic constraints leading to dynamic rotations) are often ignored. This situation, partly anticipated by some authors (*e.g.* Munk, 1990), can be explained by at least two factors. Firstly, data on capital stocks/investments in different capital goods by different farm types are not as easily accessible as other production data. Secondly, solving large dynamic market models with possibly forward-looking agents is highly challenging (*cf.* the curse of dimensionality issue in models with many state and response variables). There have been few attempts to introduce truly dynamic behaviours by farmers in market models (mostly in CGE models, notably by the French agricultural economist Jean-Marc Boussard) showing the crucial roles of price expectation schemes (*e.g.* adaptative or myopic, rational expectations, *etc.*) in the convergence properties of the model (as expected, for example, by Chavas and Holt, 1996; Chavas, 2000).

Validation

The robustness of simulation results provided by economic models is an inescapable question that was already well known thirty years ago. At that time, the emphasis was put on the plausibility of results for farm sectors in developing countries. Little statistical knowledge was accumulated in these sectors, and behavioural parameters calibrated using economic models were, by default, taken from developed countries when available. It has long been argued that sensitivity analysis is thus a second-best solution highlighting the critical parameters that need more econometric investigation. Thirty years later, we can observe that this second-best solution has been favoured by most models, with parameters calibrated on guessed estimates or fairly old econometric results. In particular, in the last decade, there have been few attempts in both developed and developing countries to estimate the parameters of a complete system of farmers' production choices/input uses that matches the specification of the market models. In fact, the situation may worsen as market models are becoming larger and larger with less available data to perform the underlying econometric estimation. For instance, the introduction of water as an explicit farm input is certainly valuable. However, necessary data on irrigation costs to truly understand farmers' behaviour and constraints are, to the best of our knowledge, rather limited at the aggregate level.

3. Acreage choice and land use models

The modelling of farmers' acreage choices is a core activity for agricultural production economists. Acreage choices are primarily farmers' decisions and major determinants of agricultural supply. This section, together with an overview of acreage choice and land use models, seeks to develop two main ideas related to future research on acreage choice modelling.

Firstly, agricultural economists mainly use two approaches for modelling acreage choices, depending on their main purpose. Farm management issues and *ex ante* simulations of agricultural policy impacts on farmers' choices are usually investigated by relying on Mathematical Programming (MP) models while *ex post* analyses of agricultural policy impacts usually rely on Multicrop Econometric (ME) models. MP models define farmers' objectives as optimisation problems with calibrated parameters. ME models define farmers' choices as functions of economic incentives with statistically estimated parameters. Even if most of research related to both approaches has been conducted in parallel so far, researchers using these approaches could benefit more from exchanging their respective experience.

Secondly, Land Use (LU) models differ from acreage choice models in that they describe how the owner of a piece of land decides to devote this piece of land to broad usages, *i.e.* crop production *versus* other uses (pasture, forest, *etc.*). Acreage choice models, on the other hand, describe how farmers allocate their farmland to different crops. These models seek to describe similar decision processes and are—from a formal viewpoint—closely related. We analyse these relationships to show how LU models may fruitfully inspire acreage choice models. Moreover, LU models have been promoted mostly by economists from outside the agricultural production economics field. These economists may challenge the modelling "standards" in agricultural production economics and may convey new ideas to this field.

Mathematical Programming models

Most models used for simulating the effects of agricultural policy on farmers' choices *ex ante* are built within a MP framework (Heckelei and Britz, 2005). In this framework, acreage choices are defined as the solutions to an explicit maximisation problem involving an assumed farm objective – *e.g.* farm expected profit or expected utility of profit – subject to constraints reducing the acreage choice set – due to, for example, limiting quantities of quasi-fixed factors (including land) or crop rotation effects. Until the late 1970s, farmers' acreage choice models were mainly defined as Linear Programming (LP) problems involving the maximisation of farms' (expected) profit levels (Hazell and Norton, 1986). These models were later extended to account for farmers' risk aversion (Hazell and Norton, 1986; Hardaker *et al.*, 2004). Since the 1990s, most agricultural supply models with micro foundations are built within the so-called Positive Mathematical Programming (PMP) framework (Howitt 1995; Heckelei *et al.*, 2012). These models can be seen as extensions of the standard LP problems. In this framework, the farms' objective functions are supplemented by a function that is smooth in the acreage levels—the so-called PMP term—and that aims at capturing the effects of unspecified constraints on acreage choices or of specific features of farmers' choices such as the heterogeneity of their plots or crop rotation effects (Howitt, 1995; Heckelei *et al.*, 2012). The PMP term is generally defined as quadratic in the acreage vector, implying that the resulting optimisation problem is a standard quadratic programming (QP) problem. PMP models have two main advantages over standard LP models. PMP models produce smooth simulated effects—whereas LP models lead to "bang-bang"-type effects—and they can be exactly calibrated with respect to a base year in a flexible way—*e.g.* PMP models can incorporate "external information" such as estimated elasticities or resource prices whereas LP models, or QP models based on mean-variance objective functions, can only be calibrated by relying on additional, and more or less debatable, constraints on acreage choices. Note that Arata *et al.* (2014) and Jansson *et al.* (2014) proposed MP models based on a combination of the mean-variance and PMP frameworks.

MP models have three main advantages. Firstly, they rely on optimisation problems that are easy to understand, even by non-economists. Secondly, they can easily accommodate a wide variety of policy instruments such as those implementing direct or indirect constraints on acreage choices. Thirdly, they allow production practices to be considered that have not previously been used by farmers, *e.g.* by considering agricultural science experimental results related to innovative production practices. Empirical models based on the MP framework have an additional advantage for *ex ante* policy simulation purposes. When calibrated for a set of farms, of farm-types or of small regions, they allow farms' heterogeneity to be accounted for. It is likely that these advantages lie at the root of MP models' success as the basis for agricultural supply models aimed at communicating economic analyses to decision-makers. In particular, the disaggregated simulations results are of interest for decisions-makers as they may identify losers and winners from intended policy reforms. Wu and Adams (2002) provide evidence that simulations of aggregated acreage responses based on disaggregated models are more accurate than those based on aggregated models.

The main drawbacks of MP models are directly linked to their main advantages. Firstly, MP models define acreage choices—or more generally activity choices—as solutions to constrained optimisation problems. These solutions need not admit analytical closed forms nor be continuously differentiable in the model parameters. This largely prevents the empirical validation of these models with classical statistical analyses and, as a result, explains why the *a priori* unknown parameters of MP models are generally calibrated rather than statistically estimated. Specific statistical approaches—based on Bayesian statistics or on the Generalised Maximum Entropy (GME) principle—have been proposed by, for example. Heckelei and Wolff (2003) or Jansson and Heckelei (2009, 2011), but they have been routinely used only by a few modellers (see, *e.g.* Heckelei *et al.*, 2012). This point is discussed in further detail below as, to a large extent, it concerns virtually any farmer production choice modelling framework. Secondly, constraints on acreage choices or a PMP can be added to "smoothe" the solutions of MP models. While additional constraints may lack agronomic or economic justification, the PMP term still lacks economic rationalisation, at least in PMP models involving capital and labour adjustment choices (Heckelei *et al.*, 2012).

Multicrop Econometric models

The development of the dual economic production theory in the 1970s and 1980s (see Chambers, 1998, for a seminal reference) led to the use of multi-output econometric models from the early 1980s. These models rely on generic properties of the multi-output production technologies—*e.g.* monotonocity and convexity—and on generic objective functions for the producers—*i.e.* profit, expected profit or expected utility of profit. The multi-output econometric models have two main advantages: they provide consistent models of output supply and input demand functions and they provide equations that are easily tractable in classical econometric analyses. In these models, farmers' production choices are designed as smooth and flexible responses functions to economic incentives.

Whereas the most direct applications of dual econometric models ignore acreage choices (see, *e.g.* Weaver, 1983), Multi-crop Econometric (ME) models with land as an allocable fixed input became widely used after the seminal articles of Chambers and Just (1989) and Chavas and Holt (1990). These models allow accounting for the effects of crop area based subsidies such as the ones introduced by the 1992 reform of the European Union's (EU) Common Agricultural Policy (CAP). These models were first developed within a static framework. The models defined along the lines of Chambers and Just (1989) assume either a riskless environment or famers' risk neutrality and rely on flexible representations of the agricultural production technology (see, *e.g.* Moore and Negri, 1992; Guyomard *et al.*, 1996; Oude Lansink and Peerlings, 1996; Oude Lansink, 1999). Chavas and Holt (1990) proposed using a mean-variance framework for analysing farmers' acreage decisions as a crop portfolio choice (see, *e.g.* Chavas and Holt, 1996; Holt, 1999). Building on the theoretical work of Coyle (1992, 1999), Sckokai and Moro (2006) proposed a model combining the main features of those of Chambers and Just (1989) and of Chavas and Holt (1990). Oude Lansink and Stefanou (1997) developed dynamic acreage choice models based on the adjustment cost framework proposed by Epstein (1981). These models were further extended to account for farmers' attitude toward risk by Sckokai and Moro (2009).

Despite their formal elegance, the ME models are more rarely used for *ex ante* simulation purposes than their MP counterparts. This can be explained by the "intrinsic" characteristics of these models and by their empirical use. These models are specifically designed to be easily estimable. The derived input demand and output supply functions are theoretically defined as solutions to the maximisation problem of an objective function under a technological constraint. The technological constraint needs not be explicit as long as the congruent netputs (*i.e.* input demand and output supply) functions satisfy some theoretical properties, are flexible in the—dual—price effects and are empirically tractable. ME models are thus especially suitable for investigating past agricultural choices and the theoretical properties (*e.g.* separability features or scale and scope economies) of existing agricultural production technologies (see, *e.g.* Asunka and Shumway, 1996). These models are highly consistent given an implicit production technology and an assumed objective function but they cannot easily be adapted to incorporate specific features of the agricultural production technology or agri-environmental policy instruments based on constraints on input or output choices. The parameters of a standard dual ME model basically sum up the effects of the currently used agricultural production technology, as well as of farmers' objective function, on farmers' reactions to economic incentives. These points were discussed by Just and Pope (2001) and Boussard and Keyser (2002). According to these authors, the "dual revolution" may have driven the agricultural production economists too far towards generic but "black box" models of production choices.

While most North American applications of ME models consider aggregate data, European applications rely on panel data sets extracted from the Farm Accountancy Data Network (FADN).[1] A large part of

[1]The FADN is by far the most widely used farm-level database in the EU, since data are collected using the same procedure in all the EU Member States. The data provide very detailed and spatially homogeneous information on many aspects of the farm business (production activities, costs of production, labour use, capital and livestock endowment, land allocation, subsidies and CAP payments, *etc.*) on a yearly basis. Moreover, the FADN sample is representative both on the regional and production sector level (*i.e.*

farms' and farmers' heterogeneity is ignored in most estimated ME models with micro-economic data and, as a result, the simulated effects of policy instruments obtained from these models appear to be unduly homogeneous across farms. This stems from the fact that key parameters of many estimated models—*e.g.* the parameters of price effects or the parameters governing the substitutions of crops within the acreage—are assumed to be the same across all farms in the sample. The ME models of Carpentier and Letort (2012) and of Oude Lansink (1999) represent two extreme examples in this respect. In the model of Carpentier and Letort (2012), all parameters are assumed to be fixed, while most parameters are farm-specific in Oude Lansink (1999). These extreme cases illustrate the basic trade-off faced by modellers discussed by, for example, Huang *et al.* (2012). Constant parameters can be precisely estimated but fail to account for much of farms' and farmers' heterogeneity while farm specific parameters cannot be precisely estimated but allow most of the heterogeneity to be captured. Of course, most estimated ME models introduce variables such as farm size, farmers' wealth, regional dummies or, more rarely, soil quality measures to control for heterogeneity. However, these variables are likely to account for only a limited amount of farms' and farmers' heterogeneity. As noted by Oude Lansink (1999) and Platoni *et al.* (2012), most researchers using panel data exploit the information content of these data by considering fixed or random effect models, *i.e.* models with additively separable farm specific effects that account for unobserved characteristics of farms and farmers. However, these models still assume the effects of key variables to be the same for all farms. Calibrated MP models, on the other hand, account for farms' and farmers' unobserved heterogeneity and deliver "heterogeneous" simulated effects, but it is widely recognized that the usual calibration procedures lack empirical validation. In fact, the ME and MP modellers face the same "heterogeneity problem" but adopt different solutions because their final objectives differ. MP modellers favour calibration procedures in order to design models able to meet decision-makers' requests whereas ME modellers impose homogeneity assumptions in order to favour the use of classical inference methods. As will be discussed below, a third approach may meet both ME and MP modellers' requirements.

Land use models and acreage choice models based on crop choices at the plot level

LU models consider broad uses of land, *e.g.* crop production, pasture, forestry or urban construction. These models are basically constructed for

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cereals, dairy, beef, fruits and vegetables, *etc.*) and each farm carries a specific weight corresponding to the number of agricultural holdings it represents. This feature is very important, since it allows rigorous procedures to be designed to generalise the sample results to the population level.

describing long-term choices of more or less large plots, each being owned by a single individual. The use of each plot is decided by one individual, independently from what other land users do (market equilibrium prices apart). LU econometric models are defined as probabilistic discrete choice models with (Plantinga and Ahn 2002; Lubowski *et al.*, 2006 and 2008; Scott, 2014) or without (Plantinga, 1996) land conversion costs. Such models are derived within the random utility—or random profit—framework: the landowner chooses the use leading to the highest utility—or profit. Usage utility levels—or profit levels—are defined up to an additively separable error accounting for the lack of knowledge of the econometrician related to the landowner's preferences and/or decision context.

Most LU models are defined as a standard MultiNomial Logit (MNL) model or as an extension of this model. Much progress has been made on discrete modelling since the pioneering work of McFadden (1973). Nested MNL probability functions have been proposed to account for similarities between choice options whereas random parameter MNL discrete choice models have been proposed to account for heterogeneity in decision-makers' preferences (see, *e.g.* Train, 2009, for a seminal reference).

MNL acreage choice models have also been used to describe farmers' short-term choices, namely technology choices (Caswell and Zilberman, 1985; Lichtenberg, 1989; Hardie and Parks, 1997) or crop acreage shares (Wu and Segerson, 1995; Miller and Plantinga, 1999; Wu and Adams, 2002; Fezzi *et al.*, 2014; Costinot *et al.*, 2014). Standard MNL acreage shares have two main practical advantages. Firstly, they lie strictly between 0 and 1 and automatically add up to 1. Secondly, their parameters are easily estimable thanks to the so-called log-linear transformation of the acreage shares. In most studies involving crop choices, the acreage choice model is implicitly obtained by aggregating, at the farm level, independent crop choices at the plot level.[2] However, if the independence assumption holds for choices of broad categories of long-term land uses (agriculture, forestry, *etc.*) by different individuals, it is more debatable for modelling short-term crop acreage choices made by a single farmer. Of course, one could argue that farmers may adapt their crop choices on a plot-*per*-plot basis, in particular if plots are heterogeneous with respect to soil quality or topography (see, *e.g.* Howitt, 1995). However, most acreage choice models proposed in the agricultural production literature (including both MP and ME models) consider that farmers' choices rely on some crop diversification motives, *i.e.* that farmers decide their crop acreages

[2]The studies by Wu and Segerson (1995) and by Miller and Plantinga (1999) are exceptions in this respect. Wu and Segerson (1995) considered the observed acreage choices as profit maximising acreage choices by farmers and merely used MNL acreage shares as convenient empirical functional forms (see also Wu and Brorsen, 1995). Miller and Plantinga (1999) derived MNL acreage shares by adopting a statistical viewpoint. Their acreage share models are defined as Maximum Entropy estimates of the observed aggregated acreage choices.

by considering a farm-level strategy. This is because farmers have to cope with limiting quantities of quasi-fixed factors (Howitt, 1995; Chambers and Just, 1989; Arnberg and Hansen, 2012), may exploit crop rotation effects (El-Nazer and McCarl, 1986; Howitt, 1995; Just *et al.*, 1983; Eckstein, 1984; Ozarem and Miranowski, 1994), or may adopt a portfolio strategy for diminishing their exposure to production and/or price uncertainty (Hazell, 1971; Chavas and Holt, 1990 and 1996). According to these models, crop acreage choices cannot be considered as aggregates of plot-level independent crop choices. Indeed, Carpentier and Letort (2014) provide a formal link between ME and MP models on the one hand, and LU models on the other hand. They showed that standard and nested MNL acreage shares can also be obtained as the solution to a profit maximisation problem similar to the one considered in the PMP framework. In PMP models, the effects of omitted costs and constraints on acreage choices are assumed to be captured in the PMP term that is defined as quadratic in the acreage choice vector. Carpentier and Letort (2012) defined a ME model based on these assumptions, *i.e.* by adding to the standard PMP model—without any constraint on acreage choices, the total land-use constraint excepted—the dual crop gross margin models based on primal quadratic yield functions. In their framework, the PMP term was defined as the "implicit management acreage cost function". Carpentier and Letort (2014) used the same approach to show that the use of an implicit management acreage cost function, defined by entropy measures of the acreage share vector, leads to standard or nested MNL acreage share models, and that these MNL acreage share models can be part of a consistent and empirically tractable ME model.

Acreage models based on discrete choice models are debatable due to their reliance on the assumption that crop decisions are made on a plot-*per*-plot basis. However, they have two main advantages. Firstly, whereas ME and MP models seek to exploit farm-level data[3], land use models can exploit plot-level data (usually available in large samples covering long time periods) when combined with suitable price information (see, *e.g.* Hendricks *et al.*, 2014; Fezzi and Bateman, 2011; Fezzi *et al.*, 2014; Costinot *et al.*, 2014). Secondly, the simple structure of the acreage choice model based on discrete choice was exploited for designing dynamic acreage choice models for crop rotation effects.[4] Hendricks *et al.* (2014) developed a dynamic acreage choice model accounting for crop rotations, under simplifying assumptions with respect to farmers' price expectations. Further empirical work on this issue can be expected in the near future thanks to recent advances in the modelling

[3]See Fezzi and Bateman (2011) or Fezzi *et al.* (2014) for exceptions.
[4]Dynamic ME models accounting for crop rotation effects were proposed by Eckstein (1984) and Ozarem and Miranowski (1994). They rely on a "fertility index" aggregating the crop rotation effects for designing the crop rotation management a single stock management problem. Such an aggregation is debatable. The model considered by Thomas (2003) focuses on nutrients stocks.

of dynamic discrete choices surveyed, *e.g.* Aguirregabiria and Mira (2010). Dynamic LU models were proposed by, *e.g.* De Pinto and Nelson (2009) or Scott (2014).

Estimation issues

The preceding sub-sections have presented the main models used for describing farmers' choices, *i.e.* the so-called MP, ME and LU models, along with their relative merits and limitations. This sub-section deals with statistical estimation issues. It aims to show that the empirical modelling of farmers' choices could be greatly improved thanks to the micro-econometric modelling and estimation techniques developed over the last two decades. These tools have been successively used in applied economic fields, *e.g.* labour economics and empirical industrial organisation.

Heckelei and Wolff (2003) suggested replacing the bi-level optimisation problem with a constrained optimisation problem involving a statistical *criterion* under the constraints provided by the first order conditions characterising farmers' optimal choices. In any case, the statistical estimation of MP models is involved when the inequality constraints of the considered model bind for some observations and do not bind for others. If the problems involved in the estimation of MP models seem to be specific to these models, they are also relevant for ME models. A typical example is provided by the so-called corner solution problem in acreage choices when using farm-level data. This problem is generally dealt with by relying on some extension of the two-step approach proposed by Heckman (1979)—and then discussed by Shonkwiler and Yen (1999) for systems of equations to estimate systems of censored equations (see, *e.g.*, Sckokai and Moro, 2006; Lacroix and Thomas, 2011; Fezzi and Bateman, 2011; Platoni *et al.*, 2012).

Another issue is related to the estimation of MP and ME models. The comparison of the ME and MP modelling frameworks stressed that MP and ME modellers have to cope with the—largely unobserved—heterogeneity of farms and farmers. A striking feature of the ME and MP literature related to this issue is that agricultural production economists do not refer much to other applied economics fields. The treatment of unobserved heterogeneity appears to be a major topic of the applied micro-econometrics literature in the last two last decades owing to the pervasive evidence of the effects of the economic agents' heterogeneity on the statistical modelling of their choices.[5] This point was discussed by Keane (2009). Translated into the panel data econometric framework, his basic argument is as follows: to consider additively separable individual effects in a linear model may not be sufficient, since the effects of many key variables may also depend on unobserved

[5]See, *e.g.* Ackerberg *et al.* (2007) and Train (2009) for consumer choice modelling, and Eaton *et al.* (2011) for trade modelling.

characteristics of the considered individuals. In other words, Keane (2009) warrants the use of models with "individual coefficients" even though the estimation of such models may rely on parametric assumptions. Empirical results recently obtained by Koutchadé *et al.* (2014) tend to confirm that farms' and farmers' heterogeneity matters for agricultural production choice modelling and that available—frequentist or classical—tools in econometric and statistical literature allow accounting for this heterogeneity in a relatively flexible way.

Discussion and perspectives

It seems that much of agricultural production economists' efforts have been devoted to theoretical issues. However, to transform theoretically-consistent economic models into econometric models does not simply require appending "error terms" to the theoretical model in order to "make statistical noise". According to current standard practice in micro-econometric literature, a micro-econometric model must be consistent in its deterministic as well as in its random parts. This issue is particularly relevant when dealing with corner solutions or unobserved heterogeneity issues. However, the consistency of micro-econometric models comes at a price: large micro-econometric models such as farmers' multicrop production choice models are difficult to estimate in practice because they involve complicated statistical *criteria*. This certainly calls for a different balance between the theoretical properties of agricultural production models and their empirical tractability. In particular, Just and Pope (2001) argue convincingly that the farmers' choice process is especially involved. To account further for the fact that farms and farmers are heterogeneous and that many of the farmers' choice determinants are unobserved implies that micro-econometric models of agricultural production choices cannot be taken too seriously. For example, most ME model are theoretically based on a single crop diversification motive such as risk spreading (Chavas and Holt, 1990) or crop rotation effects (Hendricks *et al.*, 2014). However, the estimated parameters of the acreage equations of these models are liable to capture the effects of other diversification motives since farmers' choices are likely to be shaped by several diversification motives. Moreover, the impacts of these various diversification motives might affect different farmers differently, depending on their capital endowments or their attitude towards income risk.

4. Structural and dynamic aspects of production

Among the determinants of agricultural output, the level and dynamics of land and capital investment are seldom investigated in production economics literature. The fact that current farm production is a function of several inputs, including the current level of capital, is clearly undisputed. However, the current level of capital depends on the dynamics of past investment decisions, while current investments are going to affect future production.

This dynamic decision-making process is challenging to analyse, especially from an empirical point of view, both in terms of choosing the appropriate modelling approach and in terms of data requirement. In fact, investment is a discontinuous event, which takes place at a specific point in time and is typically related to two different objectives: the replacement of the obsolete capital[6] and the increase in the farm capital endowment.

The analysis of the investment decisions becomes even more complex when we consider that farmers make such decisions under uncertainty. The most recent literature on investment has focused on the role of uncertainty, through the so-called real option approach: the irreversible nature of investment may induce a farm to delay investment decisions, and the delay is longer the greater the degree of price variability (McDonald and Siegel, 1986; Dixit and Pindyck, 1994). Thus, empirical analyses of investment decisions should explicitly recognise the uncertainty faced by farmers, especially price uncertainty.

In agriculture economics literature, the analysis of farmers' investment decisions has often been linked to the investigation of the impact of agricultural policies. Traditional policy tools such as price support and coupled direct payments are expected to have a relevant effect on long-term investment and output decisions by farmers, but decoupled payments are also expected to play a role, typically through their impact on farmers' income/wealth. In addition, many countries have often implemented specific policies aimed to stimulate farm investment in several capital items (typically buildings and machinery) through specific forms of direct payments, and some of these measures have been part of the CAP.

While the potential impact of price support and coupled payments on investment decisions is relatively straightforward, the potential linkage between decoupled payments and farm investments has been the subject of fierce debate in literature. Such potential linkage has typically been related to imperfect capital markets, which means, for example, gaps between borrowing and lending rates, binding debt constraints, high bankruptcy risk and other financial problems. In these cases, even a fully decoupled payment may stimulate farm investments, thus affecting future farm output (Vercammen, 2007).

Initial studies on investment demand in agriculture and its impact on agricultural output have been carried out in the US, typically using aggregate data. The key modelling choice of these studies is the representation of the dynamic investment decision process. Many early studies are based on the traditional theory of the maximisation of the net present value of equity, which determines the desired stock of farm capital goods through its implicit rental price, and, in turn, the desired level of investment/disinvestment in

[6]This, of course, applies to capital items subject to obsolescence such as buildings and machinery. Investment in land is always targeted to increase the endowment of the farm.

that good (see, among others, Penson *et al.*, 1981). Vasavada and Chambers (1986) is one of the first studies to estimate the investment demand for capital goods using a structural model based on dynamic inter-temporal duality in production (Epstein, 1981; and Epstein and Denny, 1983). This model is based on the so-called adjustment-cost theory, which postulates that firms suffer a short-term output loss when they change their stocks of quasi-fixed inputs since they experience some sluggishness in adjusting input levels. This is formalised by including gross investment in the production function, so that when the firm invests, it experiences a positive adjustment cost additional to the usual opportunity cost (see Vasavada and Chambers, 1986, for details). The basic model is a multi-period optimisation model in which farmers are assumed to maximise the discounted stream of profits over an infinite time horizon[7] and quasi-fixed inputs are assumed to decay geometrically at a constant rate. Farmers are assumed to be risk-neutral and price expectations are static since they are formulated in each period according to current conditions, without any dynamic consideration[8]. Dynamic programming is used to derive the equations to be estimated, *i.e.* a system of optimal output supplies/variable input demands and optimal investment demands of quasi-fixed inputs.

This type of model has been applied to agricultural production by several authors who have focused on different aspects of investment decisions in agriculture, often analysing different types of linkages between investment and agricultural policies. Many of these papers refer to one or more EU countries and to the CAP tools. Moreover, contrary to the earlier US studies, they are typically based on individual farm-level data such as the FADN database.

Stefanou *et al.* (1992) have analysed the impact of milk quotas on the investment demand by German dairy farms, finding a relevant impact of supply control in the dynamics of investments, with a relevant change in adjustment costs after the introduction of quotas and a considerable excess capacity displayed by most farms. Oude Lansink and Stefanou (1997) have extended the basic model accounting for the asymmetry in investment and disinvestment decisions, which is linked to a discontinuity in the adjustment cost function and to the presence of fixed costs associated to quasi-fixed factor adjustment. Their empirical results, obtained on a sample of Dutch arable crop farms, show that the adjustment rates tend to be significantly

[7]Continuous time is the standard assumption in these models since it allows full differentiability when deriving the dynamic programming equation.

[8]Expectations can change only in the following period when new information, together with new market and technological conditions (including the level of capital stock), make the previous expectations no longer optimal. According to Oude Lansink and Stefanou (1997), static expectations may be justified by the small size of agricultural enterprises, for which it would be costly to acquire information on future price trends.

faster in a disinvestment regime compared with the investment one[9]. Pietola and Myers (2000) have introduced into the model both non-static expectations and uncertainty on the future path of some state variables[10] while maintaining the risk neutrality assumption and the asymmetry in investment and disinvestment decisions. Their empirical analysis explores the investment behaviour of a sample of Finnish pigfarms and confirms that investments are negatively affected by price and yield uncertainty despite the relevant scale economies in the industry, which should lead farms to invest to increase their size.

Another stream of studies has adopted simpler models, with the explicit objective of analysing the empirical implications of the real option theory (Dixit and Pindyck, 1994). For example, Feinerman and Peerlings (2005) have proposed a two-period discrete time model of farmland demand under uncertainty in land availability, which is estimated on a sample of Dutch dairy farms. The interest of their model is the evaluation of the "Option Value" of postponing investment when uncertainty is resolved, as predicted by real option theory. Their results show that postponing investment is beneficial only for a minority of the farms in their sample. An alternative methodology for analysing the investment reluctance phenomenon (*i.e.* the sub-optimal investment rates observed in many farming systems) has been proposed in Hüttel *et al.* (2010) as an extension of the standard Tobin's q-model, while also considering the impact of capital market imperfections. Their empirical results, obtained on the FADN sample of German farms, confirm the relevance of these imperfections for farmers in the former East Germany, whose impact must be evaluated by explicitly considering irreversibility and the consequent investment reluctance[11].

All the above studies assume risk neutrality, and this is clearly a limitation since many studies have shown that farmers are likely to be risk averse. Thus, some recent papers extend the original dual dynamic model explicitly taking farmers' risk attitudes into account. An example, considering only price uncertainty and not yield uncertainty, can be found in Sckokai and Moro (2009), where the estimated model is used to evaluate the impact of the CAP decoupled payments on farm investments for Italian arable crop farms. A slightly modified version of the same model is adopted in Kallas *et al.* (2012), who analyse the impact of the CAP partially-coupled payments (in place before 2005) on Spanish arable crop farms. Lastly, a reduced form of this same

[9] A simplified version of this model, focused on the specification of the adjustment cost function, is provided in Gardebroek and Oude Lansink (2004).
[10] The model with non-static expectations was first proposed by Luh and Stefanou (1996) and applied to US aggregate time series data.
[11] Several earlier studies have used this approach to investigate the role of finance in farm investment demand. Among the European studies, Benjamin and Phimister (2002) addressed the issue of access to credit and its relations to the structure of agricultural credit markets in France and the United Kingdom.

model is estimated by Serra *et al.* (2009) on a sample of Kansas farms, where the lower complexity of the estimated equations allows the authors to adopt more realistic assumptions on investment farm behaviour. Serra *et al.* (2009) distinguish between three regimes of investment behaviour (investment, disinvestment and no investment) with different adjustment cost functions, while Sckokai and Moro (2009) assume a less realistic, strictly convex adjustment cost function, with smooth adjustment of the level of quasi-fixed inputs. The empirical results in this research field cannot be considered conclusive. Kallas *et al.* (2012) found a relevant impact of partially-coupled payments on investment, while Sckokai and Moro (2009) found a fairly small impact of decoupled tools on investment and, consequently, on arable crop output. On the contrary, in Serra *et al.* (2009), investment demand elasticities with respect to decoupled payments turned out to be relatively high, and their simulated impact turned out to be even stronger than the output price impact.

In the area of investment demand analysis under uncertainty, a fairly new field of research is based on the so-called "state-contingent" approach (Chambers and Quiggin, 2000). The available empirical applications in agricultural production analysis are still somewhat scarce (see, for example Serra *et al.*, 2010), but the potentials of this approach may be further explored.

In conclusion, we can certainly state that the analysis of investment decisions and their relationship with policies is quite complex and rather difficult to observe with the available data for several reasons. Firstly, as mentioned above, investments are discontinuous over time: they are typically a one-shot decision, which may be difficult to capture using unbalanced rotating panels such as the available farm-level databases (including the FADN). Secondly, the investment reluctance described by the real option theory is linked to the information available to farmers; thus, expectations play a crucial role and must be properly modelled. Thirdly, we observe a typical asymmetry between investment and disinvestment decisions, since for the latter, farmers tend to be more reluctant, and this reluctance may be difficult to capture. Fourthly, risk preferences are likely to play a crucial role, so one should explicitly consider all the variables related to the impact of risk (*i.e.* mean, variance and other moments of the price and yield distributions, risk aversion coefficients and farmers' wealth).

All these problems have important empirical implications. Firstly, the available data may be insufficient to characterise investment behaviour. For example, more detailed information on stocks and investments in capital goods would greatly help research in this area, as well as information on the type of capital goods for which the farmer makes his/her investments (*e.g.* new milking machinery, a new barn, new tomato-harvesting machinery, or new production or emission rights). Secondly, since in dynamic models the time dimension is relevant, it would help if farms would stay in the sample for a longer time period, thus allowing for better identification of unobserved heterogeneity, typically through appropriate unbalanced panel data estimation techniques. Thirdly, if risk is explicitly taken into account, assumptions about expectations and the proper computation of the moments of the price/yield distributions may become problematic[12], as well as the proper aggregation of outputs and prices under risk (Coyle, 2007). Fourthly, from a purely econometric point of view, all these models require proper treatment of censoring, since the presence of zero investment farms is very common.

5. Accounting for the environmental impacts of production decisions and markets

Over the past thirty years, the analysis of environmental impacts from agricultural activities has experienced major advances regarding the design of interlinked multidisciplinary models, the variety of bioeconomic models adapted to agricultural sectors and the scale of environmental impacts (Chavas, Chambers and Pope, 2010).

This analysis was, in many cases, in response to demands from society and the government for more detailed indicators of agriculture's overall contribution to the economy, including degradation of the quality of natural resources. More recently, agriculture's positive contributions to the provision of public goods have been addressed. Furthermore, evaluating the environmental impacts of cropping and livestock systems has been an essential stage of policy design with regard to public support for agriculture and transitions in production systems. This evaluation is therefore often considered a necessary step towards multiple-criteria analysis of production systems in a broad sense, which would help determine some "optimal" matching between impacts and regional characteristics including environmental sensitivity. For environmental impacts (negative or positive) to be balanced with contribution to food security and management of rural areas, evaluating such impacts is, of course, necessary using economic methods that are outside the scope of this paper. The extent to which research on this topic has been a companion of EU environmental policies may be difficult to assess, but it is certainly significant. For example, the development of impact models integrating spatial issues is probably due to the regionalisation of agricultural and environmental policies (Anselin *et al.*, 2004; Gaigné *et al.*, 2012).

Perhaps paradoxically, the set of environmental impacts that has been studied until now is fairly limited, and indeed far smaller than the pathways to reduce them by changing practices. Starting with the implicit definition of environmental impacts as damages due to overuse or misuse of agricultural inputs such as fertilizer and pesticide, the set is augmented with impacts on

[12]In many of the studies discussed here, it is common to resort to the approach by Chavas and Holt (1990) and Pope and Just (1991), which assumes adaptive expectations and normality for computing the moments of the price/yield distribution.

natural resources such as water and soil. A majority of studies have therefore addressed the issue of water contamination and water depletion because it is water that was considered the most frequent vector of impacts from such inputs. It is only more recently that less "local" impacts were considered, such as the contribution to global warming through greenhouse gases (Havlik *et al.*, 2013; Lankoski and Ollikainen, 2008; Lengers and Britz, 2012) and the loss of biodiversity.

The first stream of contributions represented environmental impacts as direct consequences of production decisions, focusing either on a specific (small) set of crops and specific impacts, or exploring multi-output settings with land-use modelling, often assuming constant crop yields. Furthermore, such representation included the treatment of environmental impacts as negative or "bad" outputs using the analytical framework of production analysis (in particular, Data Envelopment Analysis – DEA). By exploring the relationship between "environmental efficiency" and technical efficiency (good and bad outputs), this research provided useful insights into the potential trade-offs between objectives of food provision and environmental conservation (Bokusheva and Hockmann, 2006; Carpentier and Weaver, 1996; Coelli *et al.*, 2007; Reinhard *et al.*, 1999).

With regard to efficiency issues, many authors also addressed the question of environmental standards and regulations as exogenous factors playing as constraints on technological feasible sets for producers (Komen and Peerlings, 1998; Reinhard and Thijssen, 2000). Such constraints were fairly easy to incorporate in production models based on LP approaches, *e.g.* the incorporation of environmental policy ceilings on fertilizer application rates or water abstraction in the summer.

A major advance has been the development of models that explicitly acknowledge the need to address the following essential question: are changes in cropping or livestock practices sufficient to reach environmental objectives? In other words, to what extent should production systems be reformed to comply with environmental goals (and standards)? Placing the question of environmental impacts into the broader issue of transitions in production technology implies that an analysis of adoption drivers has to be performed (Sharma *et al.*, 2011). It also implies that crop-specific or impact-specific models were not sufficient, and that production models based on mathematical programming were not the only ones relevant to tackling this issue. Exploring the environmental impacts of joint decisions regarding cropping or livestock practices and land use or cropping systems has been a challenging task (even computationally, see Fezzi and Bateman, 2011; Lacroix and Thomas, 2011). European agricultural economists have succeeded in providing original modelling examples by incorporating methodological developments from applied mathematics, microeconomics and econometrics (*e.g.* stochastic dynamic programming, maximum entropy). The difficulty now lies in integrating more aspects into the equation in order to provide more comprehensive assessments; most empirical applications would conclude that changing cropping or livestock systems provides a more flexible answer than only adapting production practices. However, social and structural aspects need also to be accounted for when a change in production systems is proposed.

Another stream in studies on environmental impacts from agricultural production that has proved fairly successful is the structural modelling of production decisions to incorporate features such as information, specific and non-uniform policy instruments (*e.g.* contracts) and dynamic decision settings (Wossink and Gardebroek, 2006; Goetz, 1997; Mazzanti and Zoboli, 2009). Departing from usual production models based on MP (LP, PMP) meant that detailed description of farmers' activity was not the objective, but instead, exploring departures from representative agents with static decisions and average environmental impacts (Gren, 2004). Due to the computational burden associated with sophisticated structural models of production, empirical applications are still limited, and in any case, applications did not extend the range of potential environmental impacts (Bontems and Thomas, 2006). However, the structural nature of such models is not specific to coupled economic and environmental models.

Over the past 15 years, global environmental impacts have augmented the range of issues addressed by agricultural and environmental economists, and a major new factor is the challenge of climate change. Whereas previous models often dealt with local impacts on water quality, soil erosion, *etc.*, the mitigation of global warming implied extending existing models. This extension required changing the scale of analysis by matching a global impact (greenhouse gas emissions from agriculture) with agricultural decisions on a larger scale than the individual farm. As a result, land-use modelling was refined to incorporate simulation modules associated with emissions and carbon sequestration processes on a broader scale. Therefore, a third important development involved incorporating the spatial dimension into agricultural production models. Land-use models have been developed in various dimensions: coupling with environmental impact simulation models for a typology of farmers' or production orientations, spatial econometrics and development of models dedicated to changes in production (cropping, livestock) systems, *etc.* With such a change in the scale of analysis, there remains the challenge of dealing adequately with the "ecological fallacy" bias: correlation at a higher level (region, district, *etc.*) may be spurious and may not reflect the actual correlation on the farm or ecosystem level.

Lastly, the performance of public policies aiming to modify the relationship between production decisions and the environment has been thoroughly analysed. Although the socioeconomic determinants of adopting agro-environmental measures (AEMs) are now well documented, the effective impact of such policies (when adopted) on the environment is far more difficult to evaluate. However, an interesting aspect of evaluating potential effects from models dealing with adoption decisions is the variety of AEMs implemented by European countries, allowing for analyses contrasting results and drivers with characteristics of such policies (duration of AEMs, subsidy rate, *etc.*)

Data issues are particularly important and in many cases are the limiting factor for developing accurate descriptions of the relationship between agricultural activities and the environment. Firstly, models for farmers' decisions can be detailed on a particular area or sector only, when the model is calibrated or estimated from dedicated farm surveys including economic as well as technical variables. Secondly, models relevant on a larger scale can be developed from a farm typology that lacks detailed description of cropping or livestock practices, implying that the strategies for environmental conservation are limited in number. For example, even though FADN is available on the European level, more specific analyses require national data sets because technical aspects of production necessary to interlink with environmental impact simulation models are obviously lacking in FADN. Thirdly, as a combination of the two cases above, detailed modelling of environmental impacts from cropping or livestock practices can be extrapolated using an upscaling procedure, with the issue of representativeness. Turning now to environmental data, the same situation applies with a specific focus on a set of environmental variables, mostly concerning water quality and availability. The equivalent of the US Natural Resource Inventory (NRI) has prevented many modelling attempts from succeeding in providing an evaluation of environmental impacts from agricultural activity on an interesting level for policy analysis (the equivalent of a US county).

To conclude this section, there are several aspects that one can mention as interesting topics for future research. Firstly, connecting production models and land-use models with models and data for international trade allows one to examine changes in indicators such as environmental footprints on a national or a global scale. Most efforts have been devoted to carbon and water footprints with only a limited capacity to allow for modifications in cropping and livestock practices.

Secondly, connecting agricultural production with the agrofood chain in terms of final environmental impacts is usually performed with techniques such as Life Cycle Analysis (LCA), and alternative multi-criteria methods are also necessary for a better integration with economic decision models. In this line of analysis, designing interlinked models for environmental impact assessment would prove useful to accompany the development of the bioeconomy (Petersen, 2008).

Lastly, as mentioned above, most environmental impacts are still negative ones regarding agricultural practices, with, typically, an overuse or misuse of agricultural inputs. However, when looking at agriculture as a provider of public goods, this vision needs to be reformed to integrate a wider range of impacts. Considering ecosystemic services supplied or managed by agriculture (even though some are still "negative services") instead of purely environmental impacts is, of course, far from trivial (Peerlings and Polman, 2004). Because many ecosystemic services are, in fact, "bundles" affected diversely by production decisions, more research is required, in particular to help design better-suited agricultural and environmental policies (Wossink and Swinton, 2007).

6. Risk and production

The first challenge agricultural economists took up when asked to deal with risk issues was to make production models more realistic by accounting for risk preferences when representing production decisions. The quest for more "realism" was justified by the economics literature as well as empirical evidence that farmers behaved differently when confronted with different sources of risk (Gardebroek, 2006). The augmentation of usual production functions with risk measures was a first step in evaluating the contribution of production inputs to risk reduction (or increase), after the important contribution of Just and Pope (Dorward, 1994; Regev, Gotsch and Rieder, 1997).

In parallel, MP models were also adapted to cope with departures from risk neutrality. Whereas in the first case, observed behaviour of farmer decisions helped refine the description of production technology without eliciting farmer preferences, the second approach required calibration of objective functions with risk coefficients to reflect aversion to risk. It soon became clear that farmers were not only sensitive to mean and variance of profit when deciding upon an optimal input mix, but that higher-order moments (skewness and kurtosis) were also relevant in some cases. The method proposed by Antle (1987) opened the way towards more flexible approaches to production models with risk aversion, including restrictions from an underlying microeconomic model. The final step was then to move to fully structural models based on the maximisation of expected utility of profit, with joint estimates of utility parameters and production technology (Tveterås, 1999; Eggert and Tveterås, 2004). Notwithstanding the sophistication of such structural models involving often simulation-based econometric techniques, the possibility of disentangling risk preferences from technology representation was soon to be contested (Just and Pope, 2003). Many authors claimed that such identification was flawed because of, among other things, misspecification concerns and the lack of variability in risk conditions, the main message being that modellers were demanding too much from real production data (Lence, 2009; Lybbert *et al.*, 2013). Nevertheless, European agricultural economists widely adopted such structural estimation that was applied to a range of agricultural sectors, providing original developments such as the joint examination of risk preferences and production efficiency (Foudi and Erdlenbruch, 2012), as well as agricultural policies (Sckokai and Moro, 2006) and innovation adoption (Koundouri *et al.*, 2006).

Because of the concern expressed above regarding identification, alternative ways of estimating risk preferences were proposed, including experimental methods (controlled experiments and dedicated field surveys, for example). At the same time, another criticism of earlier production models with risk attitudes was addressed, namely the fact that maximisation of expected utility was not always a realistic representation of farmer behaviour. This second criticism opened the way to applications of prospect theory involving experimental economics methods, although direct experiments with real farmers was not the general rule (Hellerstein *et al.*, 2013). A major difficulty shared both by structural estimation and applications of prospect theory is the choice of the relevant approximation (or reference) point (Nelson and Escalante, 2004). In structural estimation, first-order conditions of expected utility maximisation are obtained around a non-random expected profit level, while in prospect theory, deviations from a benchmark wealth level are considered. However, the choice of reference in terms of initial wealth is challenging, as there does not seem to be an agreement as to whether past profit level, discounted stream of future profits or the value of farm assets should be preferred.

Apart from some empirical applications involving time series data for agricultural activities and the use of duality to infer risk preferences from price data only, most applications have addressed production risk (*e.g.* crop yield risk). Empirical applications dealing jointly with production and price risk have been particularly rare (see, *e.g.* Isik, 2003), probably because of CAP instruments that limited the consequences of price risk until policy reforms occurred at the beginning of the past decade (Pillar I policies and EU farm price support schemes).

However, new sources of risk are also relevant for cropping and livestock systems as a whole, not just crop-specific risk. Initially, small-scale and crop-specific risks were considered (drought, pest, water logging, animal disease) and were incorporated into technology representation, but large-scale risks and uncertainty, or risks associated with innovation (biotechnologies, *etc.*) have been explored to a far lesser degree (Lagerkvist, 2005; Barham *et al.*, 2014). With these new sources of risk, the notion of ambiguity related to absolute uncertainty (*i.e.* the lack of a sound basis for constructing probability distributions for future random events) is more relevant, and various studies have been proposed along the lines of recent developments in the economics of risk. Another interesting extension of usual production models under risk in agriculture concerns state-contingent approaches, which also correspond to the need for more realistic descriptions of production decisions with adaptation in technological choices. Empirical applications have been proposed mostly in the context of climate-change impacts (Nauges *et al.*, 2011).

A final topic related to risk concerns insurance for agriculture and forestry. Demand for insurance from crop and livestock farmers and forest managers has been the subject of numerous papers, which addressed the complementary or substitution effects between insurance instruments and public policies. Typically, with a large share of income being "guaranteed" for many farmers (for cereal and oilseed, at least) by the CAP Single Farm Payment (SFP), the fraction under risk and in need of insurance may decrease more or less significantly because of payments being decoupled from production (Serra *et al.*, 2005; Lien and Hardaker, 2001). This insurance effect is valid for both production and price risks (Coble *et al.*, 2004; Mahul, 2003). On the other hand, the demand and institutional aspects of insurance for covering specific risks such as hail or drought is a different matter. Recent experiences in some EU countries have been proposed to evaluate the impact of weather-indexed insurance schemes on production decisions, both in terms of land use and cropping practices. Spain is a particularly interesting example of the implementation of such insurance systems, whereas in France, the move from public compensation following natural events such as drought or hail to private insurance systems with partial subsidising from the State has been a much-debated topic (Mahul and Vermersch, 2000).

Under risky conditions, estimating the value of risk premiums (namely, the amount a farmer is willing to forego in order to hedge fully against risk) is essential because of possible comparisons of an equivalent to existing insurance premiums across various regions and production systems. However, another aspect that has been less analysed is the value of information under risky conditions, *i.e.* the monetary equivalent of being perfectly informed of future benefits from production, compared with the outcome of a production plan decided upon by maximising expected utility of profit. Interestingly, very few authors have addressed this issue in empirical applications, but these include some European contributions (Bontems and Thomas, 2000; Feinerman and Voet, 1995).

7. Conclusion

To conclude this paper on developments in agricultural production economics over the past thirty years with an emphasis on European research, several points are required. Firstly, the ever-increasing complexity of production models in terms of sectors, technology representation, dynamic and spatial aspects implies a parallel increase in data requirements. Although data collection efforts by European Member States and data harmonisation have improved over recent decades, much remains to be done before detailed and reliable data involving inputs, structural aspects and environmental impacts are available to researchers in a wide range of European settings. Secondly, the representation of activities underlying agricultural production has gradually included drivers of production related to the agrofood industry and environmental constraints. This implies that the discipline of production economics has succeeded in widening its initial scope devoted to static technology description by considering the environment of farmers together with dynamic, structural and stochastic dimensions. The variety of European settings in terms of factor allocation, dedicated agricultural and environmental policies and integration of farmers within the agrofood chain has been instrumental in the liveliness of European research into agricultural production economics.

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