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Farm-level bio-economic modeling of water and nitrogen use: Calibrating yield response functions with limited data

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ABSTRACT

Integrating agronomic information into economic models is required for simulating farming systems so as to better determine how agriculture can adapt to a continuously changing global economic and physical environment. In this respect, farm level mathematical programming bio-economic models can provide valuable insights for examining current and future pressures on resource use. Although a necessary condition for the effective use of such models is their calibration against observed data on input use, this information may not always be available, particularly at higher geographical scales. Imperfect or missing input markets pose an additional challenge to modelers. To overcome these difficulties, we present a theoretical framework for calibrating water-nitrogen yield response functions, which are used to represent the bio-physical aspects of crop production in bio-economic farm models at the European Union level. The method is based on the simulation results of an agronomic model, while the calibration criterion derives from the first-order conditions for farmers' profit maximization and utilizes all available information from the Farm Accountancy Data Network. The method is tested on maize-producing farms in two regions in France.

1. Introduction

The effect of climate change on crop productivity and the increase in demand for food from a rising global population present major challenges for the agricultural sector, which must now compete against other sectors for natural resources, particularly water, its prime input (De Fraiture and Wichelns, 2010). Appropriate tools for modeling farming systems are therefore required in order to better assess the impacts of different regulatory policies on agricultural production and to examine how agriculture can adapt to a continuously changing global economic and physical environment. Such modeling tools should rely not only on a thorough understanding of the bio-physical processes governing agricultural production, but also on the appropriate representation of farmers' economic behavior, i.e. the choice of activities, technology (input use) and final output levels (Ruben et al., 1998). This type of model, more generally called "bio-economic", can be defined as farm- or regional-level representations of producers' behavior that incorporate agronomic information with the aim of describing output choices, input use and associated externalities (Janssen and Van Ittersum, 2007). In what follows we focus on "mechanistic" bio-economic models that rely on mathematical programming (MP) techniques and that are probably the type of bio-economic models most frequently found in the literature, in that they have been used extensively to study environmental issues and input use in agriculture (e.g. Cortignani and Severini, 2009; Graveline and Mérel, 2014; Jayet and Petsakos, 2013; Kampas et al., 2012; Medellín-Azuara et al., 2012).

Perhaps the simplest approach for developing a bio-economic model is to assume a Leontief technology by introducing environmental indicators and agronomic coefficients that relate yields to the use of agronomic inputs (e.g. Donaldson et al., 1995; Louhichi et al., 2010; Semaan et al., 2007; Taylor et al., 1992). A second approach involves the estimation of nonlinear crop-specific response functions, typically of water and/or nitrogen, under the assumption that yields are independent of the acreage planted (e.g. Godard et al., 2008; Kampas et al., 2012; Larson et al., 1996). This method seems more consistent with farmers' real decision problem than the simple use of agronomic coefficients, since total output depends on both land allocation (extensive margin choice) and input use, which defines the final per hectare yield (intensive margin choice). While both previous methods are typically based on farm-level models and use representative farms or a farm typology for upscaling purposes, a more recent strand in the literature focuses on regional

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MP bio-economic models that incorporate formal representations of production functions, such as the Constant Elasticity of Substitution function, in which agronomic inputs are used in variable proportions with land (Graveline and Mérel, 2014; Medellín-Azuara et al., 2012; Mérel et al., 2014).

Regardless of the chosen method, the use of agronomic information in bio-economic models operating at the regional level or higher geographical scales undoubtedly constitutes a difficult calibration problem. We use the term "calibration", instead of "estimation", to describe the procedure of recovering agronomic coefficients (or parameters in response and production functions) which are consistent with farmers' observed production choices. Hence, contrary to estimation, which aims at fitting functional forms to available data, as in Brorsen and Richter (2012) and Holloway (2003), parameters derived from a calibration procedure allow the final bio-economic model to reproduce the observed input and output decisions by taking into account the underlying profit optimization problem.

Calibration is particularly difficult in the case of crop-specific response or production functions, because the optimal allocation of variable inputs (such as water and nitrogen) becomes part of a farmer's decision problem and therefore the amount of inputs used in the production process needs to be known accurately. Although this point may seem tautological, since it is not possible to calibrate a model against a variable whose reference value is not observed, it is important to note that most large-scale economic databases, such as the Farm Accounting Data Network (FADN)[2] in a European context, do not provide information on the physical quantities of inputs used. Calibration therefore entails the recovery of the function's parameters and inferring the "true" input allocation. This constitutes a major modeling obstacle, particularly for regional bio-economic models with crop-specific production functions; such models are calibrated according to the principles of Positive Mathematical Programming, which relies on observed output decisions and input use intensities.

The data problems described above explain why most bio-economic applications found in the literature carry out only local or regional analyses with a limited number of crops and/or farms, and also take the reference level of input use to be known in advance (e.g. Belhouchette et al., 2011; Finger et al., 2011; Graveline and Mérel, 2014; Mérel et al., 2014). The question that arises is how to construct and calibrate bio-economic models that can operate at higher geographical scales, while also accounting for the heterogeneity of farms across and within regions, even when the production technology (input use) is not observed. A solution proposed by the bio-economic model FSSIM (Louhichi et al., 2010), which operates at the European Union (EU) level, is to use all available soil and climate data to identify a number of homogeneous agri-environmental zones for each administrative region. Different farm-types are then linked to the various agri-environmental zones through a statistical spatialization procedure. Coupled with expert knowledge on management techniques and related costs in representative EU regions, the necessary bio-physical information for the definition of appropriate input-output coefficients for the FSSIM model can then be derived.

Although the previous approach can account for the varied farming systems characterizing European agriculture, it still involves a Leontief technology and thus all inputs are assumed to be used in fixed proportions with land. As previously explained, however, calibration is not possible in the case of crop-specific response and production functions unless the utilized amounts of all explicitly defined agronomic inputs are known in advance. To our knowledge, this problem has been addressed only by Godard et al. (2008), who proposed a method for constructing and assigning nitrogen-yield response functions to representative farm-types at the EU level. Their method involved coupling the FADN-driven MP agricultural supply model AROPAj (De Cara and Jayet, 2000) with the STICS crop model (Brisson et al., 2003), which allowed the correlation of all available geo-referenced bio-physical data with the limited number of FADN variables that actually have a spatial dimension. This finally led to the construction of a set of region-specific response functions corresponding to different management practices and physical conditions. Calibration and estimation of input use involved choosing a single response function for every crop in each farm-type, based on the profit optimality conditions with respect to nitrogen use, so that the marginal physical productivity of the chosen response function, evaluated at the observed yield level, is as close as possible to the ratio of nitrogen price to crop price.

The drawback with this approach, henceforth termed the "Godard" method, is that it focuses on the calibration of input use only and not on the calibration of the bio-economic model as a whole. In fact, calibration of output decisions is performed independently using a combination of Monte Carlo and gradient methods that aim to re-estimate certain key model parameters in each farm-type (De Cara and Jayet, 2000). Hence, the basic assumption is that the bio-economic model is solved in two steps, since solving for the optimal input use precedes the solution on the optimal land allocation. Despite this computational convention, which is justified by the mathematical complexity of the calibration process, the "Godard" method has been successful in establishing a modeling framework that has been applied at various geographical scales and for different purposes, including the assessment of agri-environmental measures and predicting the impact of climate change on agricultural systems (Humblot et al., 2013; Jayet and Petsakos, 2013; Leclère et al., 2013). Until now this approach has considered only nitrogen, whereas remaining agronomic inputs have been treated as non-limiting yield factors. As a result, it cannot be used for examining policies related to water management in agriculture. This is certainly a serious shortcoming since, in light of climate change, expected problems in water availability will have a negative impact on farm income, especially in Southern Europe (Dono and Mazzapicchio, 2010) where agricultural water demand amounts to almost 70–80% of total demand (Massarutto, 2003).

Accounting for the combined effect of water and nitrogen on crop yields, when input use is not observed, presents an interesting calibration problem, because a given yield can be achieved by infinite combinations of both inputs (an isoquant). Moreover, considering water as a variable to be calibrated with the "Godard" method creates two additional difficulties that relate to the price of the input and do not allow the direct use of the corresponding first-order optimality conditions. The first difficulty is that a water price does not always exist, because farmers often pay a fixed fee irrespective of the amount consumed (land-based fees) or because the appropriate institutions that define rights to access the resource are missing. Regardless of the institutional setting, however, farmers need to consider some kind of private irrigation costs in their production decision problem, i.e. possible water charges and/or energy costs for pumping and distributing water to the fields. Such private costs are equally difficult to infer from databases such as FADN, especially since they are aggregated at farm level. The second difficulty concerns farmers' inability to adequately irrigate their crops due to water availability problems or to technical and institutional constraints. This entails additional implicit (opportunity) costs, commonly referred to as the "resource cost" of water in the relevant literature (WATECO, 2003). In an MP modeling framework, these additional implicit costs correspond to a set of shadow prices that modify farmers' profit optimality conditions when the respective constraints are binding, and therefore should be taken into account in the calibration process.

[2] A brief description of FADN, and its included variables which can be used for farm-level modeling are given in the Appendix. For more information: http://ec.europa.eu/agriculture/rica/concept_en.cfm.