Interface between Agriculture and the Environment: Integrating Yield Response Functions in an Economic Model of EU Agriculture

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Abstract

To address the environmental impacts of agricultural production, economic models have to better take into account the relationship between inputs (fertiliser, animal feeding), outputs and the environment. We present an integrated approach which introduces yield response functions to nitrogen in our economic model AROPAj. The farm-type approach for each EU region, relying on an agro-pedo-climatic database, and the linking of a crop model (STICS) to an economic model are an innovation. The methodology was applied to two French regions and focuses here on GHG emissions. The results showed that variables were more sensitive to crop price variation.

Keywords: agricultural modelling, yield response function, nitrogen, mathematical programming, climate change.

Introduction

Agricultural activities have been widely recognized as affecting the environment, be it their positive impacts, such as landscape conservation, or their negative impacts, such as pollution. The recent CAP reform agreed in Luxembourg (2003) clearly emphasizes the importance of accounting for and monitoring the environmental impacts of agricultural production. Cross-compliance is a key feature of the reform. On a more global level, the agricultural sector may play a central role in helping the EU countries respect the greenhouse gas (GHG) levels set by international agreements, such as the Kyoto Protocol.

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In order to address the issues, economic models have to better take into account the relationships between inputs, such as nitrogen use and animal feeding, agricultural outputs, and the environment. From a policymaking standpoint, there is strong need for new modelling tools that enable integrated assessment of environmental and economic impacts in order to design appropriate economic instruments decisions can be based on. Moreover, the changing policy and environmental context argues for the development and use of generic models which can be easily re-defined and improved when data and/or policy change. This text focuses on the theoretical and numerical aspects related to the inclusion of yield response functions in the micro-economic model AROPAj. Integrated approaches, as this one, are particularly relevant when addressing the relationships between climate change and agriculture: not only does agriculture contribute to the accumulation of GHGs leading to climate change, but climate in turn will impact the agricultural production possibilities. Indeed, the main biological and biophysical processes governing plant relationships with its environment affect crop production and yields. Those effects can extend to the evolution of farming systems, through emergence and relocation of new cultivars, new species, and new management practices.

Such an integrated approach has already been implemented in various contexts. Schneider [1] uses the ASM (Agricultural Sector Model) linked to the EPIC model to analyse the reduction of agricultural GHG emissions in US regions. Angenendt et al. [2] provide a survey at the regional scale, for a typology of farming systems. As the latter, we propose a farm type approach, for each region in the EU, however, instead of a single region, all the EU regions are taken in consideration. In comparison to those two studies, the innovative factors in our study are the geographical scope, the number of regions and the ability to scale down to a single farm type. Such a scale of analysis, which enables aggregated and disaggregated reading of the CAP impacts for the whole EU was used in CAPRI [3]. Nevertheless, that method, relying on a very complete statistical data base, does not use any crop model nor does it integrate physical and management practice characteristics of the studied farm types. We chose to both use a crop model and integrate characteristics which permit the obtention of continuous yield in response to nitrogen rate for each crop and farm-type, and differing from Schneider who opted for a discrete set of fertilizer application rate.

In this text, we first present the modelling approach prior to the integration of nitrogen response curves. The second section deals with what the link between the crop model STICS and the economic model AROPAj is based on. In the third section, implementation of nitrogen response curves is illustrated through two examples. The fourth section presents our first results with the new tool. At last, needs for further research and perspectives are discussed.

Current modelling approach

The model

The AROPAj model consists of a set of independent, mixed integer and linear-programming models. Each model describes the annual supply choice of a given "farm-type" (denoted by *k*), representative of the behaviour of ν_k, "real" farmers. The farm-type representation makes it possible to account for the wide diversity of technical constraints faced by European farmers. Each farm-type *k* is assumed to choose the supply level and the input demand (x_k) in order to maximize total gross margin (Π_k). In its most general expression, the generic model for farm-type *k* can be written as follows:

$$\max_{x_k} \Pi_k (x_k) = g_k \cdot x_k$$
$$\text{s.t. } A_k \cdot x_k \leq z_k$$
$$x_k \geq 0$$

where x_k is the *n*-vector of producing activities for farm type *k*, and g_k is the *n*-vector of gross-margins. A_k is the $m \times n$ - matrix of input-output coefficients and z_k is the *m*-vector of the right-hand side parameters (capacities). Together, A_k and z_k define the *m* constraints faced by farm type *k*.

The components of x_k include the area in each crop (distinguishing between on-farm and marketed production), animal numbers in each animal category, milk and meat production, as well as the quantity of purchased animal feeding. The gross margin g_k contains series of elements corresponding to each producing activity, which, for crops gives: per-hectare revenue (yield times price) plus, when relevant, support received, minus per-hectare variable costs. As the emphasis is put on the farm-type level, each farm-type is assumed to be price-taker. Thirty-two crop producing activities are allowed for in the model and represent most of the European agricultural land use related to arable land and pasture. Crop production can be sold at the market price or used for animal feeding purposes (feed grains, forage, and pastures). As for livestock, thirty-one animal categories are represented in the model (27 for cattle plus sheep, goats, swine, and poultry).

Constraints presentation

The technically feasible production set is bounded by the constraints defined by A_k and z_k. As the total number of non-trivial constraints is fairly large, the present description focuses on constraints that are directly relevant for GHG emissions and abatement costs.

For a more detailed presentation of some of the constraints see De Cara, Houzé, Jayet [4] (http://www.grignon.inra.fr/economie-publique/docs_travail/docs_2004/2004_04.pdf) and De Cara and Jayet [5].

Total crop and grassland area is constrained by the availability of land area, defined as total farm-type k's land endowment (see appendix). In addition, crop rotation constraints are formulated as maximum area shares of individual (or groups of) crops in total area. Maximum area shares are derived from historic observations at the regional level and reflect actual agricultural practices. The corresponding constraints summarize the dynamic nature of crop rotations in a static framework.

Animal numbers are also limited by the availability of stalls, which are allowed to vary by $\pm 15\%$ of the initial animal numbers in the corresponding animal categories. This limitation concerns animal categories related to final production (i.e. mainly older males and females). In addition, cattle numbers are constrained by relationships that reflect demographic equilibrium in the distribution by age and sex classes. This approach thus corresponds to a comparative static, and is very akin to that used for crop rotation.

To feed their animals, farmers can use their own crop and forage production, or purchase concentrates and/or roughage. Four kinds of purchased concentrates and one kind or purchased roughage are considered in the model. This makes it possible to distinguish between energy- and protein-rich concentrates, as well as between straight and compound feedstuff. Farmers have to meet the minimal digestible protein and energy needs of each animal category. In addition, each cattle category is associated with a maximal quantity of ingested matter. The characteristics of feedstuff with respect to energy and protein content, dry matter fraction and digestibility, as well as the energy/protein requirements and maximal quantity of ingested matter for each animal category have been taken from Jarrige [6]. In addition, energy and protein needs are further differentiated to account for the differences of per-animal milk and meat yields.

The last important set of constraints regards the restrictions imposed by CAP measures. Set-aside requirements as well as milk and sugar beet quotas fall in this category. Mandatory and voluntary set-asides are accounted for, each type of set-aside being treated as a producing activity associated with the corresponding payments. The different types of sugar beet quotas (A, B, and C) are also included. Many of the CAP policy instruments included in the model involve the use of binary or integer variables whenever producers have to face mutually exclusive 'discrete' choices.

Data sources

The computation of the components of A_k and g_k, and the baseline levels of producing activities (x_k^0) proceeds in three major steps: (i) selection, typology, and grouping of sample farms into farm types, (ii) estimation of the parameters, and (iii) calibration. The primary source of data is the Farm Accounting Data Network (FADN). The 1997 FADN provides accounting data (revenues, variable costs, prices, yields, crop areas, animal numbers, support received, types of farming) for a sample of slightly less than 60,000 surveyed farmers. Approximately 50,000 sample farms are included in the model, which represent a total of more than 2.5 million European (full-time) farmers. Data are available at a regional level (101 regions in the EU-15). The FADN regions are represented on the website http://europa.eu.int/comm/agriculture/rica/regioncodes_en.cfm [7] and differ slightly from the NUTS 2 level regions (the details of which are given on the following website http://europa.eu.int/comm/eurostat/ramon/nuts/home_regions_en.html [8]). Because of the annual nature of the model, sample farms defined as *"Specialist horticulture"* and *"Specialist permanent crops"* are excluded (types of farming 2 and 3 in the FADN classification). The analysis is thus restricted to the remaining population of the farmers, representing annual crop and livestock farmers. This restriction is important to keep in mind when analyzing the results, as the excluded farms may represent a significant share of total agricultural area for some regions.

Farm-types

The selected sample farms are then grouped into 'farm-types' (or 'farm-groups') according to three main variables: *(i)* region (101 regions in the EU-15); *(ii)* average elevation (3 elevation classes: 0 to 300 m, 300 to 600 m, and above 600 m); and *(iii)* main type of farming (14 types of farming in the FADN classification). The typology results from the following trade-off. On the one hand, the number of *sample farms* grouped in any farm-type has to be large enough to comply with confidentiality restrictions (at least 15 sample farms for each farm-type) as well as to ensure the robustness of the estimations. On the other hand, the total number of *farm types* has to be as large as possible to reduce the aggregation bias at the regional level. Each farm-type thus results from the aggregation of sample farms that are located in the same region, are characterized by similar type(s) of farming and belong to the same elevation class(es). Farm-types may actually encompass more than one FADN type of farming and/or more than one elevation class depending on the number of sample farms and on their heterogeneity in a given region. Likewise, the grouping of sample farms may differ from one region to another: e.g. sample farms labelled in FADN as 'Specialist crops' may be aggregated with 'Mixed cropping systems' in one region and modelled separately in another, again depending on the number of sample farms and their heterogeneity. The number of farm-types by region thus varies from 1 to 15 farm-types. The farm-type approach is important in several respects. First, it takes into account the diversity of farming systems at the infra-regional level better than models that rely on regional aggregates. Farm-type results can still be aggregated at the regional level, but the region itself is not modelled as one single 'big' farm. Consequently, models based on farm-type approach are less subject to aggregation bias (e.g. see p.7 in Perez et al. [9] or p.15 in European Commission, [10]). Second, mixed farming systems being explicitly modelled, the farm-type approach better reflects the existence of a fairly diversified agriculture. Each individual farm in the FADN sample is associated with a FADN weight indicating its representativity in the regional population. The individual weights of sample farms that are grouped into farm-type k are aggregated (v_k) and used to extrapolate the results at the regional level. Following this procedure, 734 farm-types were obtained, each associated with a specific supply model.

Parameters estimation

Parameters and baseline levels of variables that are systematically estimated using FADN data include: variable costs and output prices, area and area shares for each crop, animal numbers, and support received. The estimation procedure is conducted at the farm-type level and uses the extrapolation factors provided by the FADN. As for variable costs, the model distinguishes between two categories of costs: 'fertilizer use' and 'other inputs' (seeds, fuel consumption, pesticides, etc.). Because of the accountancy nature of the FADN data, only total expenditure is available. Per-crop variable costs are therefore inferred from linear covariance analysis, using area crops and including a specific additive farm-type effect. Alternative sources of information are also used whenever relevant data is lacking in the FADN. An important alternative source of information is the Intergovernmental Panel on Climate Change [11], from which emission factors are taken. Likewise, characteristics of feeding products and animal feeding requirements are obtained from technical workbooks (Jarrige [6]). Expert knowledge is used when no other statistical or technical source is available. This is the case for the types of fertiliser used for each crop and each country or region and some feeding parameters. Other sources of economic data include Eurostat and FAOstat databases for fertilizer prices, as well as technical references for animal feeding characteristics and greenhouse gas accounting (IPCC).

Calibration

The last step entails the calibration of a subset of the parameters. Calibration is used when information is lacking or is insufficiently reliable. The subset of calibrating parameters includes: some of the parameters defining animal feeding requirements, lifetime of certain cattle categories, grassland yields, and maximal crop area shares. The calibration uses a combination of Monte-Carlo and gradient methods in order to minimize the distance between the observation data for each farm-type *k*, x_k^0, and the optimal solution x_k^* (see De Cara and Jayet, [5]).

Improvements

Relaxing the fixed yields assumption

As aforementioned, many parameters are estimated from FADN data for a given year (1997). Among others, for each farm-type *k* and crop *j*, we estimate the reference yield y_j^0 and the total expenditure for fertilizers. The AROPAj model determines the area allocated to a crop according to these fixed reference yields and fertilization levels/costs. As the model stands, it cannot take into account price variations for fertilizer or crop, to determine the optimal level of fertilization and yield which would maximize the crop gross margin. Thus the model misestimates the impacts of a change in guaranteed prices, for instance.

The first step in our analysis entails relaxing the fixed-yields assumptions. To do so we need to estimate the yield-response function to nitrogen $y_{jk}(N_{jk})$, supposed to be concave. This is done thanks to the crop model STICS. Then we calculate the nitrogen fertilization N_{jk} and the corresponding yield y_{jk} which maximize the gross-margin per unit of area π_{jk} for a given crop *j*, considering the crop selling price (p_j), fertilizer *f* price (p_f) and the share of nitrogen in fertilizer *f* (v_f) as given. Let us write the theoretical program maximizing g_{jk} per hectare (the *k*-index is omitted here):

$$\max_{N_j} \pi_j = p_j \times y_j(N_j) - \frac{p_f}{\nu_f} \times N_j \quad (\text{s.t. } N_j \geq 0)$$

The first order condition associated to fertilizer consumption is then $\frac{\partial y_j(N_j)}{\partial N_j} = \frac{p_f}{\nu_f p_j}$.

The choice of the response function type

We keep as baselines a set of usual assumptions formulated in the various disciplines where modelling is used. For instance, the usual rationality principle for guidance of the economic behaviour is kept in action. Likewise, the decreasing marginal productivity, accepted by both agronomists and economists, applies to the curves relating fertilizers and yields. This is why we refer to the Von Liebig hypothesis of the minimum (« crop yields are limited by the deficiency or lack of one nutrient necessary to crop growth ») and Mitscherlich's law ("when raising amounts of nutrients are brought to a plant, yield increases are lower the higher the amounts get"), which are commonly admitted as basic rules of fertilisation at the frontier of economics and agronomy. They convey the notions of non-substitutability between nutrients and yield plateau (or limit). Nevertheless, they do not necessarily imply the linearity between yield and nutrient (Paris [12]). Exponential production functions such as Mitscherlich-Baule's type show several advantages in our case study. Such functions are defined by $y = y_{\max} - (y_{\max} - y_{\min}) \times e^{-tN}$, where y is yield, N is the nitrogen fertilizer amount, y_{min}, y_{max}, and t standing respectively for the minimal yield, maximal yield and rate of increase. This type of function has been shown as fitting properly the pseudo-experimental data (Neeteson and Wadman [13], Oger [14]), and offering good properties to estimate economic optimum fertiliser rates (Neeteson and Wadman [13], Oger [14]). From an economic point of view, it was important that the chosen curve be concave, strictly increasing, and with a finite limit in the infinite. From an agronomic point of view, the curve also had to be increasing, with a finite positive value in zero and a finite positive limit in the infinite. Hence, we have selected the exponential production function which enabled us to meet both agronomic and economic requirements.

The choice of the STICS crop model to be linked to the economic model

Our modelling approach relies on a "soft" coupling of a micro-economic, supply-side oriented model of the EU agriculture (AROPAj), and a crop model (STICS). It thus differs from a "fully" integrated approach.

Yield-response functions vary in a large extent with soil, climate and crop management practices: those parameters need to be taken into account at any scale of analysis, from farming system to regions and countries. The required model had to be able to reflect such diversity and to be adaptable to specific modalities of nitrogen fertilisation at the European scale (for example fertilisation calendar).

The generic STICS model had been selected for its adaptability and its ability to simulate the wide range of crops and cropping systems corresponding to crop production situations of the economic model. For various examples of applications, the reader is referred to Brisson et al., 2003 [15].

An overview of the crop model STICS

STICS is a crop model that has been developed at INRA since 1996 (Brisson et al., 1998 [16]). It simulates crop growth as well as water and nitrogen soil balances all dynamically driven by daily weather data. It uses information about soil and management practices as inputs. It estimates both agricultural variables (such as yield, input consumption) and environmental indicators (such as nitrogen and water losses). Figure 1 synthesises the relationships and exchanges of information and matter between the plant and the atmosphere within the model. The underlying relationships are well-known and presented in Brisson et al., 1998 [16] and Brisson et al., 2003 [15]. The plant also interacts with soil through its root system and soil management practices.

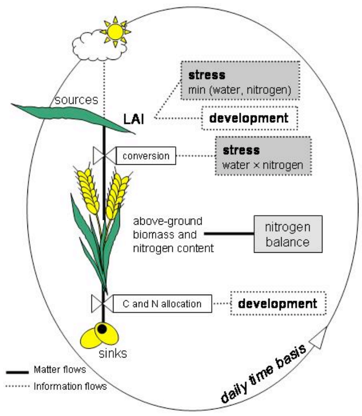

Figure 1. The plant-atmosphere system in the STICS model, after Brisson [17]
http://www.avignon.inra.fr/stics/savoir/diaposteresum/diaposteresum.php

Implementation of endogenous yields

Artix database

This approach requires a large set of information related to a variety of fields (economics, soil sciences, etc.) and various scales. The data management key feature of this research led to the elaboration of a database bringing together and organizing all the information required by the different modelling steps. The Artix database manages all the inputs, outputs, parameters, and side information necessary for model runs. Based on a Client/Server architecture model, this database is implemented on a PostGreSQL platform, but allows for the use of other relational databases. JAVA and SQL are used to program the application's components and to manipulate the database.

Artix contains data from the AROPAj estimates, and gives us the possibility to obtain more quickly and easily individual or aggregated data for farm-types. It also gathers information about soils, climate, plants, and crop management techniques mainly required by the STICS model. The Joint Research Centre (JRC, partly based in Ispra, Italy) provided spatialized meteorological, soil and phenological data. Management practices data are based on expert knowledge. In addition, GIS-based treatments of input data and results require land use information taken from Corine Land Cover inventory.

Artix results in a very helpful tool for the representation of modelling parameters and results throughout the European territory. It actually makes easier the link up with a Geographical Information System (GIS) that we use to downscale FADN regional information of farms to a sub regional level.

The generation of response functions

The basic process relies on the STICS model running apart from the economic model using specific inputs, and thus providing pseudo-experimental data to which response curves are fitted.

To do so, farm types had to be given an agronomic, pedological and climatic context to enable crop simulations. Specific constraints were forced in the agronomic model: as we only focus on nitrogen as nutrient affecting crop yield (neither available economic data nor the agronomic model dealt with phosphorus and potash), we assume there is no lack of those nutrients for the plants. So we made the hypothesis of proportional amount of potassium and phosphorus with nitrogen rate. Fertiliser combination and types were based on expert knowledge.

STICS input parameters are derived from : (i) FADN and AROPAj for organic supplies and irrigations (cf. § Current modelling approach, parameter estimation); (ii) regional experts for other crop management data; (iii) the MARS (Monitoring Agriculture with Remote Sensing) database for soil and climate parameters.

STICS inputs are either pre-determined or fitted to the economic data. Within a given region, climate inputs are related to farm-types according to their altitude class; the sowing date, fertilizer type and calendar are imposed for each crop. For one crop in one farm-type, the following set of inputs are selected so that yield and fertilizer supply meet economic data: soil type (one out of five), preceding crop (a legume or a cereal), and variety, characterized by precocity group, (one out of three). The Artix database related software combines all the inputs and launches the corresponding STICS simulation set. A non-linear fitting procedure (SAS NLIN) provides the estimation of the parameters of the response curve, $y = y_{\max} - (y_{\max} - y_{\min}) \times e^{-tN}$. Then, STICS inputs are chosen according to those which optimize the two following criteria (ranked by increasing importance): 1) the actual reference yield y_j^0 (AROPAj calibration step based on FADN) is obtained, 2) the difference is minimal between the price ratio $\frac{p_f^0}{v_f p_j^0}$ (fertilizer purchasing price over crop selling price) and the derivative value of the function where yields equals the reference yield, $\frac{\partial y_j}{\partial N_j}\left(y^{-1}\left(y_j^0\right)\right)$. An example is presented on Figure 2.

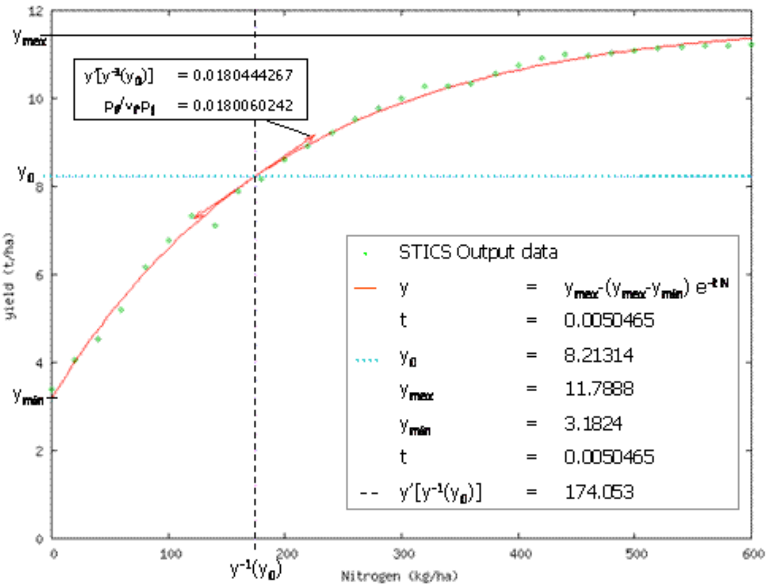

Figure 2. An example of nitrogen response curve for soft wheat from a farm-type of cereal growers in Picardie (Northern France)

Adjustment of the response curve to the calibrated basic parameters

There is no reason that the curves produced by STICS precisely fit the point defined by $\left(N_j^0, y_j^0\right)$. Likewise the slope at this point, while close, is seldom equal to the price ratio mentioned in theoretical analysis. Because of this deviation, we need to adjust the agronomic curve in order to fit the economic information upon which the economic model is calibrated. Using FADN, yields and fertilizer expenditure are computed for each farm type and for each crop. These estimations are assumed not to change during the calibration process. The assumption is that reference yield y^0 and reference expenditures for fertiliser c_f^0 represent well the baseline situation. However, an uncertainty remains on the total amount of nitrogen brought to the crop, due to the uncertainty regarding organic-nitrogen input during the reference year and regarding the type and price of market fertilizers. To ensure consistency between the yield response function and economic data, the parameters defining the curve need to be calibrated. The assumption – supported by agronomic considerations – is that the intercept yield and the asymptotic yield of the curve adjusted to STICS outputs remain unchanged. As a consequence, the only calibrating parameter is *t*, which defines the curvature of the response function.

Let us consider $y(N) = y_{\max} - (y_{\max} - y_{\min}) \times e^{-tN}$, the response function provided by STICS, and $y_a(N)$ the adjusted response function. Let us consider the price ratio $\frac{p_f^0}{v_f p_j^0}$ is derived from estimated cost c_f^0. We define $y_a(N)$ such that:

$$y_a(N) = y_{\max} - (y_{\max} - y_{\min}) \times e^{-t_a N}$$
$$y_a(N_a^0) = y^0$$
$$y_a'(N_a^0) = \frac{p_f^0}{v_f \times p_j^0}$$

Given $y_{\min} \le y_0 \le y_{\max}$, $t \ge 0$ and the equations above, we deduce the value of the adjusted growth rate t_a:

$$t_a = \frac{p_f^0}{v_f p_j^0} \times \frac{1}{y_{\max} - y^0}$$

The difference between the reference expenditure and the adjusted one should be defined as:

$$\Delta c_f^0 = c_f^0 - c_{af}^0 = c_f^0 - \frac{p_f}{v_f}(y_{\max} - y^0) \times \ln\left(\frac{y_{\max} - y_{\min}}{y_{\max} - y^0}\right)$$

Figure 3 shows how the original STICS curve is modified through this adjustment procedure.

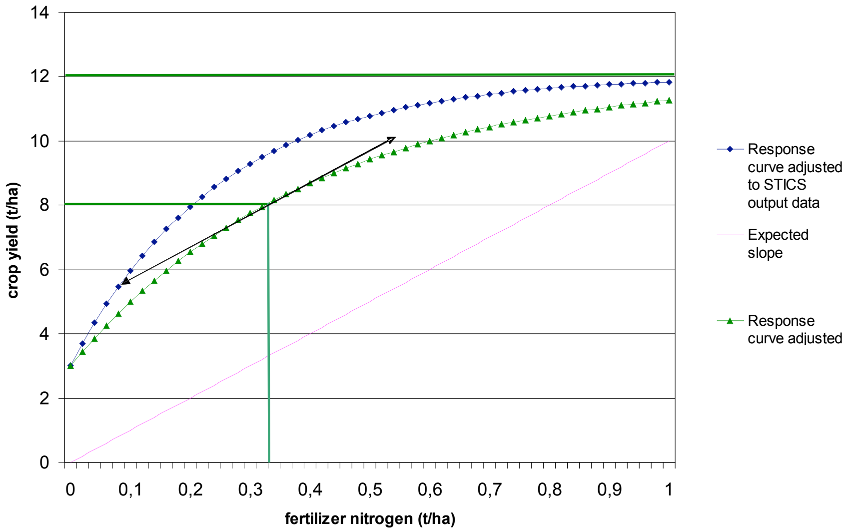

Figure 3. Adjustment of the STICS curve with respect to the calibration of the economic model based on the reference yield and the reference variable cost

Introducing yield response functions in AROPAj

The first step is dedicated to the optimization of the gross margin of each crop. As seen in a previous section, the optimal level of fertilization N_j^* and yield y_j^* related to the crop j are achieved when the marginal cost equals the marginal benefit. As the concavity assumption is fulfilled by construction, the function $y_j(N_j)$ is sufficient to determine the optimum (N_j^*, y_j^*). Then, knowing the gross-margin per hectare, we thus only have to determine the optimal area allocated to each crop to maximize the farm gross margin through the usual version of the economic model. With this two-step process, we avoid non-linear programming in the main model.

First results analysis

In this section, the impacts of the introduction of endogenous yield response function on the results of the economic model are tested. We first examine how the optimal solution is modified consecutively to a change in the output (wheat) price. Secondly, we address the issue of a change in the input price through the introduction of GHG emission tax.

Sensitivity analysis at the farm level

Using a sensitivity analysis, the contribution effects of yield response function within the economic model are our first concern. This step entails the analysis of change in land allocation, marketed crop output, and gross margin when one yield response curve is introduced in the model. Soft wheat is focused on due to the importance of this crop in the European agricultural sector. No ex-ante preference between farm types leads us to introduce this yield curve for the first farm type on the list, namely FT1 from Belgium. Simulations are based on change in crop price, keeping constant the nitrogen price. Considering 101.3 €/t as the reference price of soft wheat, we change this price from -10 to +10 € around this reference price by increments of 1€. The adjustment process is implemented with this reference price.

Figure **4** shows the sensitivity analysis results for the three variables mentioned above without and with the introduction of the adjusted yield function. As expected, the gross margin "with" is greater than the gross margin "without" yield-response function. The difference is zero only when the price is equal to the reference price. Change in land allocation is weak. Finally, again as expected, change in the marketed part of the soft wheat production is the most significant. Moreover, and consistently with the economic intuition, the marketed output is smoother with endogenous yield response than without. The difference is monotically increasing with respect to the output price.

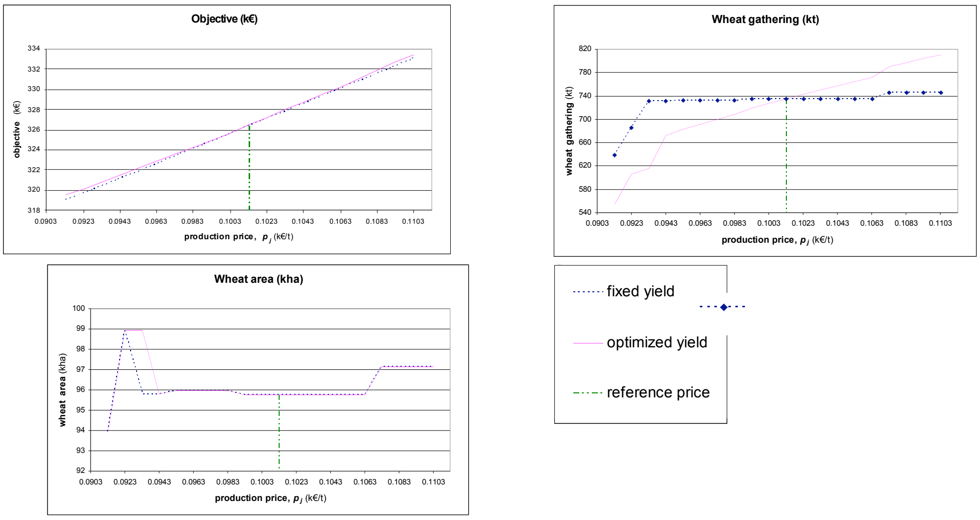

Figure 4. Sensitivity analysis of 3 variables to crop prices ranging +/- 10 euros around reference, by 1 euro increments

Endogenous yields and GHG abatement costs at the regional level

First, yield response curves were elaborated for soft wheat, maize, and sunflower and for several groups concerning the Picardie region (Northern France). This region was selected for its variability in term of crops, soils, climate and management practices; it includes crop grower, dairy and cattle raiser farm types, with different types of manure and slurry management as well as fertilizer types and fertilization calendars.

The baseline scenario corresponds to the 1997 CAP. Without tax, results with endogenous yields are the same as results with exogenous yields. The tested scenario corresponds to the introduction of a tax on GHG emissions. This is a first rank instrument which supposes GHG emissions are known. With a new CAP or environmental policy, and consequently new prices, the model results differ according to whether the yields are endogenous or not. Total GHG emissions are endogenously computed in the model through equality constraints, and are included in x_k. The corresponding component of g_k represents the per-tCO2eq tax. In the baseline scenario, the tax is assumed to be zero. First, the model optimizes the crop yield according to nitrogen price, GHG emissions tax, and crop price. Then the model optimizes the gross margin of the farm-type.

For Picardie, with exogenous yields, a tax of 30 €/t CO2eq involves an abatement of about 160 ktCO2eq compared to 2000 total emissions. With endogenous yields, the same level of tax involves an abatement of about 380 ktCO2 (Figure 5). With endogenous yields, the model takes into account a wider range of production choices. Not only can the crop area be adjusted, but also the fertiliser expense directly affecting crop yield. Marginal abatement costs are consequently reduced.

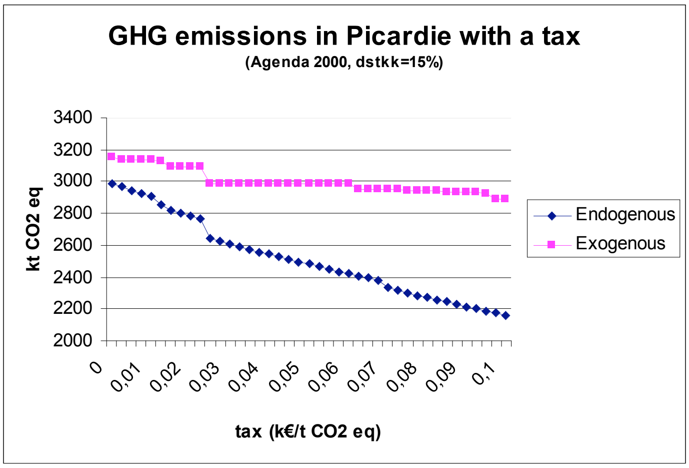

Figure 5. GHG Emissions Reductions, with or without endogenous yields

Figure 5 shows the evolution of emissions (agenda 2000 situation) with and without endogenous yields. If the emission tax is zero, endogenous yields make it possible for farmers to maximize their profit by adjusting the quantity of nitrogen used to new prices (Agenda 2000), thus involving a reduction in GHG emissions.

As the tax increases, farmers are encouraged to reduce all activities which are a source of GHG emissions. One important limitation is in this adjustment is the necessity to feed animal. Recall that farmers can only reduce their animal number by up to 15%. As purchased animal feed is less GHG producing than domestic feed, with a very high level of tax, farmers are encouraged to stop all crop activity. Or at least, they have to drop drastically their nitrogen input requirements which are responsible for GHG emissions.

Qualifying the results

To qualify the results, we have to remember that, currently, the module of endogenous crop yields does not take into account the cereal opportunity cost linked to on-farm consumption. The price ratio used in the second section, leading to the computation of the optimal yield and the input, holds when the production related to this crop is not entirely on-farm consumed (see appendix). When the crop is not marketed, we theoretically need to use the dual price of the positivity constraint related to the marketable output, which is strictly greater than the crop selling price. Therefore one may expect the per-hectare crop gross margin to be underestimated.

In this case, an iterative procedure is needed: the model is run a first time to compute initial values of the shadow prices; these prices are then used as proxy for crop price, and then the model runs again until a stable solution is reached. This calculation would be time consuming if applied to all crops of all farm types. So we set out to find an expression of this shadow price (μ_j) that would enable the calculation of its value beforehand.

The resolution of the theoretical model provides no general expression for μ_j that can be directly derived from the model parameters. However, an upper bound which applies to all situations can be computed:

$$p_j \leq \mu_j \leq \sum_{n=1}^{N} \frac{p_m t_{nij}}{u_{nim}}$$

where p_m stands for the price of feedstuff *m*, t_{nij} is the dietary value of crop *j* in nutrient *n* and u_{nim} is the dietary value of feedstuff *m* in nutrient *n*.

Conclusion and perspectives for further research

The introduction of crop yield response function to nitrogen fertilisation in the AROPAj enables to relax strong assumptions regarding fixed reference yields and fixed fertilisation levels. Therefore, this provides more flexibility in the model as both fertilisation level and land allocation can be adjusted.

Exponential response functions chosen in this study fit both agronomic and economic criteria and offer interesting properties with regard to optimisation, namely concavity, positivity and finite limit. The approach was implemented for one region chosen for its diversity of productions and for which all data were available. Changes in crop production, crop area, gross margin and GHG emissions prompted by changes in crop selling price were discussed. The results are more sensitive to price variations when yields and fertilisation are optimised. As expected, the supply elasticity with respect to a GHG emission tax increases. This is particularly true for N2O. Indeed, the adjustment of the gross margin is not only made for land allocation but for the level of nitrogen fertilisation, which is directly linked to N2O emissions. Impacts on CH4 emissions are less pronounced. All these results are valid only when the production for a crop is not entirely on-farm consumed. In such a case, the dual price for this crop should be substituted for the domestic price.

An important issue for further research will be a proper account of the possibility to substitute manure for purchased fertiliser in order to reach the optimal level of nitrogen. Indeed, a similar methodology can be used to define manure nitrogen response curve using the STICS crop model. Once the crop model has all its input determined for each crop of each farm type, a batch of runs leads to several response curves: one for fertilizer nitrogen only, others corresponding to each identified manure category (manure, slurry and poultry manure). The last response curves enable us to pinpoint the equivalent coefficients in terms of yield of nitrogen from fertilizer and nitrogen from various manure categories. These parameters will be introduced into the economic model. This way, nitrogen input not only provided by the market but partly by on-farm effluents from livestock could be included in the model.

Another field of investigations is to apply the methodology used in this article to meat and milk production. The generic yield curves related to animal production are not as well defined, but our first efforts in this field seem to be fruitful. We also need further research to properly deal with crops concerned by one or a series of quotas, as the sugar-beet is.

Further research will also be needed regarding the assessment of climate change impacts on agricultural supply. First, the weight of potential reduction in net GHG emissions, including the carbon sequestration, offered by the agricultural sector will re-inforce the interest in the interface between agriculture and the environment. Second, climate change can be considered as a major direct or indirect cause of change in land use and crop yields. While yields and related costs vary in a given territory, land cover is expected to change with the relative net price of the eligible productions. Indeed eligible crop productions are the profitable ones consistent with climate and soil conditions. Actually, climate change could deeply modify the range of such potentially grown crops (species and cultivars) on a territory by excluding the most unadapted ones, and offering favourable growing conditions for new ones. The prospective analysis of such interactions between crop production and its environment requires a step further in modelling. Indeed, it would be necessary to consider the location of productions and the feedback effects of climate change in our economic modelling approach. The technical context currently brought to the farm types constitutes a first step towards a modelling tool integrating more complex interactions. It would enable us to deal with potential agricultural changes in land cover and production allocations, apart from other factors such as demography and global economic context. Those perspectives will necessitate new collaborations between research teams implicated in climatology and environmental sciences among others.

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Appendix

Theoretical model

$$\max_{Y_j, C_{ji}, N_j, s_j, q_{mi}, a_i} \sum_{j=1}^{J} \left(p_j \times Y_j - \frac{p_f}{v_f} N_j \times s_j \right) - \sum_{m=1}^{M} \sum_{i=1}^{I} p_m q_{mi} + \sum_{i=1}^{I} v_i a_i$$

s.t.

$$\begin{array}{rclll}
\sum_{j=1}^{J} s_j & \leq & S & & (\lambda) \\
Y_j + \sum_{i=1}^{I} c_{ji} & \leq & y_j(N_j) \times s_j & \forall j & (\mu_j) \\
\sum_{m=1}^{M} (u_{nim} \times q_{mi}) + \sum_{j=1}^{J} (t_{nij} \times C_{ji} & \geq & b_{ni} \times a_i & \forall n,i & (\kappa_{ni}) \\
Y_j & \geq & 0 & \forall j & (\varphi_j) \\
s_j & \geq & 0 & \forall j & (\sigma_j) \\
N_j & \geq & 0 & \forall j & (\varepsilon_j) \\
C_{ji} & \geq & 0 & \forall j,i & (\gamma_{ji}) \\
a_i & \geq & 0 & \forall i & (\alpha_i) \\
q_{mi} & \geq & 0 & \forall m,i & (\xi_{mi})
\end{array}$$

With:

Y_j :	marketed crop j (t)
C_{ji} :	on-farm consumption of crop j by animal type I (t/head)
s_j :	area in crop j (ha)
N_j :	nitrogen fertilization level per hectare of crop j (tN/ha)
p_j :	selling price crop j (€/t)
p_f :	purchase price for fertilizer f (€/t)
v_f :	nitrogen share in fertiliser f (tN/t)
p_m :	purchase price of feedstuff m (€/t)
v_i :	gross product associated to animal type I (€/head)
a_i :	animal number, type I (head)
q_{mi} :	quantity of feedstuff m bought for cattle type i (t)
b_{ni} :	need of animal i for nutrient n (unit of n/head)
t_{nij} :	dietary value of crop j in nutrient n for animal I (unit of n/t)
u_{nim} :	dietary value of feedstuff m in nutrient n for animal I (unit of n/t)

We solve the programme, considering the number of animals fixed:

$$p_j - \mu_j + \varphi_j = 0$$

$$-\frac{p_f}{v_f} s_j + \mu_j \frac{\partial y_j}{\partial N_j} s_j + \varepsilon_j = 0$$

$$-\frac{p_f}{v_f} N - \lambda_j + \mu_j y_j(N_j) + \sigma_j = 0$$

$$-p_m + \sum_{n=1}^{N} \kappa_{ni} u_{nim} + \xi_{mi} = 0$$

$$-\mu_j + \sum_{n=1}^{N} \kappa_{ni} t_{nij} + \gamma_{ji} = 0$$

$$\lambda \times \left(s - \sum_{j=1}^{J} s_j\right) = 0$$

$$\mu_j \times \left(y_j(N_j) s_j - Y_j - \sum_{i=1}^{I} C_{ji}\right) = 0$$

$$\kappa_{ni} \times \left(\sum_{m=1}^{M} \left(u_{nim} \times q_{mi}\right) + \sum_{j=1}^{J} \left(t_{nij} \times C_{ji}\right) - b_{ni} a_i\right) = 0$$

$$\varphi_j \times Y_j = 0$$

$$\sigma_j \times s_j = 0$$

$$\varepsilon_j \times N_j = 0$$

$$\gamma_{ji} \times C_{ji} = 0$$

$$\xi_{mi} \times q_{mi} = 0$$

We deduce from the expressions above (with the positivity of dual activities):

$$\mu_j \geq p_j$$

$$\mu_j \geq \sum_{n=1}^{N} \kappa_{ni} t_{nij}$$

$\sum_{n=1}^{N} \kappa_{ni} u_{nim} \leq p_m$, which implies $\kappa_{ni} \leq \frac{p_m}{u_{nim}}$ (due to positivity constraints)

When the entire output in crop j is on-farm consumed we have:

$$\mu_j > p_j$$

$$\mu_j = \sum_{n=1}^{N} \kappa_{ni} t_{nij} \quad (\text{as } \gamma_{ji} = 0)$$

$$\kappa_{ni} \leq \frac{p_m}{u_{nim}}$$

So we have a lower and upper bounds for μ_j, which applies to every situation:

$$p_j \leq \mu_j \leq \sum_{n=1}^{N} \frac{p_m t_{nij}}{u_{nim}}$$