Soil resources and the profitability and sustainability of farms: An empirical bioeconomic model

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Abstract

Agro-ecology is a long term approach according to which agricultural productivity is based on an intensive use of ecosystem services. However, inappropriate farming practices can trigger a soil degradation that leads to a decrease in ecosystem services (Lal, 2015). In this article, we build an empirical intertemporal model to establish whether adopting agroecology practices allows farmers to achieve a productive, profitable and sustainable agriculture. The model is used to determine which farming practices (tillage intensity, nitrogen fertilizers inputs, crop rotations, residues use) are optimum when the farmer maximises his profit under a soil organic matter (SOM) dynamics constraint. The intertemporal setting of our problem allows for an environmental feedback of soil quality changes, where SOM is used as a proxy for soil quality. Our model is adapted to the climatic and soil conditions of the Grand Ouest of France, with crop production functions and soil quality dynamics functions calibrated and estimated from a farm representative in terms of crop grown in the Grand Ouest. Our results show that the use of long rotations, lower levels of N fertilizers as well as an important use of residues, lead to an optimum in all our scenarii. The farmer invests in his soil through tillage. However, SOM stocks decrease linearly in all scenarii to reach similar SOM end values. This does not meet the objective of agroecology since soil resource quality is depleted in the long run. Besides, in our simulations, the economic incentives to increase SOM have no significant impact on SOM dynamics. This suggests that one cannot increase significantly soil quality by monitoring only N fertilizers, tillage intensity and crop residue use. Such practices have to be integrated in a larger set of practices to be really efficient to increase SOM content in soils, especially in an economic context that is favorable to the use of N fertilizers as a substitute for soil quality.

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1 Introduction

Agriculture is faced with an expected increase in food demand caused by an increase in the global population of 9 billion people by the middle of this century. On a national scale, competitiveness and economic growth issues are at stake. To ensure an increase in production, there are two solutions : extend the proportion of agricultural lands at the expense of natural ecosystems and increase agricultural productivity.

The latter is favored by the agro-ecology concept, used in the French Outline Agricultural Act of January 2014 (Musson and Rousselière, 2016). Agro-ecology is a long term approach that consists in producing more with less. With such an approach, the agricultural productivity is based on an intensive use of ecosystem services, a lot of which are closely linked to soil resource (food, feed, elemental cycling for instance) (Lal, 2015). When considering soil resource, the agroecology approach corresponds to a strategy of maintenance or increase in the quality of this resource. The techniques relative to such strategy include conservation agriculture practices. Actually, inappropriate farming practices can trigger an ever-increasing downward spiral of soil degradation, that leads to a decrease in ecosystem services, soil use efficiency and soil resilience. Such negative process can be mitigate through the adoption of soil conservation practices (Lal, 2015). However, the implementation of suitable practices is site-specific, both in terms of environmental and economic contexts. Indeed, the farmer faces a trade-off between a short-term objective of productivity and profitability, and a long-term objective of sustainability - which includes the soil sustainability.

To investigate such trade-off, dynamic bioeconomic modeling is the relevant tool to be used. It allows considering both the socio-economic and biophysical conditions necessary to the farmer's decision making process. Through such models, it is also possible to study the interlinks between economical objectives and the existing biological dynamics and constraints. They also allow evaluating changes in the economic context, and assessing changes in policy. For instance, Holden *et al* (2005), Louhichi *et al* (1999 and 2010) have used dynamic bioeconomic models in order to assess the impacts of existing or alternative policies. Smith et al (2000) have used bioeconomic modeling to determine the optimal cropping systems in a specific agricultural region of Canada. Berazneva et al (2014) have developed a bioeconomic model to determine the optimal management of a Kenyan farming system over time.

The models mentioned take into account soil dynamics: soil erosion in Louhichi *et al* (1999), soil erosion and soil nutrients (soil nitrogen stocks) in Holden *et al* (2005), soil erosion and soil organic carbon in Smith *et al* (2000). In all models, different scenarii of farming practices are simulated in order to evaluate their impact on the indicators of soil quality considered, among other objectives. These models are context and site specific. Holden *et al* (2005) study the case of a farming household in Ethiopia, with specific soil, climatic and economic conditions. Similarly, the soil contexts of the Dark Brown Chernozem (Typic Boroll) soils of the Canadian plains in Smith *et al* (2000) or of the western Kenyan highlands soils are very different from the soil context of France. The results obtained and the crop production functions and soil quality parameter dynamics cannot be transfered to a French case. This the limitation we address here.

The objective of this article is to built an empirical model in order to establish whether indeed, adopting and agroecology decision making process can allow farmers to achieve a productive, profitable and sustainable agriculture in a context where fertilizers and energy prices are rising. To do so, we propose an empirical model adapted to the climatic and soil conditions of the Grand Ouest of France, with crop production functions and soil quality dynamics functions calibrated and estimated from a farm representative in terms of crop grown in the Grand Ouest in the Vienne department. The model is used to determine which farming practices (tillage intensity, nitrogen fertilizers inputs, crop rotations, residues use) are the best suited when the farmer maximises its profit while considering his soil quality dynamics. This model is also used to identify the incentives or impediments to the adoption of soil conservation practices.

In most features, the model proposed by Smith *et al* (2000) is close to ours. They consider soil organic carbon (SOC) as a production factor. However, in Smith *et al* (2000), changes in SOC are considered through a biological long-term equilibrium of SOC. This long-term equilibrium depends on cropping intensity, the use of fertilizers (1 or 0) and the use of tillage (1 or 0). This function is used to determined the SOC target level attained for each simulated combination of these farming practices. Hence, SOC end value is not determined endogenously during the optimization process. In our model, we also consider SOC (expressed as soil organic matter (SOM)), since it is a reliable indicator of changes in soil quality as well as a soil quality parameter well studied and present in most soil analysis. Hence, it is an indicator for which there are data and which is simulated by several biophysical modeling system. However, contrary to Smith *et al* (2000), we consider SOC as an endogenous production factor in our model, wherein SOC end value is determined endogenously through the optimization process.

The bioeconomic model proposed here is an intertemporal model. It takes into account the long-term dynamics of soil quality characteristics, as well as their cumulative changes. The intertemporal setting of our problem allows for a environmental feedback of soil quality changes. Besides, these changes are taken into account in the farmer's decision making process. We introduce soil organic matter dynamics as a production constraint that the farmer takes into account when maximizing his revenue. During the optimization process, the intensity of farming practices is endogenously determined. We address the conflict between short-term objective of profitability and productivity and the long-term objective of sustainability, putting the emphasis on soil resource sustainability. Actually, since soil resource is both a production support and a production factor, the question of its conservation is of high importance. Soil erosion is not taken into account since it is not a primary concern in our region. Besides, since soil quality investments usually involves a low tillage intensity, such measures also reduce soil erosion.

First, the empirical bioeconomic model is described, along with its different components. It is a dynamic intertemporal optimal control model that incorporates directly the soil quality dynamics function and the crop production function. Then, the soil quality indicator dynamics function and the crop yield functions used are presented in more details. These functions have been estimated using the biological simulation model CropSyst, in order to capture the specific effects of N fertilizers inputs, tillage and crop residues use on soil quality ; and the effects of N fertilizers and soil quality on crop yields. The soil quality indicator used here is soil organic carbon. We present the calibration and validation of the model. We briefly present the software and solver used to run our simulations, as well as the main limits of our empirical model. Finally, the results of our simulations are presented and discussed.

2 The empirical bioeconomic control model

The crop yield function per hectare is determined by the production function f_C and depends on fertilizers inputs N, soil endogenous quality OC for each activity level area.

$$f_C(N_t, OC_t) \tag{1}$$

The profit of the farmer is composed of the amount of money received for the total crop yields sold, which corresponds to the current price of a culture multiplied by the crop yield, minus the costs associated to the different inputs used on each activity level area X (variable costs), and the fixed costs associated.

$$(\sum_{pc}\sum_{c}\sum_{s}(P_{c,t}f_{s,c,t}(N_{c,s,t}, OM_{c,s,t}))\,X_{pc,c,s,t} - \sum_{i} C_i M_{i,pc,c} X_{pc,c,s,t} + FC \times X_{pc,c,s,t} \tag{2}$$

The CAP aids, composed of the coupled premium for each crop multiplied by the corresponding activity level area, the Basic Payment Scheme BPS, the Green Direct Payment GDP, redistributive payment RP and contracted agri-environmental measures AEM.

$$\sum_{pc}\sum_{c}\sum_{l} X_{pc,c,s,t} Pr_{c,t} + BPS_t + GDP_t + RP_t + AEM_t \tag{3}$$

Soil quality over time depends on the previous state of soil quality, here captured by the soil organic matter OM, N fertilizers use N, tillage intensity Z, residue use D and previous crop c :

$$OM_{c,s,t} = OM_{c,s,t-1} + h(OM_{c,s,t-1}, N_{c,s,t-1}, Z_{c,s,t-1}, D_{c,s,t-1}) \tag{4}$$

We also consider cropland constraint, that considers the limited availability of cropland on a farm and rotation choices constraints. Rotations choices are such that, for each soil type, the total area allocated to each crop this year cannot exceed the total area allocated the previous year to the preceding crops matching the current crop considered. In addition, we impose some agronomic constraints to the rotation choices, based on the following pattern, with the possibility of including alfalfa crop after sunflower :

STRAW → RAPESEED → STRAW → SUNFLOWER or MAIZE GRAIN → STRAW

In the simulations, the farmer can choose the crops to be grown at each period, as long as his choice respects the preceding crop constraint. Besides, there is a pre-determined amount of work time availability per year on the farm ($TTIMAVAIL$), corresponding to two full time jobs through the year, with two part time job during the months of July and August. The constraint states that the actual yearly working time ($WTIME$) shall not exceed this available working time. A liquidity constraint expresses the necessity for the farmer to be able to pay his rent and his fixed and variables charges at the end of each exercise. This constraint may be relaxed.

It is assumed that the farmer's objective is to maximise his expected revenue. The objective function of the model is the expected present value of returns over a T time period:

$$\underset{Z,N,D}{\text{Max}}\, U = \sum_{t=1}^{T} (1+r)^{-t} \mathbb{E}(\pi_t) \tag{5}$$

subject to: $OM_{c,s,t} = OM_{c,s,t-1} + h(OM_{c,s,t-1}, N_{c,s,t-1}, Z_{c,s,t-1}, D_{c,s,t-1})$ Soil organic matter motion (6)

$0 \leq OM_{c,s,t} \leq OM_{max}$ Bounds on soil organic matter levels (7)

$OM(0) = OM_0$ Initial soil quality (8)

$0 \leq Z_t \leq 1$ Bounds on tillage intensity (9)

Cropland constraint, rotation constraint, cropland accounting (10)

Labour constraint (11)

Liquidity constraint (12)

$0 \leq D_t \leq 1$ Bounds on crop residues (13)

$0 \leq N_t \leq N_{max}$ Bounds on N fertilizers inputs (14)

(15)

where:
c = crop, Z = tillage intensity, N = nitrogen fertilizers, D = crop residues, s = soil type, OM = soil organic matter, r = discount rate, % taux d'actualisation π = profit, T = terminal year in the planning horizon

and

$$\pi_t = \sum_{pc}\sum_{c}\sum_{s}\left(P_c f_{c,s,t}(N_{c,s,t}, OM_{c,s,t})\right) X_{pc,C,s,t} - \sum_{i} C_i M_{i,pc,c} X_{pc,c,s,t} - FC \times X_{pc,c,s,t} + \sum_{pc}\sum_{c}\sum_{s} X_{pc,c,s,t} Pr_{c,t} + BPS_t + GDP_t + RP_t + AEM_t \quad (16)$$

where:
pc = preceding crop, c = crop, s = soil type, P = price, f = production function, X = activity level area, C = cost, i = input index, OM = soil organic matter, N = N fertilizers, M = inputs, FC = fixed costs, Pr = coupled premium, BPS = Basic Payment Scheme, GDP = Green Direct Payment, RP = Redistributive Payment, AEM = Agri-Environmental Measure.

3 Methodology

Two important functions have to be considered here: the crop production functions and the soil organic carbon (SOC) dynamics functions.

To proceed to the calibration of the bioeconomic model and perform simulations, data are required relative to farming practices, soil characteristics, and inputs and outputs prices. Data used to construct our model come mostly from the farmer's documentation on his practices and from estimates given par the farmer or his farming counselor. When necessary, other sources of information have been used, such as technical reports and documentation from the Chambers of Agriculture or the Agreste website (French agricultural statistics, evaluation and forecasting) as well as data from a previous case study applied to this same cereal farm (in Ghali, 2013). Not enough data were available to estimate soil quality dynamics functions and crop production functions from actual data. Hence, the functions have been estimated using the biological simulation software CropSyst. Phosphorus and potassium inputs are considered as fixed in our model. Actually, CropSyst only considers lack of phosphorus, but does not allow to monitor precisely the amount of phosphorus applied for each crop. Precipitations are not taken explicitly into account. The characteristics climatic conditions of the study area are taken into account within CropSyst.

For the soil quality dynamics functions and the crop production functions, the three representative soil types are distinguished:

- **S1 soil type : Loam soils**: 60,2 % of sands, 11.5 % of clay, 28.4 % of silts
- **S2 soil type : Clay-limestone soils**: 30.8 % of sands, 20.1 % of clay, 35.0 % of silts
- **S3 soil type : Clay-silt soils**: 26.8 % of sands, 27.2 % of clay, 45 % of silts

3.1 Estimation of the soil quality dynamics functions

Here, soil quality dynamics is considered through soil organic carbon. Soil organic carbon pool is a reliable indicator of soil quality changes (Lal, 2015). Furthermore, soil organic carbon is an important factor of sustainability (Lal, 2015). Actually, the biological software used, CropSyst, considers soil organic matter. In soil analysis, it is the organic carbon that is measured, and the result that appears on soil analysis is organic matter, through the use of a commonly accepted factor of 1.72.

To capture the impact of farming practices on SOM dynamics, one can consider the following functional form:

$$\begin{aligned} OM(c,s,t) = OM(c,s,t-1) &+ (\alpha_0 + \alpha_1 OM(c,s,t-1) + \alpha_2 OM(c,s,t-1)^2 + \alpha_3 N(c,s,t-1) \\ &+ \alpha_4 N(c,s,t-1)^2 + \alpha_5 Z(c,s,t-1) + \alpha_6 Z(c,s,t-1)^2 \\ &+ \alpha_7 D(c,s,t-1) + \alpha_8 D(c,s,t-1)^2 + \alpha_9 N(c,s,t-1)Z(c,s,t-1) \\ &+ \alpha_{10} N(c,s,t-1)D(c,s,t-1) + \alpha_{11} Z(c,s,t-1)D(c,s,t-1) \\ &+ \alpha_{12} OM(c,s,t-1)N(c,s,t-1) + \alpha_{13} OM(c,s,t-1)D(c,s,t-1) \\ &+ \alpha_{14} OM(c,s,t-1)Z(c,s,t-1) + \varepsilon) \end{aligned} \tag{17}$$

where
OM= soil organic mater, s= soil type, c= crop cultivated, D=crop residues left and buried, N = amount of N fertilizer used, Z = tillage (superficial or profond), ε =error term

Hence, we consider that the level of SOM of a given parcel at time t is the initial value of SOM in the previous period $t-1$, to which we add the variation caused by the practices implemented and the crop grown throughout the year $t-1$ on this parcel.

The SOM dynamics functions are calibrated using soil analysis provided by the farmer and using information relative to his tillage practice, residue use and N fertilization practice.

In order to estimate the soil organic matter (SOM) function, a database was built, based on CropSyst simulations. A particular set of techniques was simulated for the same soil type and crop during a period of thirty years. The objective was to be able to simulate significant and lasting impacts of these practices on SOM dynamics. The simulations are made for three soil types and seven crops. For each soil type/crop bundle, the same set of simulations are run. These simulation had a different combination of N inputs (three different values), OM initial stock (three different values, 11.6 g/kg; 22.8 g/kg and 40 g/kg), tillage practices (simplified or "conventional"), and residues use (shredded and incorporated at the surface, or not). The results of the simulations are used to estimate the different crop production functions, for each soil type. We use the software R, and the *lm* function. All regressions respect the homoscedasticity condition, and there are no correlation between residues. Results of the regressions are displayed in Annex 1.

3.2 *Estimation of the crop production functions*

The production function is specified as a quadratic crop-yield function, similarly to Smith et al (2000). It allows us to consider the second order effect of the production factors (N mineral fertilizers and SOM) as well as their cooperation relationship.

Hence, the crop-yield function is specified as:

$$\begin{aligned} y(c,s,t) =& \beta_0 + \beta_1 N(c,s,t) + \beta_2 N(c,s,t)^2 + \beta_3 OM(c,s,t) + \beta_4 OM(c,s,t)^2 \\ &+ \beta_5 N(c,s,t) OM(c,s,t) + \varepsilon \end{aligned} \tag{18}$$

where
y = yield, s= soil type, c= crop, N = applied nitrogen (kg/ha), OM = soil organic matter concentration (g OM/kg soil), β = parameters to be estimated, ε = error term.

The coefficients of N and SOM are expected to be positive. Interactions among N and OC represent complementarity and substitutability among soil quality and chemical input intensity (or management intensity), and are of undetermined sign. The second order effects are supposed to be negative.

The crop functions are calibrated using actual crop yield data for each crop present on the farm and taken into account by CropSyst, for each of the three main soil types identified. N fertilizers inputs are taken from actual data shared by our farmer. The crop production functions are calibrated for the year 2015 or 2014, for the representative parcels considered. For the crop files specifications, most files are directly parameterized in CropSyst, except for rapeseed crop, for which we used data from Donatelli et al (2015). To calibrate CropSyst in order to obtain a close estimation of the crop yield observed, we have modified the unstressed harvest index.

The simulations are made for three soil types and six crops. For each soil type/crop bundle, the same set of simulations are run. These simulation had a different combination of N inputs (five different values) and OC soil (three different values). No production function is estimated for alfalfa. Actually, it is not possible to calibrate forage crops in CropSyst.

The results of the simulations are used to estimate the different crop production functions, for each soil type. We use the software R, and the *lm function.* All data respect the homoscedasticity condition, and there are no correlation between residues. Results of the regressions are displayed in Annex 2.

Crop (soil type)	Observed yield	Simulated yield (CropSyst)	Computed yield
Winter durum wheat (S3)	8.5 t/ha	8.516 t/ha	8.968 t/ha
Winter soft wheat (S1)	8.0 t/ha	8.061 t/ha	8.184 t/ha
Winter soft wheat (S2)	8.0 t/ha	8.016 t/ha	8.543 t/ha
Winter soft wheat (S3)	8.0 t/ha	8.014 t/ha	8.231 t/ha
Sunflower (S2)	3.5 t/ha	3.48 t/ha	3.121 t/ha
Maize grain (S2)	8.0 t/ha	8.025 t/ha	8.165 t/ha
Barley (S1)	5.4 t/ha	5.435 t/ha	5.175 t/ha
Rapeseed (S2)	3.235 t/ha	3.238 t/ha	3.471 t/ha

Table 1 – Crop yields functions validation.
(*Source: the author from CropSyst simulations*)

	Initial SOM (2008)	Observed SOM (2015)	Computed SOM (2015)
S1 parcel	1.26%	1.16 %	1.16 %
	Initial SOM (2010)	Observed SOM (2015)	Computed SOM (2015)
S2 parcel	2.42 %	2.7 %	2.21 %
	Initial SOM (2008)	Observed SOM (2015)	Computed SOM (2015)
S3 parcel	2.62%	2.28 %	2.37 %

Table 2 – SOM dynamics functions validation.
(*Source: the author from CropSyst simulations*)

4 Model validation

Here, the model validation consists in the computation of the yields and OM dynamics with the functions estimated while using the practices actually implemented by the farmer, and to compare these computations with the observed yield (see Tables 1 and 2). The computations are made in the same conditions than the calibration simulations, which are the situations for which we have data relative to farming practices and soil analysis.

The results are satisfactory for the crop yields functions estimations. For the SOM dynamics functions, the computed SOM corresponds to what is observed for the S1 parcel and S3 parcel. However, the S2 parcel computed 2015 SOM does not correspond to what is observed in the soil analysis. Since all crop yields functions are valid and the other SOM computations are consistent with reality, we assume that there is an unobserved and unknown factor that has a sufficiently high impact on S2 parcel SOM dynamics to trigger an increase in SOM, instead of a decrease. Indeed, we could not simulate all farming practices performed by the farmer on his lands, and we did not consider other soil quality parameters that impact and are impacted by SOM, due to a lack of data.

5 Scenarii tested and planning horizon

Four scenarii are simulated (see Table 3). The base scenario is built from the 2017 situation. Crop prices considered for the base scenario are mean prices over a 7 year period, in constant prices. Hence, this mean price encompasses price volatility. In this scenario, prices and costs remain constant throughout the planning horizon.

In the dynamic costs scenario, changes in N fertilizer costs and fuel price are introduced gradually (Table 3). It reflects the expected increase in N fertilizers and energy prices induced by a rarefaction of fossil energies (prospects from the French Energy and Raw Materials Division, as quoted in the professional press). The rate at which each value increases is set in order to reach the end values of 2.44 €/kg for N inputs costs and 1 €/L for fuel costs.

In the dynamic costs and carbon premium scenario, a carbon price is introduced and both inputs prices and carbon values increase throughout the planning horizon. The rate at which each value increases is set in order to reach the end values of 2.44 €/kg for N inputs costs, 1 €/L for fuel costs and 200 €/TeqCO2 for carbon prices. Here the carbon price is attached to the variation of SOM concentration in the farmer's soil. When SOM increases, the farmer will be paid proportionally, and reversely. The farmer is rewarded for increasing his soil quality (carbon sequestration), and pays to deplete his SOM stock. It corresponds to the polluter-payer principle [1]. The initial carbon price considered is the current carbon price as planned in the French law, for a value of 30.5 €/T eq CO2. The end value carbon price is an expected carbon price value for 2050. Since in 2030 the carbon price is expected to be around 100 €/T eq CO2, we extrapolated in our 2050 horizon scenario a carbon price valued at 200 €/T eq CO2 (*Ministère de l'Environnement, de l'Énergie et de la Mer*, 2016).

In the last scenario (Dynamic costs scenario+CP+alfalfa premium), in addition to carbon price, we doubled the coupled premium associated with alfalfa. It is a way to simulate a Common Agricultural Policy (CAP) incentive in favor of leguminous crops allowing carbon sequestration (Arrouays et al, 2002).

Scenarii are run for a 50 years planning horizon. We chose to not impose any terminal conditions. Results are displayed in period 30, we are in an intermediate situation, where the farmer is still in a production perspective: either the land is passed on his heir, or the land is sold. In both cases, the land continues to serve a crop production purpose. We chose to set up our model as an inter-temporal model. Hence, in our simulations, the farmer optimize his objective function over the whole time period. This allows the intertemporal environmental feedbacks of SOM changes throughout the planning horizon. Actually, from one year to another,

1. The difference in SOM content is expressed in g/kg of soil. First, we convert SOM in SOC, applying the conventional conversion factor ($SOC = SOM * 0.58$). Then, we convert from g/kg of soil to T/ha ($SOCt/ha = SOCg/kg * 0.003$). Having the value of ton of carbon per hectare, while carbon prices are in fact the price applied to TCO2eq, we convert the tons of carbon into tons of CO2 eq ($tCO2eq/ha = 3.666tC/ha$).

Parameters	N fertilizers costs (€/kg)	Fuel costs (€/L)	Carbon price (€/TeqCO2)	Discount rate	Coupled premium (alfalfa)
Scenario					
Baseline scenario	1.22	0.5	0	5%	300
Dynamic costs scenario	1.22 at T1 with an annual increase in 1.5 %	0.5 at T1, with an annual increase in 2%	0	5 %	300
Dynamic costs scenario + carbon premium (CP)	1.22 at T1 with an annual increase in 1.5 %	0.5 at T1, with an annual increase in 2%	30.5 at T1, with an annual increase in 4.7 %	5 %	300
Dynamic costs scenario + CP + Alfalfa premium	1.22 at T1 with an annual increase in 1.5 %	0.5 at T1, with an annual increase in 2%	30.5 at T1, with an annual increase in 4.7 %	5 %	600
This set of scenarii is simulated over a planning horizon of 50 years.					

Table 3 – Scenarii and base model.
(*Source: the author*)

SOM changes can be neglected, especially at average levels. It is the cumulative and continuous changes in SOM that is relevant to consider (Saliba, 1985). In addition, this feature allows for nonlinearities in constraints as in the objective function (Holden et al, 2005), which is our case. The discount rate r is equal to 5%, since it is the risk free rate for medium term horizons (between 50 and 100 years) recommended by Gollier (2002) in the case of France [2]. We used this discount rate since uncertainty is not taken into account in our model.

We used the GAMS/MINOS solver to run our simulations. The MINOS solution procedure requires to set properly the initial values of our problem, in order to obtain a solution that is both feasible and optimal. We use as initial values for our different variables, the data obtained from the farmer and his farming advisor relative to the farmer's farming practices, initial SOM and current crop rotation. We have performed the simulations of our scenarii with different set of initial values, to check whether the solutions found followed the same trends, indicating solution robustness (Smith et al, 2000).

6 Main limits of our empirical model

The biophysical software used to estimate SOM dynamics functions and crop yield functions, CropSyst, has been chosen for its ability to perform long-term simulations and rotation simulations with good performances in France. However, it only simulates dynamically SOM values through time. Other physical indicators are not taken into account.

This model has been calibrated on a particular farm, in conservation agriculture since

2. Assuming that the private discount rate r equals the social discount rate.

the 1990's. The important number of farming practices implemented on this farm could not all be properly considered and simulated here. While we consider the main farming practices impacting soil quality dynamics, there are still numerous practices that are likely to impact soil quality, and that are not taken into account, mostly because of the limitations of CropSyst. Besides, in our model, decision rules are proposed for the crop rotation choices. These rules have been established based on past farmer's choices and suggestions of a farming advisor. Nonetheless, the choices simulated in our model are constrained. These omissions reduce the levers of actions and possible strategies of the farmer.

Another limit of our model is that it does not take into account risk and uncertainty. Risk related to sustainable practices as well as market and climate risks should have been included in the analysis, in order to have a more realistic model. Apart from inter-annual climate risk, could also be considered risks induced by climate change. Indeed, crop-yield and SOM dynamics functions are sensitive to climatic conditions. Actually, climate change and the increase in temperature associated might impact negatively SOC content, even on non-agricultural lands, and could even cancel the positive impact on conservation practices on SOC content and carbon storage (Métay et al, 2009). Although through CropSyst we take into account average climatic conditions, risk or uncertainty linked to climatic conditions and their impact on crop yields are not considered. However, when considering long term planning horizon, one can assume that annual risks are smoothed over the period considered.

7 Results and Discussion

Results of the simulations are presented in Table 4.In these tables are presented the annualized objective function, the changes in endogenous practices of the farmer and the evolution of SOM stock for each scenario.

Non-intensive rotations												
	OBJ (€/ha/year)[3]		Mean residue use[4]	Tillage intensity	N inputs (kg/ha)[5]						SOM (g/kg)[6]	Crop area[7]
					S. wheat	D. wheat	Barley	Rapeseed	Maize grain	Sunflower		
Base scenario 5%	347.80	S1	1	0	180 → 190 → 180	215 → 215 → 215	140 → 140 → 140	180 → 180 → 180	150 → 150 → 150	80 → 80 → 80	11.6 → 10.86 → 7.37	3.4
		S2	0.732 → 0.7→ 0.662	0	190 → 190 → 190	150 → 215 → 215	126 → 140 → 140	124 → 180 → 180	120 → 150 → 150	80 → 80→ 60	27 → 25.09 → 15.81	82.06
		S3	0.861 → 1 → 1	0	171 → 176 → 190	170 → 215 → 226	140 → 140 → 150	138 → 180 → 180	150 → 150 → 150	80→ 80 → 60	22.8 → 21.07 → 12.87	62.36
Dynamic costs scenario (5 %)	330.83	S1	1→ 1→ 1	0 → 1 → 1	0 → 187 → 162	0 → 0 → 0	0 → 0 → 0	180 → 180 → 162	0 → 0 → 0	80→ 60 → 60	11.6 → 10.85 → 7.2	3.4 → 2.764 → 3.4 $_{T1 \to T14 \to T30}$
		S2	0.617 → 0.658 → 1	0 → 0.915 → 1	190 → 190 → 0	150 → 0 → 0	126 → 0 → 0	124 → 180 → 162	120 → 160 → 142	80 → 80 → 80	27→ 25.08 → 15.93	82.06→ 65.753 → 82.06 $_{T1 \to T26 \to T30}$
		S3	0.861 → 1 → 1	0 → 0.920 → 1	171 → 173 → 0	171 → 0 → 0	0 → 0 → 0	138 → 180 → 162	0 → 0 → 0	80 → 80 → 80	22.8→ 21.06 → 13.08	62.36→ 51.087 $_{T1 \to T30}$
Dynamic costs scenario + carbon price (5 %)	330.26	S1	1→ 1→ 1	0 → 1 → 1	0 → 190 → 0	0 → 0 → 0	0 → 0 → 0	180 → 180 → 162	0 → 0 → 0	80→ 80 → 80	11.6 → 10.85 → 7.32	3.4 → 2.9 → 2.765 $_{T1 \to T7 \to T30}$
		S2	0.732 → 0.686 → 0.473	0 → 0.859 → 1	190 → 190 → 0	150 → 236 → 0	126 → 150 → 0	124 → 180 → 0	120 → 0 → 145	80 → 80 → 80	27→ 25.08 → 15.9	82.06→ 74.782 → 82.06 $_{T1 \to T28 \to T30}$
		S3	0.861 → 1 → 1	0 → 1 → 1	171 → 173 → 0	171 → 0 → 0	0 → 0 → 0	138 → 180 → 162	0 → 0 → 0	80 → 80 → 80	22.8→ 21.05 → 13.11	62.36→ 54.168 → 49.932 $_{T1 \to T28 \to T30}$
Dynamic costs scenario + carbon price + alfafa premium (5 %)	360.79	S1	1→ 1→ 1	0 → 1 → 1	0 → 190 → 162	0 → 0 → 0	0 → 0 → 0	180 → 180 → 162	0 → 0 → 0	80→ 0 → 0	11.6 → 10.85 → 7.12	3.4 → 2.9 → 3.197 $_{T1 \to T7 \to T30}$
		S2	0.732 → 0.827 → 0.596	0 → 1 → 1	190 → 190 → 162	150 → 0 → 167	126 → 0 → 0	124 → 180 → 162	120 → 160 → 0	80 → 80 → 80	27→ 25.08 → 15.92	82.06
		S3	0.861 → 1 →0.812	0 → 0.92 → 1	171 → 173 → 162	170 → 0 → 0	0 → 0 → 0	138 → 180 → 162	0 → 0 → 0	80 → 80 → 80	22.8→ 21.06 → 12.96	62.36

Table 4 – GAMS simulations results - Long non-intensive rotations.

(*Source: the author from GAMS simulations*)

3. It corresponds to the objective function value expressed as an annuity.
4. The arrows (→) indicate a change in the horizon time. Here, the values are for period 1, 5 and 30 or 1, 3 and 5 respectively.
5. The arrows (→) indicate a change in the horizon time. Here, the values are for period 1, 5 and 30 or 1, 3 and 5 respectively.
6. The arrows (→) indicate a change in the horizon time. Here, the values are for period 1, 5 and 30 or 1 and 5 respectively.
7. The arrows (→) indicate a change in the horizon time. We precise after the value at which time period significant changes occur.

7.1 Changes in farming practices in the different scenarii

The base scenario simulation has for starting point what corresponds to the actual farming practices implemented in our study case. The annualized objective value for this scenario is 347.8 €/ha (see Table 4). Throughout the temporal horizon, we can observed an important use of crop residues. For this scenario, a regular level of N fertilizer inputs is used: 180 kg/ha for soft wheat and 80 kg/ha for durum wheat for instance (Figures 1, 2). Besides, all crop area is entirely cultivated throughout the time horizon.

When introducing a dynamic and progressive increase in N fertilizers and fuel prices, we observe as expected from our theoretical models, an average decrease in N fertilizers use for most crops (see Table 5) also observable in the N fertilization strategy depicted in Table 4 for years 1, 5 and 30. Actually, it seems to be part of the fertilization strategy to not apply any fertilization for some crops, at some period, and there is more heterogeneity in the fertilization planning through time (Figures 1, 2). One explanation is that the farmer has no interest in fertilizing some crops, especially those rarely cultivated, and for which the economic ratio between fertilizers expenses and crop yield prices is less favorable. In this scenario, residue use is similar than in the baseline case. However, tillage intensity increases. It is not systematic, but profound tillage is quite largely used. We also observe a decrease in the annualized objective value of 5% with respect to the baseline scenario.

Introducing the carbon premium does not change much the annualized objective value (-0.1 %). The N fertilization strategy is slightly different than in the simpler dynamic scenario, with lower levels of N fertilization. N fertilization levels are lower than in the baseline scenario for most crops. Residue use and tillage intensity are comparable to what is obtained for the previous dynamic scenario (Figures 1, 2). The management of cultivated crop area is slightly different than in the previous case, however the areas dedicated to each crops are very similar in the dynamic scenarii with or without carbon premium (Figure 3).

The scenario where alfalfa premium is introduced has unexpected consequences: the total crop area where alfalfa is grown in this scenario is lower than in all our previous scenarii (see Figure 3). In addition it is the dynamic scenario where almost all cropping area is cultivated, compared to the others. Residue use, tillage intensity and fertilization strategies are similar in this scenario than in the other dynamics scenarii.

Changes in scenarii do not impact the use of crop residues, which is commonly used across time and scenarii. When introducing an increase in input prices, profound tillage is practiced, which is not the case when inputs prices are constant. The increase in inputs prices trigger a global decrease in N fertilization use strategy (see Tables 4 and 5), however the crops for which N fertilizers use stay at a relatively high level are also the more cultivated, namely soft wheat and sunflower (Tables 4 and 5 and Figure 3). As a consequence, the overall amount of

N fertilizers applied may not be that much diminished between the baseline scenario and the other scenarii. Overall, the N fertilization strategies are similar across the different dynamic scenarii compared to the baseline one.

Including the baseline scenario, the principal crop rotation used in our scenarii is the rotation "*soft wheat* x*1* - *alfalfa* x *3*- *sunflower* x*1*". This might be explained by the attractiveness of alfalfa in our model: it requires none N fertilization and it has a constant yield, in addition to a coupled premium (as currently set in the common agricultural policy). Hence, with alfalfa, the farmer secures a constant revenue per hectare of 1371 €[8], while this value changes for other crops .

	Baseline scenario	Dynamic costs scenario	Dynamic costs + carbon premium scenario	Dynamic costs + carbon premium scenario + alfalfa premium
Soft wheat S1	183	117	116	110
Soft wheat S2	190	161	167	152
Soft wheat S3	184	139	127	173
Durum wheat S1	215	0	0	12
Durum wheat S2	210	35	53	34
Durum wheat S3	212	57	23	43
Sunflower S1	76	72	53	48
Sunflower S2	79	77	72	77
Sunflower S3	78	77	74	80
Rapeseed S1	180	177	177 0	177
Rapeseed S2	146	167	161	162
Rapeseed S3	1596	172	167	167
Barley S1	140	0	0	0
Barley S2	140	13	18	13
Barley S3	136	5	0	0
Maize grain S1	150	0	0	5
Maize grain S2	148	91	64	51
Maize grain S3	150	47	42	58

Table 5 – GAMS simulations results - Mean N fertilization dose applied over the planning horizon for long rotations (g/kg), per crop and soil type.
(*Source: the author from GAMS simulations*)

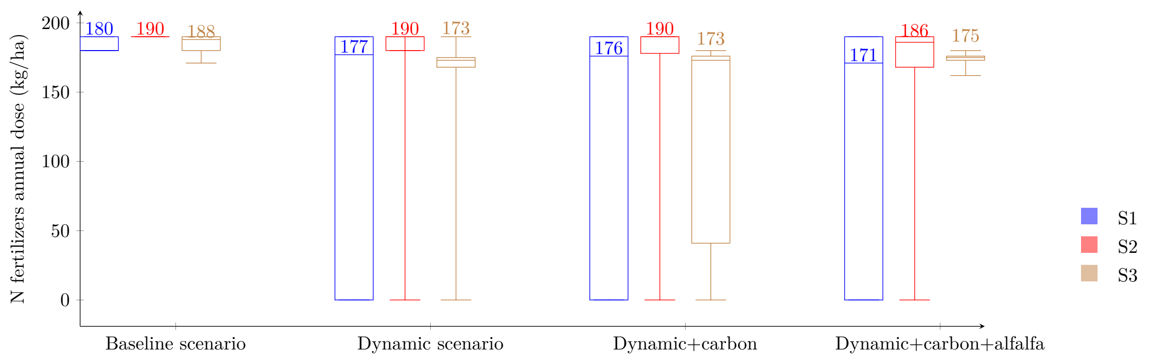

Figure 1 – Boxplot and median of the N fertilization optimal strategy over the planning horizon for soft wheat (kg/ha).
(*Source: the author from GAMS simulations*)

8. With a constant alfalfa yield price of 174.5 €/qt, a coupled premium of 150 €/ha and a constant yield of 7 qt/ha, with no N fertilization costs, without considering other charges and costs

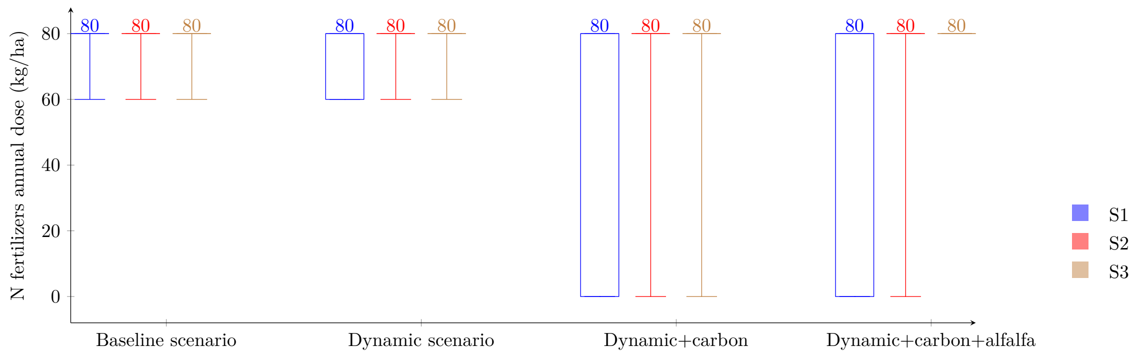

Figure 2 – Boxplot and median of the N fertilization optimal strategy over the planning horizon for sunflower (kg/ha).
(*Source: the author from GAMS simulations*)

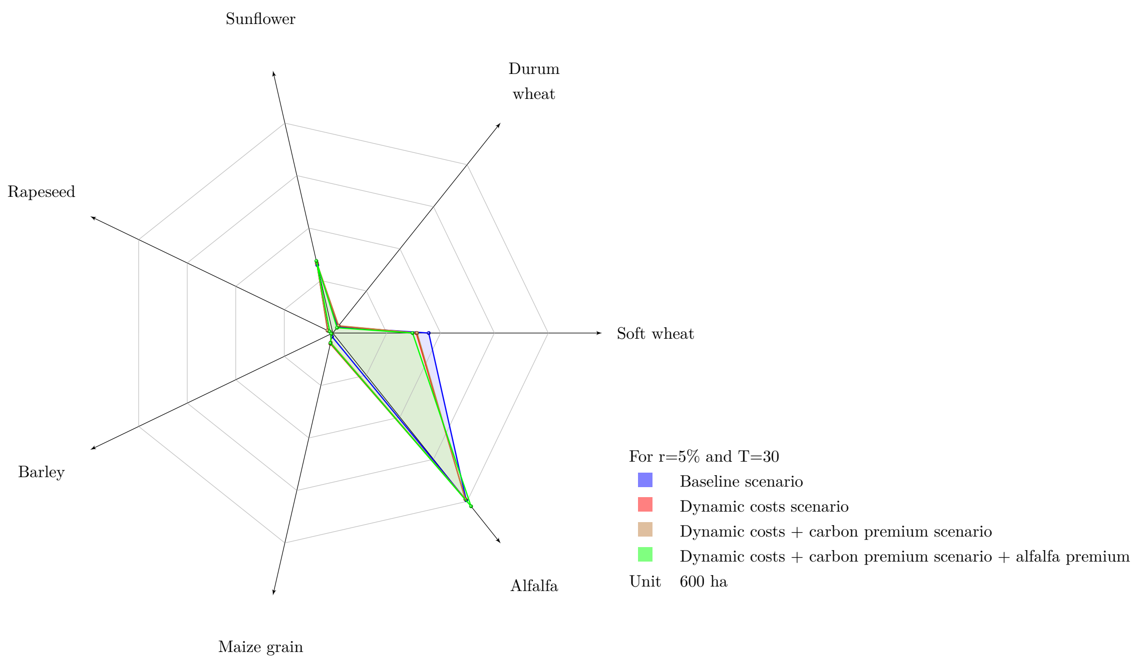

Figure 3 – Cumulated surfaces cultivated for each crop over the planning horizon (ha) .
(*Source: the author from GAMS simulations*)

7.2 Changes in SOM dynamics

In our simulations, the evolutions of SOM values are similar, despite of a decreased use of N fertilizers and a constant use of crop residues. For S1 parcel, in all scenarii, SOM end values range between 7.12 g/kg and 7.38 g/kg at year 30. SOM end values in S2 parcel range between 15.81 g/kg and 16.05 g/kg, while in S3 parcel, they are comprised between 12.87 g/kg and 13.11 g/kg (see Figures 4, 5, 6). In all scenarii, we observe a decrease in SOM, that cannot be efficiently mitigate by the economic instruments tested.

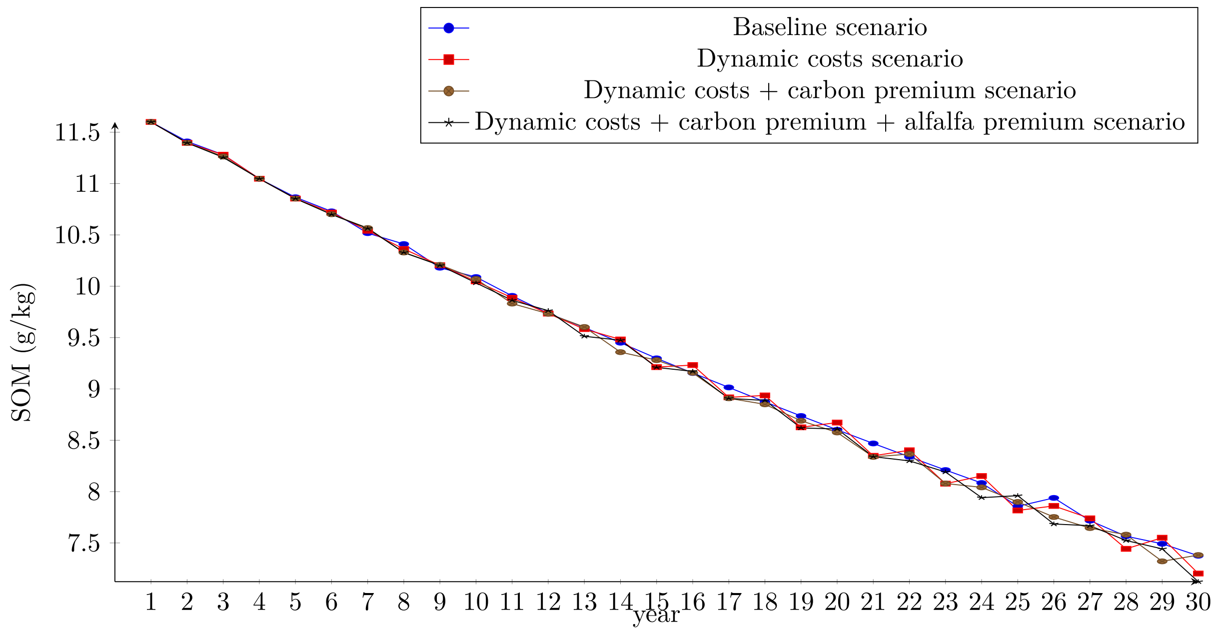

Figure 4 – SOM dynamics in parcel S1 for the different scenarii (Long-term optimization and discount rate 5 %)
(*Source: the author from GAMS simulations*)

In the baseline case, at the end of the time horizon, the stocks of SOM have decreased in all soil types. For soil type 1, SOM has decreased by 36.4 %, and by 41.4 % and 43.55 % respectively for soil type 2 and 3. It seems that the economic instruments simulated here do not favor SOM conservation (Table 4 and Figures 4, 5, 6).

It is in parcel S1 that more fluctuations can be observed in SOM dynamics. It is due to the changes in area cultivated for S1 which fluctuates earlier in the planning horizon for S1 than for the other soil types. As a result, SOM dynamics is less linear than for the other parcels.

A significant difference in SOM dynamics appears between year 12 and 19 for the S2 parcel (see Figure 5) in favor of the baseline scenario. It is explained by crop rotation choices. Actually, alfalfa is massively grown on this parcel during the previous years, leading to a temporary higher level of SOM in the baseline scenario.

7.3 Impacts on crop yields

Table 6 presents the changes in crop yields throughout the time horizon. What can be first noticed is that crop yields evolutions are mostly the same in all scenarii. These results are explained by the similar N inputs strategies and the fairly similar amounts of SOM at the end period of all our scenarii. Actually, the impact of SOM on crop yields is the most apparent in the difference between first-period and end-period yields in the same scenario (provided that

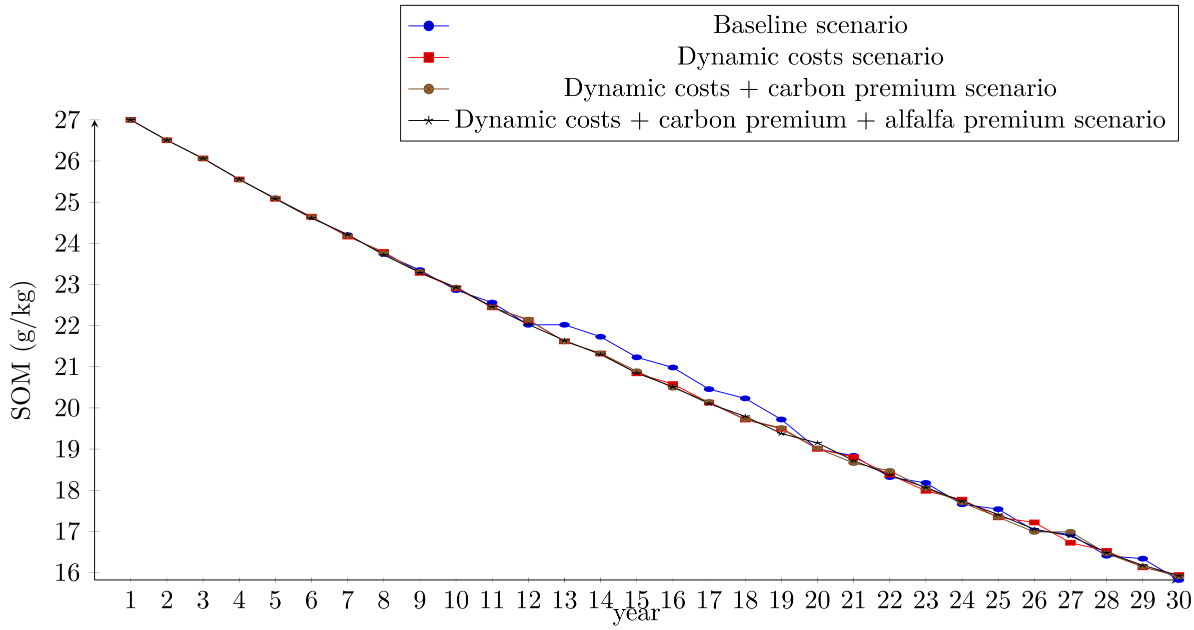

Figure 5 – SOM dynamics in parcel S2 for the different scenarii (Long-term optimization and discount rate 5 %)
(*Source: the author from GAMS simulations*)

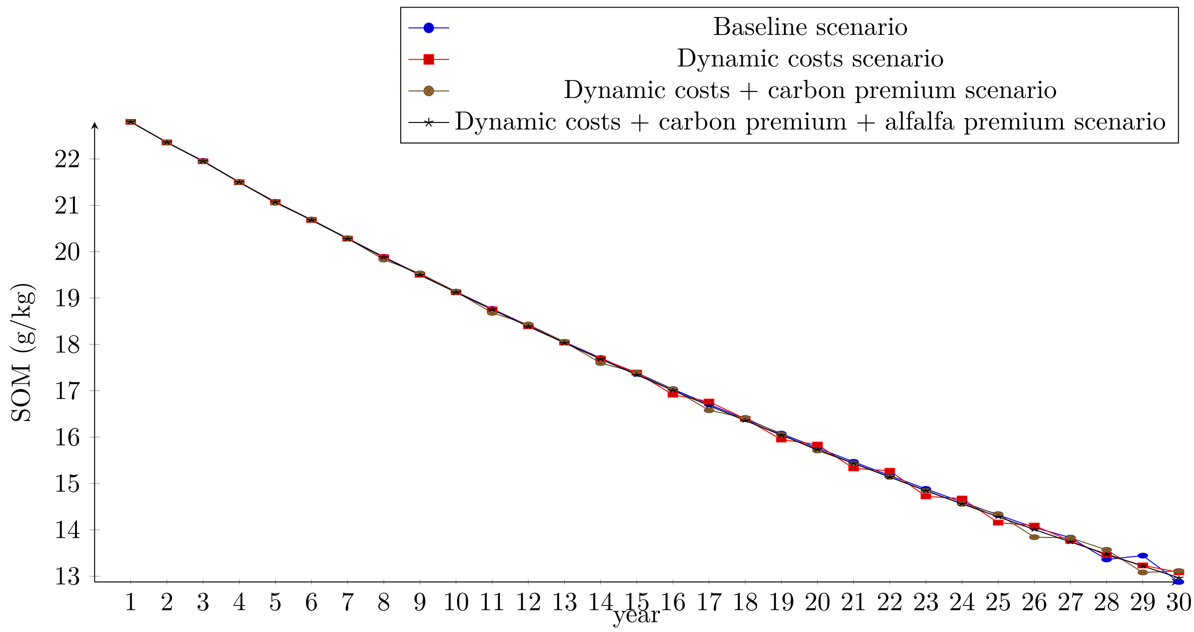

Figure 6 – SOM dynamics in parcel S3 for the different scenarii (Long-term optimization and discount rate 5 %)
(*Source: the author from GAMS simulations*)

the level of N fertilization does not vary too much), than in the difference between end-period yields of scenarii having the same N inputs (see Table 4).

From Table 6, it appears that the decrease in SOM has a negative impact that differs from crops and soil type. For instance for soft wheat, for similar (in S1 and S2) and higher (in S3) N fertilization, crop yield decreases in 3.7% on S1, 12.8 % in S2 and 4.8 % in S3. When the decrease in SOM is coupled with a decrease or an absence in N fertilizers, the decrease in crop yield is very important. However, the decrease in crop yield due to a lack of N fertilization is far more important that the one cause by a decrease in SOM.

Long rotations scenarii							
scenarii	*Soil type*	Soft wheat yield (qt/ha)[9]	Durum wheat yield (qt/ha)	Barley yield (qt/ha)	Rapeseed yield (qt/ha)	Maize grain yield (qt/ha)	Sunflower yield (qt/ha)
Base scenario (5%)	S1	79 → 80 → 76	82 → 81 → 78	54 →53 → 51	22 → 22 → 20	49 → 49 → 44	30 → 25 →26
	S2	109 → 106 → 95	88 → 90 → 85	61 → 62 → 58	33 →23 → 32	79 → 80→ 71	46 → 45 → 32
	S3	82 → 82 → 78	87 → 89 → 84	61 → 60 → 58	32 →33 → 31	74 → 73 → 64	41 →40 → 29
Dynamic costs scenario (5%)	S1	29 → 79 → 73	36 → 34 → 26	18 → 17 → 12	22 → 22 →20	28 → 26 → 18	30 → 25 →22
	S2	109 → 107 → 33	88→ 64 → 47	62 → 34 → 24	33 →34 →31	79 → 80 → 69	46 → 45 →37
	S3	82 → 81 → 30	87 → 59 → 43	32 → 30 → 21	32 → 33 → 30	52 → 49 →31	41 → 40 →33
Dynamic costs scenario + carbon price (5%)	S1	29 → 79 → 22	36 → 34 → 26	18 → 17 → 12	22 → 22 →20	28 → 26 → 18	30 → 9 → 26
	S2	109 → 107 → 33	88→ 64 → 48	62 → 34 → 24	33 →34 →17	79 → 80 → 70	46 → 45 →37
	S3	82 → 81 → 30	87 → 59 → 43	32 → 30 → 21	32 → 33 → 30	52 → 49 →31	41 → 40 →33
Dynamic costs scenario + carbon price + alfafa premium (5%)	S1	29 → 79 → 73	36 → 34 → 26	18 → 17 → 12	22 → 22 →20	28 → 26 → 18	30 → 9 → 6
	S2	109 → 107 → 90	88→ 64 → 81	62 → 34 → 23	33 →34 →31	79 → 80 → 35	46 → 45 →37
	S3	82 → 81 → 75	87 → 59 → 43	32 → 30 → 20	32 → 33 → 30	52 → 49 →31	41 → 40 →33

Table 6 – GAMS simulations results - Crop yields at the beginning and at the end of the planning horizon (Long rotations).
(*Source: the author from GAMS simulations*)

7.4 Changes in profitability in the different scenarii

The evolution of the expected profit throughout the planning horizon is not linear (see Figures 7). These fluctuations are mainly due to crop rotation choices and changes in the total area cultivated.

Consistently with the annualized objective values per hectare of Table 4, the expected profit curves of the baseline scenario and the alfalfa premium scenario are overall higher than the curves of the other two scenarii. The alfalfa premium more than compensates for the increase in prices, while having no significant impact on farming practices or alfalfa surfaces. This is the illustration of a dead-weight effect.

Actually, the expected profits do not decrease much throughout the planning horizon, and the fluctuation in profits cannot be explained by the linear decreasing SOM curves. Actually, the impact of SOM on crop yields is much lower than the impact of N fertilizers. Hence, the

8. The arrows (→) indicate a change in the horizon time. Here, the values are for period 1, 5 and 30 respectively.

impact of SOM on crop yield is advantageously compensated for by the use of N fertilizers for the most grown crops, as shown by the relatively constant expected profits through time. Actually the fairly constant expected profits across time and scenarii suggest that the increase in inputs prices as simulated here, following current projections, does not jeopardize the farmer's revenue.

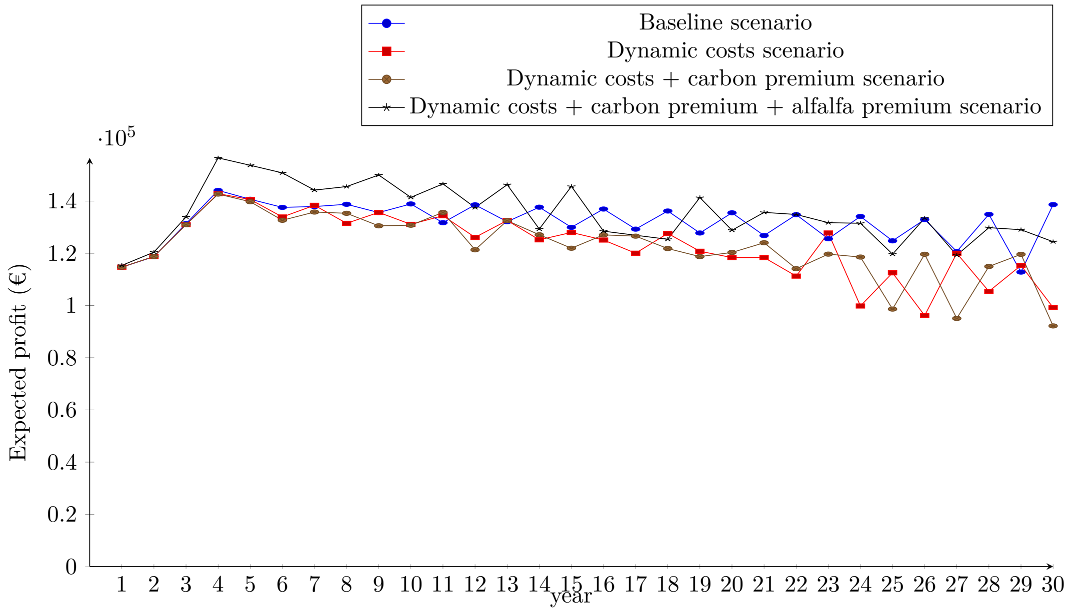

Figure 7 – Evolution of expected profits for the different scenarii (Long-term optimization and discount rate 5 %)
(*Source: the author from GAMS simulations*)

7.5 Tillage intensity choices in the dynamic scenarii: deep tillage in optimal strategies, a counter-intuitive result ?

In all our dynamic scenarii, which all have in common a continuous increase in fuel and N fertilizers prices, we observe an important use of deep tillage in the optimal strategies of the farmer. However, one of our hypothesis is that deep tillage is detrimental to numerous aspects of soil quality (auxiliaries, soil structure disturbance). At the contrary, a shallow tillage associated with sound crop residue use and crop rotation is beneficial to soil quality.

Nonetheless, deep tillage is favored in our dynamic scenarii. Actually, when looking at our SOM dynamics functions estimated from CropSyst simulations, it appears that depending on soil type and crops, deep tillage can have a positive impact on SOM dynamics. This is the case for soft wheat on S3, for maize grain, sunflower and rapeseed. In addition, in all our dynamic scenarii, we observe in average an important decrease in N fertilizers, as a reaction to the anticipated increase in N fertilizer prices. Since for numerous crops and soil type N fertilizers and tillage intensity are not cooperating in terms of SOM dynamics, the decrease in N fertilizers can trigger an increase in tillage intensity, especially in cases where tillage intensity have a small yet positive impact on SOM dynamics.

Hence, in our dynamic scenarii, the farmer invests in his soil quality through tillage, which otherwise only represents an extra-cost. Nonetheless, we observe a linear decrease in SOM content in our simulations. One explanation is that the levers in terms of farming practices put at the disposal of the farmer in our model are not sufficiently efficient in terms of SOM depletion mitigation to trigger an inversion of the SOM dynamics curves, regardless of the scenario considered.

8 Conclusion

The objective of this article was to built an empirical model in order to establish whether indeed, adopting and agroecology decision making process can allow farmers to achieve a productive, profitable and sustainable agriculture in a context where fertilizers and energy prices are rising.

The study case approach has allowed us to collect a sufficient amount of data to estimate a production function for the main crops grown on the farm, and to estimate soil organic matter dynamics functions specific to each of these crops and the main soil types of the farm. Once the model designed, different scenarii are proposed. The baseline scenario is established from the current economic situation with constant prices and costs throughout the planning horizon. The other scenarii are variations from this baseline scenario, with changes in energy price and N fertilizer price, as well as the introduction of a carbon price and an extra alfalfa premium.

Our results show that the use of long rotations, lower levels of N fertilizers as well as an important use of residues in most periods, lead to an optimum in the dynamic scenarii, where the most grown crops are soft wheat, alfalfa and sunflower. The farmer invests in his soil quality through the use of tillage. The different scenarii have also an important impact on the cultivated area, that can dramatically decrease, jeopardizing the farmer's revenue. Through our results, it appears that economic incentives to increase SOM have no significant impact on SOM dynamics.

However SOM stocks decrease linearly in all scenarii to reach SOM end values for each soil type that are fairly close in all scenarii. Considering SOM as a proxy for soil quality, the outcomes of our simulations do not meet the objective of agroecology to have a sustainable use of soil ecosystem services, since soil resource quality is depleted in the long run in all our scenarii, regardless of the initial SOM endowment.

This suggests that one cannot hope to increase significantly his soil quality by monitoring only N fertilizers, tillage intensity and crop residue use. Such practices do play their role, but have to be integrated in a larger set of practices to be really efficient to increase SOM content in soils. Actually, the farmer of our study case uses a more important set of practices to monitor his soil quality. In addition, the economic context is still favorable to the use of N fertilizers as a substitute for SOM in terms of crop production.

Acknowledgements

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Annex 1: SOM regression results - CropSyst

The levels of N fertilizers simulated to estimate the SOM dynamics functions for each crop are the following (see Table 7).

Inorganic nitrogen inputs level	Durum wheat	Soft wheat	Barley	Maize	Sunflower	Rapeseed	Alfalfa
N0	0	0	0	0	0	0	0
N1	215	180	140	150	60	180	50
N2	300	300	250	300	120	300	100

Table 7 – The different levels of nitrogen fertilizers applied, per crop.
(*Source: from the author*)

Two sets of tillage practices are designed: one under conventional tillage, and one with superficial till (see Table 8). These two scenarii are based on the statements of the farmer (for the superficial till scenario) and on two technical documents from the Chambers of Agriculture of *Languedoc Rousillon* (2009) and *Nouvelle-Calédonie* (undated) as well as statements of the farmer's counselor (for the conventional till scenario).

		Till scenario		**Superficial till scenario**
	Residue use	Activity - tool used	CropSyst Activities	Activity - tool used
Step 1	Residue left	Shredder	RESIDUE (FLAIL, CHOP, BUST)	Shredder
	Residue removed	Shredder	-	Shredder
Step 2	Residue left	*Cover crop* - shallow stubble cultivation	15 - PRIMARY DISC PLOW SHALLOW	*Cover crop* - shallow stubble cultivation
	Residue removed	-	-	-
Step 3		Till, deep	19 - PRIMARY MOLDBOARD 15 - PRIMARY DISC PLOW SHALLOW	*Cover crop*
Step 4		Superficial secondary tillage - *Outil à dents*	35 - SPRING TOOTH CULTIVATOR	Superficial secondary tillage - *Outil à dents*
Step 5		Seeding (*semoir à dents*)	52 - HOE DRILL	Seeding (*semoir à dents)*

Table 8 – Two tillage crop managements: Till (T1) and No-Till (T0).
(*Source: from the author*)

Explaining variables	Explained variable					
	SOM variation when growing soft wheat					
Soil type	S1		S2		S3	
	Est.	p.value	Est.	p.value	Est.	p.value
Intercept	-1.080e-02	8.18e-07 ***	3.520e-02	5.54e-05 ***	-0.014191882	0.0054 **
N fertilizers inputs	1.243e-04	9.68e-15 ***	-1.113e-04	0.00179 **	0.000126129	< 2e-16 ***
N fertilizers inputs second order effect	-2.327e-07	1.03e-11 ***	4.198e-08	0.61532	-0.000000204	0.0001 ***
Initial soil organic matter	-1.693e-02	< 2e-16 ***	-1.895e-02	< 2e-16 ***	-0.020102221	< 2e-16 ***
Initial soil organic matter second order effect	3.708e-06	0.105	3.842e-06	0.69553	0.000005783	0.3983
Tillage intensity	-2.887e-04	0.799	-2.400e-17	1.000	0.001569264	0.2375
Residue use (left or not)	5.835e-03	2.80e-05 ***	-2.605e-02	2.41e-05 ***	0.008270744	0.0001 ***
Cross effect of soil organic matter and N fertilizers inputs	-8.708e-07	2.03e-06 ***	1.494e-06	0.02253 **	-0.000001081	0.0099**
Cross effect of N fertilizers inputs and tillage intensity	-1.049e-06	0.748	6.243e-20	1.000	0.000000322	0.9379
Cross effect of N fertilizers inputs and residue use	5.494e-06	0.103	1.106e-04	7.35e-08 ***	0.000005526	0.3946
Cross effect of tillage intensity and residue use	-8.519e-04	0.293	-1.496e-17	1.00	-0.001099151	0.3320
Cross effect of soil organic matter and residue use	-2.556e-04	1.17e-07 ***	-6.458e-05	0.67012	-0.000347168	< 2e-16 ***
Cross effect of soil organic matter and tillage intensity	1.799e-05	0.601	6.251e-19	1.000	-0.000021166	0.5721
Number of observations	36		36		36	
Multiple R-squared	1		0.9996			
Adjusted R-squared	1		0.9994			
Signif. codes : 0.001***, 0.01**, 0.05*, 0.1·						

Table 9 – CropSyst Simulations - Soft wheat soil OM dynamics regressions results. (*Source: the author from CropSyst simulations*)

Explaining variables	Explained variable					
	SOM variation when growing durum wheat					
Soil type	S1		S2		S3	
	Est.	p.value	Est.	p.value	Est.	p.value
Intercept	-1.268e-02	1.62e-07 ***	-0.005051624	0.8194	-6.198e-03	0.47708
N fertilizers inputs	1.122e-04	2.06e-12 ***	0.000164898	0.0094**	1.430e-04	0.00223 **
N fertilizers inputs second order effect	-1.702e-07	5.07e-07 ***	-0.000000140	0.4694	-2.293e-07	0.07630 .
Initial soil organic matter	-1.683e-02	< 2e-16 ***	-0.020478200	< 2e-16 ***	-2.087e-02	< 2e-16 ***
Initial soil organic matter second order effect	2.749e-06	0.24249	0.000043604	0.1542	1.933e-05	0.10493
Tillage intensity	-7.513e-04	0.53541	-0.003598741	0.3566	-1.023e-02	0.09988 .
Residue use (left or not)	9.095e-03	9.85e-08 ***	0.008425523	0.1559	1.485e-02	0.02056 *
Cross effect of soil organic matter and N fertilizers inputs	-1.181e-06	1.72e-08 ***	-0.000003549	0.0289 *	-1.242e-06	0.08929 .
Cross effect of N fertilizers inputs and tillage intensity	-1.379e-06	0.67723	-0.000019962	0.1040 .	2.151e-05	0.20143
Cross effect of N fertilizers inputs and residue use	1.109e-05	0.00253 **	-0.000010192	0.6148	-1.114e-05	0.50274
Cross effect of tillage intensity and residue use	-9.877e-04	0.24405	0.004841112	0.1293	3.543e-03	0.39973
Cross effect of soil organic matter and residue use	-2.414e-04	5.84e-07 ***	-0.000134727	0.4320	-3.453e-04	0.06303 .
Cross effect of soil organic matter and tillage intensity	4.134e-05	0.25441	0.000290453	0.0128 **	1.189e-04	0.50787
Number of observations	36		36		36	
Multiple R-squared	1				0.9996	
Adjusted R-squared	1				0.9993	
Signif. codes : $0.001^{***}, 0.01^{**}, 0.05^{*}, 0.1^{\cdot}$						

Table 10 – CropSyst Simulations - Durum wheat soil OM dynamics regressions results. (*Source: the author from CropSyst simulations*)

Explaining variables	Explained variable					
	SOM variation when growing barley					
Soil type	S1		S2		S3	
	Est.	p.value	Est.	p.value	Est.	p.value
Intercept	-1.391e-02	0.00951 **	-1.238e-02	0.062027 .	-1.242e-02	0.042402 *
N fertilizers inputs	2.085e-04	3.71e-08 ***	2.235e-04	7.11e-07 ***	2.117e-04	4.17e-07 ***
N fertilizers inputs second order effect	-4.359e-07	2.38e-05 ***	-4.713e-07	0.000187 ***	-4.486e-07	0.000121 ***
Initial soil organic matter	-1.676e-02	< 2e-16 ***	-1.900e-02	< 2e-16 ***	-2.003e-02	< 2e-16 ***
Initial soil organic matter second order effect	2.960e-06	0.65996	4.733e-06	0.584088	3.264e-06	0.679657
Tillage intensity	-6.338e-03	0.07613 .	-1.202e-02	0.011566 *	-1.022e-02	0.018009 *
Residue use (left or not)	2.024e-02	4.80e-06 ***	2.000e-02	0.000137 ***	2.098e-02	2.64e-05 ***
Cross effect of soil organic matter and N fertilizers inputs	-2.058e-06	0.00043 ***	-2.064e-06	0.003884 **	-2.004e-06	0.002442 **
Cross effect of N fertilizers inputs and tillage intensity	-6.428e-07	0.95667	5.408e-06	0.722096	3.132e-06	0.821905
Cross effect of N fertilizers inputs and residue use	3.152e-05	0.01297 *	2.653e-05	0.090587 .	2.899e-05	0.046185 *
Cross effect of tillage intensity and residue use	4.259e-03	0.08854 .	1.123e-02	0.001318 **	8.543e-03	0.005877 **
Cross effect of soil organic matter and residue use	-3.789e-04	0.00119 **	-5.851e-04	0.000185 ***	-5.209e-04	0.000251 ***
Cross effect of soil organic matter and tillage intensity	2.609e-04	0.01809 *	4.582e-04	0.002011 **	4.005e-04	0.002953 **
Number of observations	36		36		36	
Multiple R-squared	0.9998		1		0.9996	
Adjusted R-squared	0.9997		0.9999		0.9993	
Signif. codes : $0.001^{***}, 0.01^{**}, 0.05^{*}, 0.1^{\cdot}$						

Table 11 – CropSyst Simulations - Barley soil OM dynamics regressions results.
(*Source: the author from CropSyst simulations*)

Explaining variables	Explained variable					
	SOM variation when growing maize grain					
Soil type	S1		S2		S3	
	Est.	p.value	Est.	p.value	Est.	p.value
Intercept	-1.019e-02	0.001153 **	-1.051e-02	0.000810 ***	-1.004e-02	0.001030 **
N fertilizers inputs	1.296e-04	2.12e-10 ***	1.405e-04	3.91e-11 ***	1.286e-04	1.47e-10 ***
N fertilizers inputs second order effect	-2.488e-07	5.93e-08 ***	-2.765e-07	8.38e-09 ***	-2.535e-07	2.70e-08 ***
Initial soil organic matter	-1.634e-02	$<$ 2e-16 ***	-1.856e-02	$<$ 2e-16 ***	-1.959e-02	$<$ 2e-16 ***
Initial soil organic matter second order effect	2.624e-06	0.488710	2.823e-06	0.453943	1.556e-06	0.672063
Tillage intensity	8.607e-04	0.655229	8.204e-07	0.999658	5.758e-04	0.758645
Residue use (left or not)	1.471e-02	7.62e-08 ***	1.520e-02	3.93e-08 ***	1.580e-02	1.39e-08 ***
Cross effect of soil organic matter and N fertilizers inputs	-1.012e-06	0.000261 ***	-9.578e-07	0.000437 ***	-8.723e-07	0.000892 ***
Cross effect of N fertilizers inputs and tillage intensity	-5.247e-06	0.349086	-4.444e-06	0.423586	-4.691e-06	0.388998
Cross effect of N fertilizers inputs and residue use	3.080e-05	1.04e-05 ***	3.086e-05	9.27e-06 ***	3.049e-05	8.22e-06 ***
Cross effect of tillage intensity and residue use	-3.086e-03	0.031161 *	-1.617e-03	0.238444	-2.778e-03	0.044781 *
Cross effect of soil organic matter and residue use	-5.497e-04	1.81e-09 ***	-6.399e-04	8.85e-11 ***	-6.060e-04	1.70e-10 ***
Cross effect of soil organic matter and tillage intensity	1.014e-06	0.986103	3.033e-05	0.600990	9.140e-06	0.871833
Number of observations	36		36		36	
Multiple R-squared	0.9999		0.9999		1	
Adjusted R-squared	0.9999		0.9999		0.9999	
Signif. codes : $0.001^{***}, 0.01^{**}, 0.05^{*}, 0.1^{\cdot}$						

Table 12 – CropSyst Simulations - Maize grain soil OM dynamics regressions results. (*Source: the author from CropSyst simulations*)

Explaining variables	Explained variable					
	SOM variation when growing sunflower					
Soil type	S1		S2		S3	
	Est.	p.value	Est.	p.value	Est.	p.value
Intercept	-2.287e-02	4.10e-06 ***	-2.041e-02	2.18e-05 ***	-1.959e-02	4.47e-05 ***
N fertilizers inputs	2.928e-04	4.35e-07 ***	2.515e-04	4.86e-06 ***	2.335e-04	1.67e-05 ***
N fertilizers inputs second order effect	-8.719e-07	0.00429 **	-7.034e-07	0.01848 *	-6.481e-07	0.03079 *
Initial soil organic matter	-1.549e-02	< 2e-16 ***	-1.784e-02	< 2e-16 ***	-1.889e-02	< 2e-16 ***
Initial soil organic matter second order effect	-8.510e-07	0.87096	1.092e-06	0.83623	-3.453e-07	0.94865
Tillage intensity	7.259e-03	0.01150 *	7.029e-03	0.01470 *	7.455e-03	0.01126 *
Residue use (left or not)	2.111e-02	4.43e-08 ***	2.231e-02	1.94e-08 ***	2.299e-02	1.51e-08 ***
Cross effect of soil organic matter and N fertilizers inputs	-3.933e-06	7.30e-05 ***	-2.937e-06	0.00162 **	-2.948e-06	0.00180 **
Cross effect of N fertilizers inputs and tillage intensity	-2.346e-05	0.23101	-2.330e-05	0.23766	-2.377e-05	0.23565
Cross effect of N fertilizers inputs and residue use	1.043e-04	1.46e-05 ***	1.085e-04	9.57e-06 ***	1.080e-04	1.25e-05 ***
Cross effect of tillage intensity and residue use	-1.286e-02	5.07e-07 ***	-1.302e-02	4.74e-07 ***	-1.402e-02	1.84e-07 ***
Cross effect of soil organic matter and residue use	4.255e-05	0.59975	1.855e-05	0.82003	2.548e-05	0.75835
Cross effect of soil organic matter and tillage intensity	-2.345e-04	0.00749 **	-2.251e-04	0.01036 *	-2.416e-04	0.00715 **
Number of observations	36		36		36	
Multiple R-squared	0.9999		0.9999		0.9999	
Adjusted R-squared	0.9998		0.9998		0.9998	
Signif. codes : 0.001***, 0.01**, 0.05*, 0.1·						

Table 13 – CropSyst Simulations - Sunflower soil OM dynamics regressions results. (*Source: the author from CropSyst simulations*)

Explaining variables	Explained variable					
	SOM variation when growing rapeseed					
Soil type	S1		S2		S3	
	Est.	p.value	Est.	p.value	Est.	p.value
Intercept	-1.811e-02	7.32e-05 ***	-1.660e-02	2.14e-05 ***	-1.499e-02	8.16e-05 ***
N fertilizers inputs	1.164e-04	3.67e-07 ***	1.019e-04	1.83e-07 ***	9.169e-05	9.22e-07 ***
N fertilizers inputs second order effect	-1.857e-07	0.000418 ***	-1.536e-07	0.00048 ***	-1.406e-07	0.00109 **
Initial soil organic matter	-1.555e-02	< 2e-16 ***	-1.752e-02	< 2e-16 ***	-1.872e-02	< 2e-16 ***
Initial soil organic matter second order effect	-3.155e-06	0.538932	-2.841e-06	0.50974	-2.827e-06	0.51017
Tillage intensity	6.437e-03	0.021559 *	5.338e-03	0.02287 *	5.732e-03	0.01502 *
Residue use (left or not)	2.421e-02	3.10e-09 ***	2.666e-02	1.65e-11 ***	2.706e-02	1.13e-11 ***
Cross effect of soil organic matter and N fertilizers inputs	-1.519e-06	7.74e-05 ***	-1.445e-06	1.57e-05 ***	-1.306e-06	5.45e-05 ***
Cross effect of N fertilizers inputs and tillage intensity	-8.382e-06	0.268848	-6.205e-06	0.32752	-6.222e-06	0.32451
Cross effect of N fertilizers inputs and residue use	2.887e-05	0.000717 ***	2.251e-05	0.00140 **	2.229e-05	0.00149 **
Cross effect of tillage intensity and residue use	-1.428e-02	6.18e-08 ***	-1.365e-02	6.21e-09 ***	-1.457e-02	1.77e-09 ***
Cross effect of soil organic matter and residue use	-2.207e-04	0.009565 **	-3.340e-04	3.63e-05 ***	-3.105e-04	8.46e-05 ***
Cross effect of soil organic matter and tillage intensity	-2.050e-04	0.015137 *	-1.737e-04	0.01421 *	-1.895e-04	0.00798 **
Number of observations	36		36		36	
Multiple R-squared	0.9999		0.9999		0.9999	
Adjusted R-squared	0.9998		0.9998		0.9999	
Signif. codes : $0.001^{***}, 0.01^{**}, 0.05^{*}, 0.1^{\cdot}$						

Table 14 – CropSyst Simulations - Rapeseed soil OM dynamics regressions results. (*Source: the author from CropSyst simulations*)

Explaining variables	Explained variable					
	SOM variation when growing alfalfa					
Soil type	S1		S2		S3	
	Est.	p.value	Est.	p.value	Est.	p.value
Intercept	3.137e-02	0.000452 ***	3.520e-02	5.54e-05 ***	3.451e-02	6.82e-05 ***
N fertilizers inputs	-4.353e-04	0.000277 ***	-3.338e-04	0.00179 **	-3.945e-04	0.000356 ***
N fertilizers inputs second order effect	1.207e-06	0.143384	3.778e-07	0.61532	8.222e-07	0.277687
Initial soil organic matter	-1.629e-02	< 2e-16 ***	-1.895e-02	< 2e-16 ***	-1.989e-02	< 2e-16 ***
Initial soil organic matter second order effect	-6.395e-06	0.545404	3.842e-06	0.69553	1.694e-06	0.862461
Tillage intensity	-4.096e-19	1.0000	-2.713e-17	1.000	-3.474e-17	1.000
Residue use (left or not)	-2.754e-02	32.98e-05 ***	-2.605e-02	2.41e-05 ***	-2.611e-02	2.26e-05 ***
Cross effect of soil organic matter and N fertilizers inputs	2.843e-06	0.162321	4.483e-06	0.02253 *	4.423e-06	0.023812 *
Cross effect of N fertilizers inputs and tillage intensity	7.249e-20	1.000	2.347e-19	1.00	2.166e-19	1.0000
Cross effect of N fertilizers inputs and residue use	3.659e-04	4.75e-08 ***	3.319e-04	7.35e-08 ***	3.274e-04	8.80e-08 ***
Cross effect of tillage intensity and residue use	-1.294e-17	1.0000	-1.951e-17	1.0000	2.054e-18	1.00
Cross effect of soil organic matter and residue use	-1.192e-04	0.466083	-6.458e-05	0.67012	-4.753e-05	0.752993
Cross effect of soil organic matter and tillage intensity	8.588e-20	1.000	7.266e-19	1.000	6.567e-19	1.000000
Number of observations	36		36		36	
Multiple R-squared	0.9995		0.9996		0.9997	
Adjusted R-squared	0.9992		0.9994		0.9995	
Signif. codes : $0.001^{***}, 0.01^{**}, 0.05^{*}, 0.1^{\cdot}$						

Table 15 – CropSyst Simulations - Alfalfa soil OM dynamics regressions results. (*Source: the author from CropSyst simulations*)

Inorganic nitrogen inputs level	Durum wheat	Soft wheat	Barley	Maize	Sunflower	rapeseed
N0	0	0	0	0	0	0
N1	50	45	35	35	15	45
N2	107	90	70	75	30	90
N3	215	180	140	150	60	180
N4	300	300	250	300	120	300

Table 16 – The different levels of nitrogen fertilizers applied, per crop. (*Source: from the author*)

Annex 2: Crop yield regressions results - CropSyst

The various values of nitrogen fertilizers inputs and OM soil contents are determined using the farmer's practices and soil analysis as a benchmark. For nitrogen fertilizers inputs levels, five levels are distinguished (see Table 16).

Explaining variables	Explained variable					
Crop	Soft Wheat yield					
Soil type	S1		S2		S3	
	Est.	p.value	Est.	p.value	Est.	p.value
Intercept	1.030e+01	0.061735 .	1.105e+01	0.020984 *	8.745e+00	0.0722 .
N fertilizers inputs	4.868e-01	< 2e-16 ***	4.837e-01	< 2e-16 ***	4.651e-01	< 2e-16 ***
N fertilizers inputs second order effect	-8.436e-04	1.07e-12 ***	-8.228e-04	2.36e-14 ***	-7.686e-04	4.45e-13 ***
Soil organic matter	1.740e+00	0.000353 ***	1.505e+00	0.000321 ***	1.833e+00	3.60e-05 ***
Soil organic matter second order effect	-1.056e-02	0.208656	-6.048e-03	0.398329	-1.151e-02	0.1229
Cross effect of soil organic matter and N fertilizers inputs	-4.839e-03	6.96e-10 ***	-4.771e-03	1.86e-11 ***	-4.897e-03	2.08e-11 ***
Number of observations	47		47		47	
Multiple R-squared	0.9284		0.948		0.9424	
Adjusted R-squared	0.9192		0.9413		0.935	
Signif. codes : 0.001***, 0.01**, 0.05*, 0.1·						

Table 17 – CropSyst Simulations - Soft wheat production regressions results. (*Source: the author from CropSyst simulations*)

Explaining variables	Explained variable					
Crop	Durum Wheat yield					
Soil type	S1		S2		S3	
	Est.	p.value	Est.	p.value	Est.	p.value
Intercept	9.864e+00	0.03124 *	12.4465642	0.01413 *	1.344e+01	0.00951 **
N fertilizers inputs	4.013e-01	< 2e-16 ***	3.695e-01	7.19e-16 ***	0.3594484	7.79e-16 ***
N fertilizers inputs second order effect	-5.521e-04	9.67e-10 ***	-5.031e-04	6.78e-08 ***	-0.0004924	1.51e-07 ***
Soil organic matter	2.516e+00	2.81e-08 ***	2.693e+00	4.83e-08 ***	2.7424617	4.70e-08 ***
Soil organic matter second order effect	-1.972e-02	0.00572 **	-2.451e-02	0.00201 **	-0.0262222	0.00124 **
Cross effect of soil organic matter and N fertilizers inputs	-5.879e-03	.61e-15 ***	-5.643e-03	2.71e-13 ***	-0.0054962	9.60e-13 ***
Number of observations	47		47		47	
Multiple R-squared	0.9437		0.922		0.9149	
Adjusted R-squared	0.9365		0.912		0.904	
Signif. codes : $0.001^{***}, 0.01^{**}, 0.05^{*}, 0.1^{\cdot}$						

Table 18 – CropSyst Simulations - Durum wheat production regressions results. (*Source: the author from CropSyst simulations*)

Explaining variables	Explained variable					
Crop	Barley yield					
Soil type	S1		S2		S3	
	Est.	p.value	Est.	p.value	Est.	p.value
Intercept	3.084e+00	0.3347	3.6573376	0.2274	4.174e+00	0.1627
N fertilizers inputs	4.219e-01	< 2e-16 ***	0.4254657	< 2e-16 ***	4.225e-01	< 2e-16 ***
N fertilizers inputs second order effect	-8.156e-04	2.69e-14 ***	-0.0008025	7.65e-15 ***	-7.984e-04	5.37e-15 ***
Soil organic matter	1.408e+00	4.11e-06 ***	1.4633330	7.39e-07 ***	1.453e+00	6.16e-07 ***
Soil organic matter second order effect	-8.661e-03	0.0843 .	-0.0092884	0.0513 .	-8.831e-03	0.0591 .
Cross effect of soil organic matter and N fertilizers inputs	-4.474e-03	6.32e-13 ***	-0.0044866	1.08e-13 ***	-4.574e-03	3.66e-14 ***
Number of observations	47		47		47	
Multiple R-squared	0.9565		0.9638		0.9638	
Adjusted R-squared	0.9509		0.9591		0.9592	
Signif. codes : $0.001^{***}, 0.01^{**}, 0.05^{*}, 0.1^{\cdot}$						

Table 19 – CropSyst Simulations - Barley production regressions results. (*Source: the author from CropSyst simulations*)

Explaining variables	Explained variable					
Crop	Maize grain yield					
Soil type	S1		S2		S3	
	Est.	p.value	Est.	p.value	Est.	p.value
Intercept	0.7660063	0.924725	-7.5628559	0.3220	-4.5769782	0.57518
N fertilizers inputs	0.2748838	6.7e-07 ***	4.515e-01	8.65e-13 ***	0.3913730	2.94e-10 ***
N fertilizers inputs second order effect	-0.0004844	0.000468 ***	-7.201e-04	4.21e-07 ***	-0.0006346	1.35e-05 ***
Soil organic matter	2.7314102	0.000241 ***	3.236e+00	8.66e-06 ***	3.2825044	2.12e-05 ***
Soil organic matter second order effect	-0.0330194	0.012302 *	-2.969e-02	0.0159 *	-0.0348813	0.00879 **
Cross effect of soil organic matter and N fertilizers inputs	-0.0048194	5.1e-06 ***	-7.017e-03	4.84e-10 ***	-0.0064554	1.89e-08 ***
Number of observations	47		47		47	
Multiple R-squared	0.6482		0.8589		0.7919	
Adjusted R-squared	0.6031		0.8408		0.7652	
Signif. codes : 0.001***, 0.01**, 0.05*, 0.1·						

Table 20 – CropSyst Simulations - Maize grain production regressions results. (*Source: the author from CropSyst simulations*)

Explaining variables	Explained variable					
Crop	Sunflower yield					
Soil type	S1		S2		S3	
	Est.	p.value	Est.	p.value	Est.	p.value
Intercept	-2.6665614	0.10050	-2.8446621	0.09763 .	-3.1801918	0.03736 *
N fertilizers inputs	0.2967300	1.03e-15 ***	0.3034878	2.96e-15 ***	0.2876380	2.81e-16 ***
N fertilizers inputs second order effect	-0.0005683	0.00078 ***	-0.0003711	0.03012 *	-0.0004955	0.00151 **
Soil organic matter	1.2419849	1.64e-11 ***	1.2831703	3.07e-11 ***	1.4298219	3.54e-14 ***
Soil organic matter second order effect	-0.0113055	4.74e-05 ***	-0.0091572	0.00117 **	-0.0144318	2.16e-07 ***
Cross effect of soil organic matter and N fertilizers inputs	-0.0059480	5.30e-16 ***	-0.0060637	1.70e-15 ***	-0.0058711	$<$ 2e-16 ***
Number of observations	47		47		47	
Multiple R-squared	0.9553		0.9695		0.9641	
Adjusted R-squared	0.9495		0.9656		0.9595	
Signif. codes : 0.001***, 0.01**, 0.05*, 0.1·						

Table 21 – CropSyst Simulations - Sunflower production regressions results. (*Source: the author from CropSyst simulations*)

Explaining variables	Explained variable					
Crop	rapeseed yield					
Soil type	S1		S2		S3	
	Est.	p.value	Est.	p.value	Est.	p.value
Intercept	4.822e+00	0.17134	4.420e+00	0.0652 .	5.518e+00	0.0281 *
N fertilizers inputs	9.518e-02	1.55e-05 ***	1.609e-01	4.22e-15 ***	1.546e-01	4.67e-14 ***
N fertilizers inputs second order effect	-1.596e-04	0.00447 **	-2.474e-04	2.50e-08 ***	-2.405e-04	1.03e-07 ***
Soil organic matter	9.301e-01	0.00247 **	9.581e-01	1.45e-05 ***	9.357e-01	3.65e-05 ***
Soil organic matter second order effect	-1.080e-02	0.04977 *	-8.577e-03	0.0219 *	-8.634e-03	0.0260 *
Cross effect of soil organic matter and N fertilizers inputs	-1.703e-03	7.88e-05 ***	-2.102e-03	7.24e-10 ***	-2.002e-03	5.73e-09 ***
Number of observations	47		47		47	
Multiple R-squared	0.5483		0.8916		0.8738	
Adjusted R-squared	0.4904		0.8777		0.8576	
Signif. codes : 0.001***, 0.01**, 0.05*, 0.1·						

Table 22 – CropSyst Simulations - rapeseed production regressions results. (*Source: the author from CropSyst simulations*)