QUANTIFYING THE HETEROGENEITY OF ABATEMENT COSTS UNDER CLIMATIC AND ENVIRONMENTAL REGULATION CHANGES: AN INTEGRATED MODELLING APPROACH

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ABSTRACT

We present here preliminary results of an integrated modelling approach combining a crop model (STICS) and an economic model (AROPAj) of European agricultural supply. This modelling framework is designed to perform quantitative analysis, regarding climate change impacts on agriculture and more generally the interactions between soils, land use, agriculture and climate integrating physical and economical elements (data, process, models). It explicitly integrates an agricultural diversity dimension with regards to economic set of choices and soil climate spatial variability.

First results are given in term of quantitative analysis combining optimal land allocation (economic optimality) and "dose-response" functions related to a large set of crops in Europe, at the farm group level, covering part of the European Union (EU15). They indicate that accounting for economical and spatial variability may impact both regional aggregated scales results.

INTRODUCTION

Agricultural activities are highly sensitive to climate mean state and variability, and will most probably have to face a projected climate change for the next centuries (IPCC, 2007). They are also, among other environmental effects, partly responsible for the anthropogenic perturbation of the climate system, mainly through non-CO_2 GHG emissions due to agriculture management in the case of Europe. They are also quoted as carrying a substantial share in overall anthropogenic GHG emission abatement potential, through the development of sequestration and bio energy crops. Assessing their dependency to and impact on environmental factors in various situations is thus a critical issue, which is subject to elevated uncertainty.

But the evolution of European agricultural activities, from the local scale (in terms of land allocation and management) to larger scales (level and spatial distribution of agricultural goods supply, income and external environmental effects) also depends on complex economical effects such as technology development, market interactions and regulations (e.g. Common Agricultural Policy and Bio energy and Frame Water Directives) (Ewert et al 2005, Olesen and Bindi 2002). Furthermore, environmental economics theory provides a relatively rich framework for diagnosing cost-benefit and economical assessments at several time and space scales, and interacting with decision-makers.

In this context, modelisation offers a relatively interesting tool to articulate climatic, economical and agronomical approaches, allowing for integrated diagnosis and uncertainty accounting. Reviews of such approaches (e.g. Turner et al 2007, Agarwal et al 2004) show that they are growing in number and diversity. None of them is able to fully break scale and conceptual issues from agronomical and economical processes at the farm scale to climate model scenarios and economical full accounting of market and regulation effects. To do so, one should ideally be able to represent altogether the sensibility of (i) individual farms adjustment possibilities to these forcings, (ii) market exchange and trade feedbacks. Classically, adjustments possibilities are distinguished between short and long-term adjustments, the latter involving significant changes in either technology or agricultural production orientation or both. Short-terms adjustments imply softer changes in terms of production orientation, spatial redistributions, land allocation and management (Ewert et al.

2002, Olesen and Bindi 2003). Sensibility of both adaption types to climate change and potential GHG abatement and economical efficiency of mitigation policies are highly sensible to the spatial and temporal variability of climate, soils and economical conditions (Tubiello et al. 2007, Challinor et al. 2009).

Here we propose a modelling framework under development linking a generic crop model (STICS, Brisson et al 2003) to an economical model of European agricultural supply (AROPAj) allowing to account for soil, management, climate change and economical changes scenario of agricultural supply at the FADN region scale. The methodology used is first presented, and then preliminary results are evaluated and used to illustrate the modelling framework performance.

METHODOLOGY

1. Implementing a spatially explicit sensitivity to climate and soil

The European agricultural production is economically represented by AROPAj supply-side model, which is based on a micro-economic approach applied to a set of representative farms, and augmented by additional blocks dedicated to GHG emissions (De Cara et al, 2005). Mathematically the model is based on a set of mixed integer linear programs, each of them letting autonomous the economic behaviour of price-taker representative agents distributed among FADN regions (Farm Accounting Data Network, a renewable sample of European farms selected on a regional basis). Here we use the version covering EU-15 and based on 2002 FADN census data. Within FADN regions, producers differ by their altitude and technico-economic orientation (defined by typical ranges of agricultural activities share in total producer gross margin) and are statistically representative of the variety of farmers within a FADN region, excluding permanent crops – horticulture, wine and grapes, arboriculture - and limited by FADN census confidentiality clause in the number of agents considered.

Each agent k is represented by the following optimisation program:

$$[1] \quad max_{\{x_k\}}\left(\pi_k(\{x_k\})\right) = g_k.x_k$$
$$s.t. \begin{cases} A_k.x_k \le z_k \\ \forall i, \ x_{k,i} \ge 0 \end{cases}$$

where x_k, g_k, A_k, z_k respectively denote agricultural activities, margin and cost vectors, and resources.

In order to be able to account for present day and future spatial heterogeneity of major European crops production in terms of climate and soil conditions, we use a method developed by Godard et al (2005, 2008) consisting in simulating crop yield response to nitrogen input in various soil, climate and management conditions with STICS generic crop model, and then interpolating these responses as production functions for each crop of each economical agent considered in AROPAj, using the following function:

$$[2] \quad Y_{[crop\ C,\ agent\ A]}: N \to B - (B - A).e^{-TAU.N}$$

with the crop and farm group dependant parameters A (no fertilisation yield), B (N non limiting yield) and TAU (yield sensitivity to N input).

Each agricultural producer of AROPAj is located in a FADN region, and is associated with a set of specific cropping conditions used to run STICS (Godard, 2005):

(i)   *Climate data*

The mean FADN region climate (daily minimal and maximal temperatures, precipitation, incoming short wave radiation, wind and water partial vapour pressure) is derived from RCA3 regional climate model outputs (Kjellström et al 2010) RCA3 is driven by ECHAM5 climate model continuous runs over the period 1950-2100. The two climate scenarios we consider, hereafter referred to respectively as CTL and A2H2, are the following : a set of 30 years (1976-2005) under historical CO_2 concentration (until 1990) continued by first years of SRES scenario A2; and 30 years (1971-2100) under SRES scenario A2 CO_2 concentrations. The original RCA3 data of the 3 most representative consecutive years (in terms of monthly mean temperature and cumulated precipitation gradients through Europe) for each scenario was first selected with an Expectation-Maximization (McLachlan and Peet 2000) method and then re-aggregated from a $0,5° \times 0,5°$ grid to the FADN regions.

(ii)   *Soil data*

The five most representative soils of the region are tested for each crop, each of them being transferred to a STICS soil entry (from the European soil database V.1.0 and pedo-transfert rules, see Godard 2005 for further details);

(iii)   *Management rules per crop*

We considered a set of different options for CTL climate:

a) irrigation was determined for each crop of each agent (between non limiting irrigation and no irrigation, based on FADN census declared total irrigated area and allocation rules),
b) mineral fertilisation type and calendar have been determined with regards to fertilizers available in the country (based on EUROSTAT and FAO data) and simple allocation rules at specific crop development stages.
c) two different preceding crops can be used, the preceding crop being run with STICS to initialize the soil state for the interest crop.
d) cultivars and sowing dates are determined together, providing three options for cycle length start and duration management, depending on the crop (either 3 sowing dates and one cultivar or one sowing date and three cultivars). Sowing dates have been computed spatially on the climate data grid as the mean day over 20 years for which linearly interpolated monthly 2m air temperatures reached crop specific thresholds. These thresholds have been calibrated such that CTL sowing dates matches the JRC crop calendar reference (Willekens et al. 1998).

Together with the five possible soils, the six management options generate 30 cropping scenarios (hereafter referred to as soil-ITK options) for each crop of each economical agent for CTL experiment (with CTL climate data and a CO2 concentration level of 352 ppm). Yield response to nitrogen input of 9 crops (soft and hard wheat, barley, rapeseed, potato, sugar beet, maize, soybean and sunflower) under these 30 soil-ITK options are obtained by running STICS with 31 levels of nitrogen input (from 0 to 600 kgN/ha, by steps of 20 kgN/ha), with agent-specific soil-ITK options and climate data.

Crop yield responses under each soil-ITK option are then interpolated as production functions (eq. [1]). A progressive procedure is used to keep only one production function (and bound soil-ITK option), first excluding scenarios for which the agent FADN 2002 reference yield isn't within [A, B], and finally keeping the scenario for which the production function has its derivative value while crossing reference yield the closest to the fertilizer unit buying price ω over crop selling price p ratio, assuming that the producer reaches first order conditions of the following optimisation program with regard to the crop:

$$[2] \qquad \max_{N,s}\big(\pi(N)\big)$$

$$\text{s.t.} \begin{cases} N \geq 0, \\ s1 \leq s \leq s2 \end{cases}$$

$$[3] \quad \text{with } \pi(N) = (p - \omega).N.s$$

Since the optimal crop yield and fertilisation rate are highly sensible to the interpolated parameters and STICS model did not always generate reasonable simulated points, a few adaptations were added to the method developed by Godard et al. 2008: a higher weight has been given to yield simulated points with a fertilisation rate higher than 300 kgN/ha during the interpolation least square process in order to be sure that TAU values aren't too low, and B was bound not to be higher than the simulated yield with a 400 kg/ha fertilisation rate.

A tolerance is allowed for selection if none of the 30 options crosses reference yield but at least one of {A}soil-ITK options or {B}soil-ITK options being within reference yield ± 15 % : the reference yield is lowered/increased by 15% according to the case, and a production function can thus be selected. If it's not the case, no producing function can be generated the crop-agent couple.

2. Accounting for climate change

The soil-ITK option selected for CTL climate scenario was then kept unchanged while running STICS with the A2H2 climate data and a CO2 concentration of 724 ppm, in order to calculate a climate change effect on economical agents. Thus no agronomic adaptation is allowed to cope with climate change but changing crop allocation and fertiliser rate, which can be seen as restrictive for calculating a realistic climate change impact, and yields values under climate change are expected to underestimate with respect to an agronomical optimal point of view.

3. Implementing a carbon tax as a mitigation scenario

Based on climate change projections from the Intergovernmental Panel on Climate Change reports, the projected climate change is highly dependent on future anthropogenic GHG emissions. Despite no agreement has been found yet on common tools to regulate European agricultural emissions, we estimate that GHG emissions regulation tools aiming at mitigating climate change will probably be implemented in the agricultural sector, as this sector is the major source of methane and nitrous oxide European anthropogenic emissions, and is often quoted as potential carbon sink. Previous studies have found that incentive based tools such as a carbon tax or cap-and-trade systems could be economically more efficient than uniform quotas (e.g. De Cara 2005).

Tax and quota are easily implemented in a mathematical programming model such as AROPAj. The "primal approach" is selected through taxing of direct agricultural GHG emissions, when the tax is seen as a "carbon price" (CO2-equivalent price) which makes costly the direct emissions. We thus introduced a tax on GHG emissions to evaluate the GHG abatement potential within the European agricultural sector, and its evolution under climate change. The emissions subject to taxations are CH4 and N20 direct emissions calculated by applying IPCC coefficients to agricultural activities, and AROPAj was run with tax levels ranging from 0 to 1000 €/teqCO2. Other economical forcings remained fixed: the CAP policy scenario remained unchanged (an implementation of Agenda 2000 policy) and both crop and fertilizers prices were kept identical in case of climate change and mitigation scenarios.

We can thus estimate climate change impact and mitigation potential both in case mitigation effort or climate change occurred solely or altogether.

RESULTS AND DISCUSSION

1. Production functions response to climate change

We were able to establish a production function for 67 % of 5076 of crop-agent cases to be treated, which represented in 2002 83% of the total agricultural area to be treated, and 37% of total European agricultural area. Figure 1 shows the selection rate details per crop (a) and per country (b) and the share of European total agricultural area covered in each case. Worst selection rates were obtained for maize, soybean and sunflower, and over Mediterranean and Nordic countries. Cases not selected account for 7% of FADN 2002 total agricultural area.

Production functions parameters can be found for both climate scenarios in table 1, where reference yield values are given for evaluation of CTL values. CTL none fertilisation yield values (A) are systematically lower than minimum reference yields, suggesting that our approach may not perform very well in no fertilisation conditions. This points the main limit of our evaluation of crop sensitivity to Nitrogen input (TAU) which highly determines the economically optimum fertilisation rate. The fertilisation rate being determined by the derivative value equalizing fertilizer unit buying price over output selling price ratio, if TAU is too low relatively to this price ratio the fertilisation rate will be overestimate. This effect can be enhanced if the difference between no fertilisation and N non limiting yields (B-A) is too high. In our case, B values can be twice the observed yields, which is not unreasonable giving that yields are only limited by genetic potential, climatic stresses and plant nitrogen

uptake (the crop model do not include weeds, diseases), and soil-ITK options can be more comfortable than reality (e.g. irrigation is unlimited when available). If the fertilizer price sufficiently low, we can expect the producer to apply higher fertilisation rates than reality, and probably obtain higher yields than in reality.
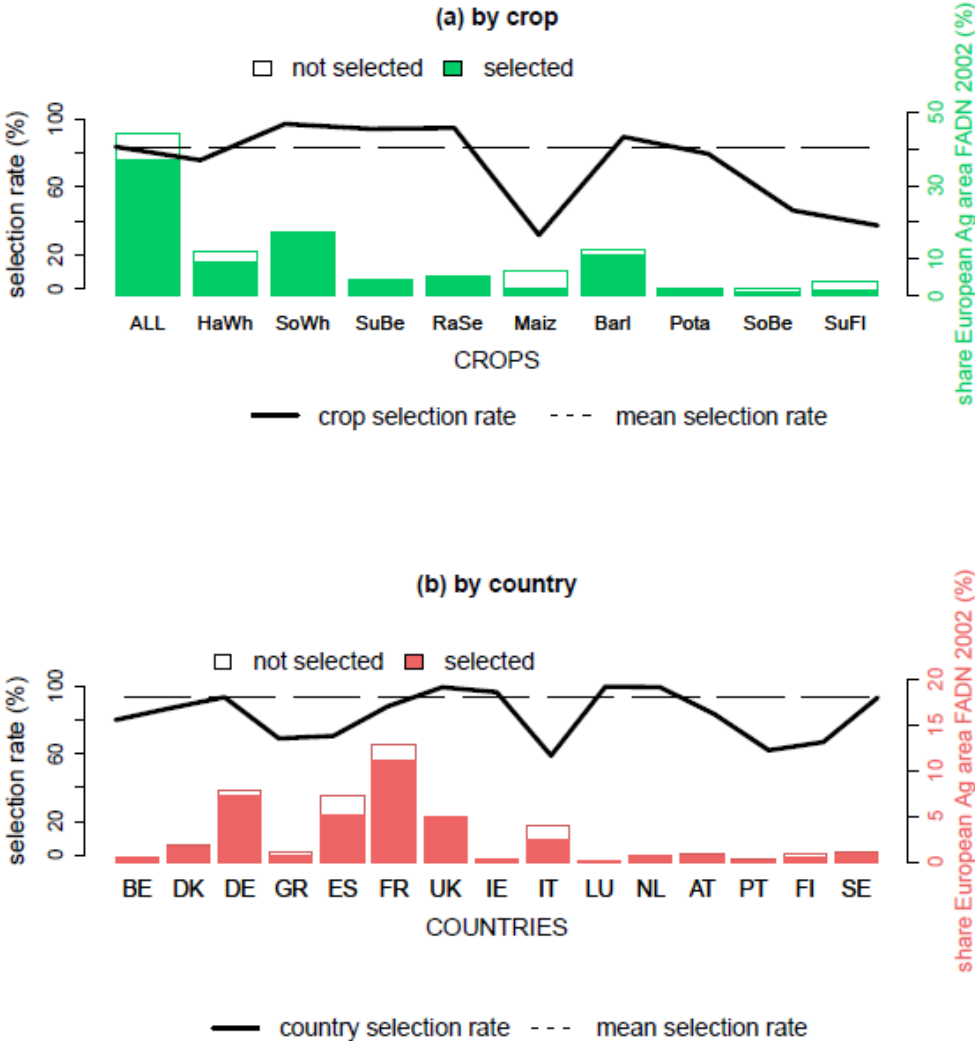

Figure 1 – Selection rate detail by crops (a) and countries (b) [%, left scale] and bound share of cases within FADN 2002 total European agricultural area [%, right scales].

Climate change affects parameters values differently among crops: mean value of (B-A) i.e. yield variation range with N input, is significantly lowered for soft wheat, maize and potato, while stays equivalent for hard wheat, rapeseed, barley and sunflower. Some crops see a increase in this range, like sugar beet and soybean. The mean yield level -which can be assessed by ½ (B+A) prior to economical allocation of fertiliser rate- is significantly increased for soybean, while significantly lowered for maize and potato. Profitability of a given crop is an integrated signal of the mean yield level associated with its range of variation with N input and its sensibility to increasing input, TAU. Mean TAU values under climate change are either lowered (sugar beet, maize, barley, soybean) or nearly constant (wheat, rapeseed, potato) except for sunflower, for which climate change greatly increase its sensibility to N input. We can thus expect that mean profitability of the different crops over EU15 regions will differ significantly, this diagnosis being even more sensible with respect to its spatial variability.

To our knowledge, no similar approach exists for comparison of EU15-wide yield response spatial distribution at the FADN region scale, involving only one single generic crop model, run with all 5 five climate forcing fields at FADN regional scale of climate change impacts on the nine crops considered. A more precise evaluation against particular cases (in terms of crop model, location, scale, climate and management scenarios) remains to be done, and a proper evaluation of climate change impact on agricultural supply would need to run at least other climate scenarios and include adaptation scenarios.

CROP	Clim	A			B			Ref Yield FADN 2002			TAU		
		Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
HaWh	CTL	0.1	5.3	2.3	7.7	11.5	9.4	1.2	7.0	3.9	6	13	8
	A2H2	0.1	6.5	1.9	0.2	11.5	9.3	-	-	-	1	15	8
SoWh	CTL	0.1	6.7	2.8	4.3	14.2	11.5	1.7	8.6	5.5	6	12	8
	A2H2	0.1	7.6	2.7	0.2	14.4	9.9	-	-	-	1	12	7
SuBe	CTL	1.9	71.2	43.9	37.4	135.6	102.5	32.4	89.9	60.5	10	51	14
	A2H2	0.1	91.3	43.3	0.2	147.1	107.8	-	-	-	1	24	11
RaSe	CTL	0.1	3.1	2.1	2.4	7.7	5.7	1.3	3.9	2.9	6	18	8
	A2H2	0.1	5.4	2.3	0.2	8.3	5.9	-	-	-	1	16	7
Maiz	CTL	0.1	11.3	4.2	3.5	15.9	9.7	1.4	11.8	7.3	4	164	14
	A2H2	0.1	10.2	2.5	0.1	14.3	4.8	-	-	-	0	2	1
Barl	CTL	0.1	5.8	3.1	3.2	12.8	9.7	1.2	7.8	4.9	6	94	13
	A2H2	0.1	6.2	3.3	0.2	12.8	9.5	-	-	-	1	54	10
Pota	CTL	0.1	52.7	22.0	18.8	114.4	61.5	11.7	62.2	30.0	8	26	14
	A2H2	0.1	73.0	24.1	0.2	100.3	45.6	-	-	-	1	68	13
SoBe	CTL	0.1	2.9	1.1	2.4	5.8	3.9	0.3	4.2	2.6	7	71	17
	A2H2	0.1	3.3	1.1	0.4	5.8	4.3	-	-	-	1	47	11
SuFl	CTL	0.1	3.4	2.2	0.7	5.8	2.9	0.6	4.0	2.4	5	196	14
	A2H2	0.1	4.2	2.3	0.2	5.1	2.8	-	-	-	1	823	26

Table 1 – min, max and mean values of FADN regions averaged production function parameters obtained after simulation and interpolation, for both climate scenarios and for 9 crops. A and B are in t[agricultural production]/ha, and TAU in tN^{-1}.

2. Economical evaluation of climate change and mitigation policies solely impacts on EU15 agricultural supply

Table 2 shows AROPAj countries detailed values of gross margin (in billions €), total GHG emissions without mitigation (in million tonnes of CO_2 equivalent), tax level allowing an 8% abatement rate at the country level (except for EU15 values) and the total abatement reached with a tax level of 50 €. Results shown here have to be taken with caution since they were not fully analysed: final results rely on a complex set of possible substitutions within agricultural activities that still need to be explored.

Climate change impact on agricultural supply can be illustrated by gross margin change values under climate change (Δ(Clim) values): climate change is responsible for a loss of 5% in gross margin EU averaged, and most countries stays within a range of -11% to +5%, except for Belgium and southern Spain, which are known to be problematic countries with regards to their calibration and behaviour in AROPAj.

The effect of a mitigation policy solely can be illustrated by the tax level needed to achieve a 8% GHG emissions abatement target at the level of individual countries (CTL) and the gross margin change values under a EU15 20€/tCO2eq tax implementation. As expected

the tax level needed to reach a 8% GHG emissions abatement target at EU15 level is about 20€/tCO2eq and is significantly lower than in case no production function is implemented: production functions allow for more flexibility while reducing GHG emissions and is a source of lower abatement costs estimates (Vermont & De Cara 2010). For comparison with climate change impact on gross margins, the EU averaged loss due to a European target of 8% abatement in GHG emissions is comparable in EU15 average (-6%) its distribution among countries is more narrow (within -3 to -11%).

Country	Gross Margin no tax [G€]			Total emissions no tax [MtCO2eq]			Tax level for 8 % abatement rate [€]			Gross margin with a 20 € tax [%]				
	CTL	A2H2	ΔCLIM [%]	CTL	A2H2	ΔCLIM [%]	CTL	A2H2	ΔCLIM [%]	CTL	A2H2	Δ(TAX, CTL) [%]	Δ(TAX, A2H2) [%]	Δ(CLIM, TAX) [%]
belg	3,5	2	-43	12,9	12,5	-3	25	35	40	3.2	1,8	-9	-10	(-)
dani	2,8	2,5	-11	9,3	9,1	-2	35	45	29	2.6	2,3	-7	-8	(-)
deu1	9,7	9,7	0	28,7	28,6	0	25	25	0	9.1	9,1	-6	-6	*
deu2	10,9	10,7	-2	24,7	24,9	1	30	30	0	10.4	10,2	-3	-5	(-)
ella	3,4	3,4	0	10	10,1	1	50	50	0	3.2	3,2	-6	-6	*
esp1	6,6	6,7	1	23,9	23,4	-2	20	10	-50	6.1	6,3	-8	-6	(+)
esp2	4,6	3,4	-26	14,3	12,2	-15	5	5	0	4.3	3,2	-6	-6	*
fra1	21,3	19,8	-7	59,6	62	4	20	15	-25	20.2	18,6	-5	-6	(-)
fra2	8,9	8,7	-2	36	35,3	-2	20	20	0	8.1	8,0	-9	-8	(+)
gbre	13,8	13,6	-1	45,4	45,4	0	20	15	-25	12.9	12,7	-7	-8	(-)
irla	2,8	2,8	0	14,6	14,8	1	20	15	-25	2.5	2,5	-11	-10	(+)
ita1	12,7	12,5	-2	16,8	16,6	-1	15	15	0	12.3	12,2	-3	-2	(+)
ita2	5,8	5,3	-9	10	9,6	- 4	20	20	0	5.6	5,1	-3	-4	(+)
ita3	3,6	3,3	-8	7,5	7,4	-1	10	10	0	3.4	3,2	-6	-3	(+)
luxe	0,2	0,2	0	0,5	0,5	0	35	40	15	0.2	0,2	*	*	*
nede	6	6,1	2	15,5	15,5	0	20	25	25	5.7	5,8	-5	-5	*
osto	2,5	2,6	4	6,6	6,8	3	50	25	-50	2.4	2,5	-4	-4	*
port	2,1	2,2	5	8,3	8,4	1	25	20	-20	1.9	2,0	-10	-9	(+)
suom	1,9	1,7	-11	5,2	5,1	-2	10	10	0	1.8	1,6	-5	-6	(+)
sver	2,6	2,4	-8	9	8,9	-1	10	10	0	2.4	2,3	-8	-4	(+)
EU15	125,4	119,5	- 5	358,9	357	0	20	20	0	118,4	112,7	-6	-6	*

Table 2 – Country detailed gross margins [G€], total GHG emissions (N_2O + CH_4, [MtCO2eq]) without mitigation, tax level [€/tCO2eq] allowing to reach 8% abatement, gross margin change [%] with a 20€ tax, for CTL and A2H2 climate scenarios, and relative difference between climate scenarios as (A2H2-CTL)/CTL in percentages. Three last columns are respectively the 20 €/tCO2eq tax effect on gross margins [%] for both climate scenarios -namely Δ(TAX,CTL) and Δ(TAX,A2H2) - and the sign of the climate change effect on gross margins change while implementing a mitigation scenario.

3. Interactions between climate change and mitigation policy impacts

The simulation set-up could allow for diagnosing cross effects of climate change and mitigation scenarios on the European agricultural supply. As an illustration, three last columns of table 2 gives the mitigation scenario effect (with a European uniform tax of 20€/teqCO2) on gross margins for both climate scenarios, and the sign of climate changed induced change in gross margins variations under the mitigation scenario. As such, results are

to be taken with even more caution than separate effects of climate change and mitigation scenarios. This particular cross effect is relatively low, and both country specific and European average signs are subject to high uncertainty.

CONCLUSIONS

Our modelling framework allows for representing spatial soil, climatic and economic sensitivity of European agricultural activities through the combination of crop model simulations of 9 crops (covering 36% of total European agricultural area according to FADN 2002) and a supply-side economical model.

Preliminary results show that the model can capture and differentiate the spatial variability signal of a set of climate change and mitigation policy scenarios. For both scenarios the spatial variability may be significant with regards to their mean European properties, meaning that the European agricultural supply may be resilient at an aggregated scale but more sensible at regional scales. Moreover the enhanced flexibility of economical agents generated by introducing nitrogen function responses seams significant.

These results highlight the importance of combining the diversity of climatic, management, production and input demand, and environmental regulation schemes. Nevertheless, the robustness of our modelling framework need to be evaluated since all mechanisms were not fully explored and only a limited number of scenarios were tested.

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