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Short-term farm level adaptations of EU15 agricultural supply to climate change

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ABSTRACT

Assessing climate change impact on agriculture is a complex task involving a wide range of economical and physical processes, leading to significant uncertainties. At European scale, climate change impacts on agricultural supply have been appraised to be of relatively less important driver by the end of century compared to other global drivers. However these diagnoses are incomplete due to a limited representation of both spatial heterogeneity in important determinants of agricultural supply (soil, management practices and producer typology) and fine scale processes such as farm scale autonomous adaptation. We propose a complementary approach based on a modeling framework including a spatially explicit representation of productivity and producer behavior with regard to heterogeneity in soil, climate, and producer socio-economic context to appraise climate change impacts including autonomous farm-scale adaptations of EU15 agricultural supply to climate change. Our results suggest that without accounting for autonomous adaptation European agricultural supply may have interesting resilience properties at an aggregated scale despite significant heterogeneity at smaller resolution. Accounting for autonomous adaptations result in significant yield gains, and may lead to (i) a significant increase in the relative profitability of crops compared to other land-covers, thus possibly increasing its agricultural land-use share over other land covers, and (ii) an increase in total European production which may have impacts on agricultural goods markets, thus highlighting the need for integrating fine scale processes such as autonomous adaptation.

INTRODUCTION

Climate change impacts on agriculture have been appraised with various methodologies and tools for more than two decades, and cover a wide range issues from biological processes at the crop level to worldwide economy. However the previously unrecorded nature of projected climate and the intertwined nature of agronomic, environmental and socio-economic dimensions of agriculture lead to considerable uncertainty in these assessments.

Existing approaches are based on separate or combined estimates of (i) climate change driven changes in agricultural productivity, (ii) various forms and levels of adaptation and (iii) local to worldwide economy feedbacks [1]. Ricardian approaches project statistically isolated meteorological variables' effect on observed measures of agricultural activities outcomes while controlling for other relevant effects with cross-sectional analysis [2-4]. Process-based approaches estimate changes in productivity first, and then production and commodity prices changes for various spatially aggregated scales. They can account for supply-demand dynamics on agricultural and other economic sectors using partial and computable general equilibrium models and trends in effects of relevant drivers not explicitly modeled [5-7]. Contrary to Ricardian approaches, these modeling approaches allow for disentangling individual drivers effect and account for climate change effects not observed in the past (e.g. fertilisation effect from [CO_2] concentration elevation) but can only account for explicitly modeled phenomena [2]. They considerably differ in terms of scope, spatial scale and tools, often focusing on a particular issue at the cost of accuracy for other issues. While global extent appraisals are

better suited for capturing the effects of trade and world-wide economy, they rely on evaluation of future productivity and agricultural land-use at a relatively coarse resolution, and skip appropriated finer scale processes for heterogeneity diagnosis at the scale of European sub-national regions ([8]).

Recent finer scale appraisals of future European agricultural supply and land-use integrating climate change effects ([9,10]) have stated that climate change may be a relatively less important driver compared to global rise in agricultural goods, trade liberalization, technological progress and environmental regulation. This diagnosis rely on relatively simple diagnosis of climate change induced crop area and yield distributions and carbon dioxide concentration ([CO_2]) fertilisation effect [11-13], defining climate change induced change in agricultural supply. However, as recognized by the authors, the methodology is not designed to compute accurately climate change induced changes in crop productivity: its estimation is based on statistical inference of yield correlation to Environmental Strata (EnS, [12]) defined by a set of environmental variables excluding soil properties, agricultural management practices and socio-economic producer's environment and behavior, despite the fact that these latter variables have been pointed as of particular importance for explaining actual yields over Europe and their relation to climate [4,8,14-20]. However, more elaborated studies of crop productivity using crop modeling tools at the European extent [15,16,21] do not integrate economic effects such as farm scale adaptations (e.g. substitutions and interactions between agricultural activities). Such adaptations are defined [22,23] as short-term (or autonomous) adaptations and cover a wide range of changes at farm scale delineated by two main ideas: (i) they explicitly target production optimization at farm scale without major structural changes (in terms of producer typology and technology) and (ii) they rely on changes elaborated with no other sector (e.g. policy, research and technological developments) involved. They are generally opposed to long-term (or planned adaptation) relying on policy oriented structural changes in agricultural supply systems for which autonomous adaptations won't be sufficient to reduce their vulnerabilities to climate change, or technological development involving other stakeholders (e.g. breeding research).

In this paper we propose to quantify the specific role of short-term adaptations in the European agricultural supply response to climate change including spatial heterogeneity, relying on the coupling of a micro-economic European agricultural supply-side model (AROPAj) with a widely-used generic crop model (STICS, [24,25]) at farm scale following modeling philosophy of [17,26]. This modeling framework, integrating physical and economical elements, is designed to perform quantitative analysis, regarding climate change impacts on agriculture through diagnosis of agricultural supply outcomes at farms to continental-wide aggregated level, resulting from individual heterogeneous independent agents' behavior at farm-level response to climate change. It can thus address short-term adaptations through both (i) alternative field scale crop management scenarios design, and (ii) appraisal of farm-scale optimization among activities to cope with climate change (and changes in crop management) simulated changes in productivity of major European crops. Moreover its relatively detailed spatial and socio-economic resolution with regard to producing agents allows for systematic heterogeneity diagnosis among European regions. Changes in European agricultural supply induced by climate change and short-term adaptation are

thus appraised in terms of productivity, land re-allocation, production, gross margin and non-CO_2 greenhouse gas – GHG – emissions at Farm Accountancy Data Network (FADN) regions resolution.

METHODOLOGY

The European agricultural production is represented by AROPAj supply-side model belonging to the 'agricultural input-output models' category identified by [27], and is based on a micro-economic approach applied to a set of representative farms, and augmented by additional blocks dedicated to GHG emissions ([28,29]). Initially designed to assess Common Agricultural Policy (CAP) reforms' impact [30,31], the model is based on a set of mixed integer linear programs, each of them letting autonomous the economic behavior 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 a version of the model covering EU-15 and based on 2002 FADN census data and including last up-to-date Common Agricultural Policy (CAP) bindings. Within FADN regions, producers differ by altitude and total gross margin classes, 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 mathematical program (P_k):

$$(P_k) \begin{cases} \max_{x_k}[\pi_k(x_k)] = g_k \cdot x_k \\ s.t. \begin{cases} A_k \cdot x_k \leq z_k \\ \forall\, i, x_{k,i} \geq 0 \end{cases} \end{cases} \quad [1]$$

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

1. **Spatially explicit sensitivity of crop yields to regional weather, soil and crop management**

In order to be able to account for productivity present day and future spatial heterogeneity with respects to climate, soil and management practices, we used a method developed by [32,33] to replace observed yields and nitrogen input by simulated production functions linking crop yields to nitrogen input, extended to EU15 [34]. Yield responses to nitrogen input are simulated with STICS generic crop model, and then interpolated these responses as production functions $Y_{C,k}$ for each crop C of each economical agent k considered in AROPAj, using the following function:

$$\begin{aligned} Y_{C,k} : \mathbb{R}^+ &\to \mathbb{R}^+ \\ N &\mapsto B_{C,k} - \left(B_{C,k} - A_{C,k}\right) \cdot e^{-TAU_{C,k} \cdot N} \end{aligned} \quad [2]$$

with the crop C and farm group k dependant parameters $A_{C,k}$ (no fertilisation yield), $B_{C,k}$ (N non limiting yield) and $TAU_{C,k}$ (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. Due to lack of

accurate data for soil and crop C management rules for each agent k, the first step is the generation of a production function ensemble $\{Y_{C,K}\}_{i=1..30}$ with 6 crop management scenarios and 5 soil scenarios, leading to 30 possible production functions:

(i) *Climate data*

Daily weather data of each FADN region (daily minimal and maximal temperatures, precipitation, incoming short wave radiation, wind and water partial vapor pressure) is derived from RCA3 regional climate model outputs [35,36], itself being driven by ECHAM5 climate model continuous runs over the period 1950-2100. The reference present-day climate scenario we consider, hereafter referred to as CTL, is designed as follows: a set of 30 years (1976-2005) under historical CO2 concentration (until 1990) continued by first years of SRES scenario A2 is extracted. Then RCA3 daily data is extracted from the most representative 3 consecutive years (in terms of monthly mean temperature and cumulated precipitation gradients through Europe) selected by an Expectation-Maximization [37] method and then re-aggregated from RCA3 0.5° x 0.5° grid to FADN region level. [CO_2] level was fixed to 352 ppm.

(ii) *Soil data*

The 5 most representative soils of the region (in area coverage) are tested, each of them being transferred to a STICS soil entry (from the European soil database V.1.0 and pedo-transfert rules, see [32,33]);

(iii) *Management rules per crop*

We considered 6 scenarios for CTL climate and for each soil:

a) 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.
b) 2 different preceding crops are tested (winter wheat and spring leguminous), the preceding crop being run with STICS to initialize the soil state for the interest crop.
c) cultivars and sowing dates are determined together, providing 3 options for cycle length start and duration management, depending on the crop (either 3 sowing dates and 1 cultivar or 1 sowing date and 3 cultivars). Mean 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 JRC crop calendar reference [38].
d) 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 among crops based on expert

knowledge. When irrigation is undetermined, both options are considered (doubling possible production functions for that crop).

Yield response to nitrogen input of 9 crops (soft and hard wheat, barley, rapeseed, potato, sugar beet, maize, soybean and sunflower) under these 30 options are obtained by running STICS with 31 levels of nitrogen input (from 0 to 600 kgN/ha, by steps of 20 kgN/ha). Crop yield responses under each soil-ITK option are then interpolated as production functions (eq. [2]).

A unique production function (and related soil-crop management option i_{CTL}) for CTL climate scenario $Y_{C,k}^{CTL}$ is then selected with the following: options for which $[A,B]_{C,k,i}$ interval doesn't cover FADN 2002 reference yield are excluded, and the option selected among remaining scenarios is the one for which the production function's derivative value (while crossing reference yield) the closest to the fertilizer unit buying price ω_C over crop selling price p_C ratio, assuming that the producer k reaches first order conditions of the following optimization program ($F_{C,k}$) with regard to crop C fertilization rate:

$$(F_{C,k}) \quad \begin{cases} \max_{N_{C,k}}[\pi_{F,C,k}(N_{C,k})] = p_{C,k} \cdot Y_{C,k}(N_{C,k}) - \omega_{C,k} \cdot N_{C,k} \\ s.t.\ N_{C,k} \geq 0 \end{cases} \qquad [3]$$

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: (i) yields have been generally roofed by a linear trend for fertilization rates higher than N0=400 kgN/ha ($\forall N \geq N0,\ Y(N) \leq Y(N0) \cdot [1 + \frac{0.002(N-N0)}{N0}]$); (ii) cases were reference yield is reached for a fertilization rate higher than N0 are excluded; (iii) during the interpolation procedure, yields with a fertilization rate higher than 300 kgN/ha have been given higher; and (iv) a tolerance is allowed for selection if none of the 30 options crosses reference yield but at least one of $\{A\}_i$ or $\{B\}_i$ options being within reference yield x (1 ± α): the reference yield is lowered/increased by α according to the case, and a production function can thus be selected (α=20%for all crops, excepted maize and sunflower for which α=40%). If it's not the case, no producing function can be generated the crop-agent couple, and reference yield and fertilization rate will be kept.

2. Accounting for climate change and adaptation

Two climate change scenarios (namely A2 and B1) have been included through the simulation of new production functions with STICS crop model being imposed new weather data from the regional climate model RCA3 outputs (also driven by global climate model ECHAM5 simulations) respectively for A2 and B1 SRES emission scenarios at a 2071-2100 horizon. [CO_2] levels used were respectively 724 ppm and 533 ppm (based on SRES scenarios), and 3 consecutive years of weather data were extracted from RCA3 outputs by the same expectation-maximization procedure.

Two additional scenarios were considered with regard to adoption of new crop management rules, defining altogether the 5 scenarios defined in table 1:

- "no-adapt": the same management rules as CTL (i_{CTL}) were used to generate productions for each crop C of agent k (with climate change induced new weather data, $Y_{no\text{-}adapt}^{A2}$ and $Y_{no\text{-}adapt}^{B1}$),

- "adapt": a set of 6 production functions ($\{Y_{C,k,i}^{A2}\}_{i=1..6}$ and $\{Y_{C,k,i}^{B1}\}_{i=1..6}$ corresponding to new weather data and the 6 CTL management scenarios) were generated (if the crop wasn't irrigated in CTL, simulations were done with and without irrigation, leading to 12 different management rules runs per climate change scenario). The adapted production functions ($Y_{C,k}^{A2,adapt}$ and $Y_{C,k}^{B1,adapt}$) were then selected among these management scenarios as the one that maximize per hectare crop specific gross margin (using optimal fertilization rate and yields defined by eq. [3]).

Climate / ***Crop management***	**CTL**	**A2**	**B1**
no-adapt (i_{CTL})	CTL	$A2_{no\text{-}adapt}$	$B1_{no\text{-}adapt}$
adapt (i_{A2}, i_{B1})	-	$A2_{adapt}$	$B1_{adapt}$

Table 1 – Climate and crop management scenarios considered for production functions

For each of these scenarios, the optimal fertilization rate and yields are deduced from ($F_{C,k}$) mathematical programs (eq. [3]) and used to replace fix FADN reference yields and fertilization rates in the AROPAj model, allowing the EU15 agricultural supply to account for climate change impact in terms of yield and its sensitivity to nitrogen input, and a first level of adaptation concerning crop management rules. For each scenario, a second level of adaptation is generated: the agricultural supply model determines farm-scale optimal set of activities with respect to gross margin maximization (share in total utilized agricultural area by land-cover type – either crops, meadow, or set-aside land –, share of marketed vs. on-farm used production, cattle number and feeding).

It is important to notice that for short-term adaptation appraisal only, the following issues are not accounted for:

(i) changes in prices (from future levels of marketed goods demand and input supply or market feedbacks), technology and policies (CAP, commercial and environmental policies);

(ii) changes in the distribution and typology of producing agents (number, total utilized agricultural area – UAA - , activity abandonment or new activity adoption beyond technico-economic typology bindings);

Two other specifications are noteworthy: (iii) we account only for changes in mean climate, thus excluding extreme climatic events impact; and (iv) crop management adaptation considered are based on a limited set of scenarios with respect to an agronomic optimal point of view, and these scenarios are excepted to underestimate crop management adaptation potential.

RESULTS & DISCUSSION

1. Regional distribution of yield changes and crop management adaptation

We were able to generate production functions for 85% (in area coverage) of {C,k} crop-agent cases, allowing an explicit sensitivity of productivity to soil, climate

and socio-economic environment for 38% of European total utilized agricultural area (UAA). Worst succeed rates were obtained for soybean (43%), sunflower (52%) and maize (62%, see Table 1 for details by crop and corresponding CTL area shares over EU15 total UAA) and located mainly in central Spain and upper alpine regions of Italy. Productivity of these remaining 7% of total EU15 UAA was kept fixed to FADN reference values. CTL simulated yields (after determination of optimal fertilization rates) were evaluated against FADN data, showing a mean over regions difference to FADN reference lower than ±30% for most crops (except for durum wheat – 20% of total CTL wheat area -) which is considered as a good agreement given the high cumulated uncertainty concerning CTL climate scenario, crop management and fertilizer costs data available, and crop model uncertainty.

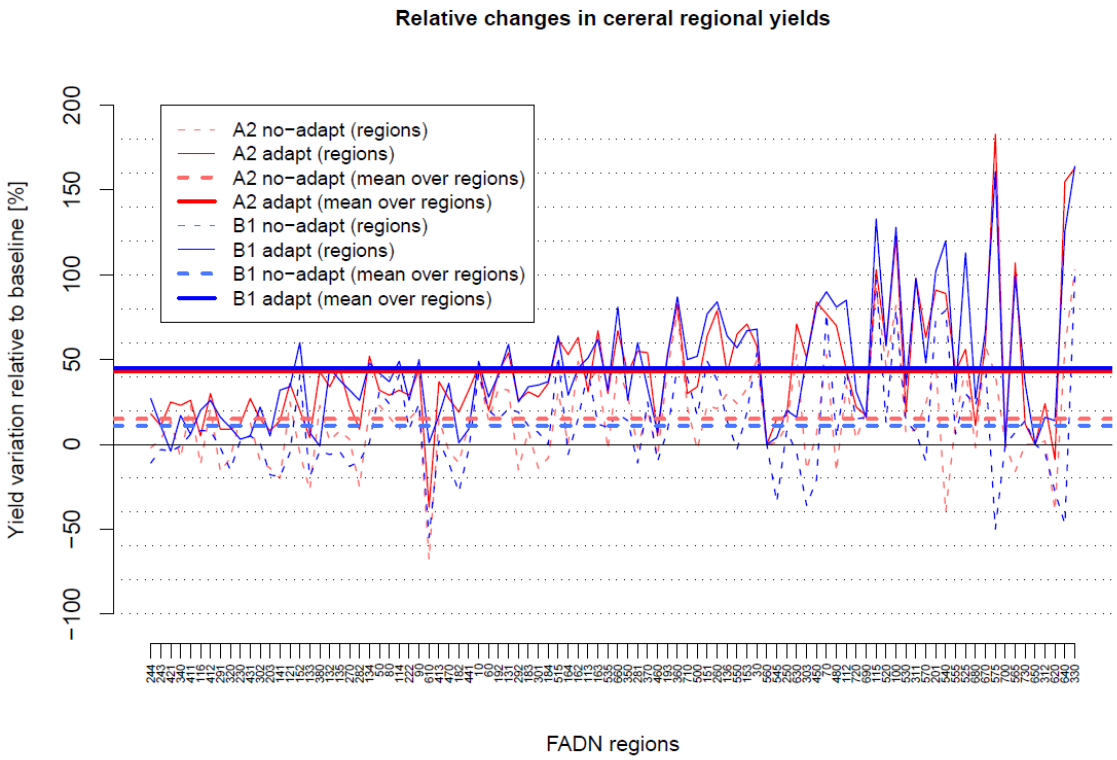

Figure 1 – Relative changes in cereals regionally averaged yield values for each scenario relative to CTL reference (in percentage, red and blue colors are respectively A2 and B1 climate change scenario, and solid and doted lines are respectively scenarios with and without adaptation). Solid and doted thick lines represent *EU* and *m* from Table 2. FADN regions are labeled by their FADN number, and ordered by decreasing yield values under CTL reference scenario.

As illustrated for cereals in figure 1, without adaptation of crop management mean yield over regions is generally increased by climate change, with significant differences among crops and regions. Table 2 presents changes in yields for EU15 averaged mean yield (*EU*), and mean (*m*) and standard deviations (*sd*) of changes over FADN regions yield for 8 crops (wheat, barley, maize, sugarbeet, potato, rapeseed, sunflower and soybean) and aggregated crop groups (cereals, root and tuber crops and oil and seed crops). Increases in mean among region and EU15 yields are the greatest for cereals (respectively +15±28 % and +11±29% for A2-no-adapt and B1-no-adapt mean

changes over regions) except for maize, and the weakest for root and tuber crops (respectively +5±69% and -1±73%), and in all cases are subject to high variability among regions (illustrated by standard deviations higher than mean values and differences between EU15 mean and mean among regions – not weighted by the area of each region dedicated to each crop).

In case crop management adaptations are accounted for, very high gains in European average yields can be expected from climate change, by both reducing negative impacts on yields and increasing potential gains from climate change (figure 1). Gains from crop management adaptations are the strongest for root and tuber crops and oil and seed crops, leading to an increase of roughly +50% for all crop groups, with increased variability among regions. Adaptations measured proposed are a mix of costless simple changes in crop cycle length and timing, and the adaptation of non-limiting irrigation, the latter being less reasonable in regions where water resources already limit irrigation and are projected to decline, or for cases not already irrigated, for which we have no information on associated variable costs. This question will be further investigated.

Scenario			**A2**						**B1**					
Crop			**no adapt**			**adapt**			**no adapt**			**adapt**		
Crop	*S. rate [%]*	*CTL A. share [%]*	*EU*	*m*	*sd*	*EU*	*m*	*sd*	*EU*	*m*	*sd*	*EU*	*m*	*Sd*
CERE	**-**	**-**	**18**	**15**	**±28**	**48**	**43**	**±36**	**11**	**11**	**±29**	**28**	**37**	**±57**
Wheat	97	19	31	34	±45	58	88	±98	21	20	±44	59	82	±81
Barley	78	12	10	10	±22	19	31	±41	5	11	±23	10	29	±42
Maize	62	4	-2	-9	±35	19	21	±46	-4	-4	±43	24	27	±53
ROTU	**-**	**-**	**7**	**5**	**±69**	**45**	**55**	**±91**	**-8**	**-1**	**±73**	**44**	**49**	**±81**
Sugarbeet	94	2	7	-1	±36	37	33	±30	-11	-14	±41	38	34	±41
Potato	82	1	2	8	±76	50	67	±123	-13	10	±89	45	62	±115
SEED	**-**	**-**	**10**	**11**	**±38**	**72**	**58**	**±63**	**12**	**9**	**±36**	**64**	**53**	**±66**
Rapeseed	93	3	9	21	±44	80	79	±65	19	20	±41	77	75	±73
Sunflower	52	2	5	7	±34	61	39	±41	-34	0	±49	27	42	±60
Soybean	43	0	1	0	±1	4	0	±1	-1	-1	±2	5	0	±2

Table 2 – Selection rate (S. rate) and area share (A. share) in EU15 total utilized agricultural area (according to FADN 2002 area data) and relative changes in EU15 and FADN regions averaged yields for different crops and crop groups, for scenarios (CTL-T20, CTL-T40, CTL-T80, A2H2, B1H2). EU, m, sd denotes respectively change in EU15 average yield, mean and standard deviation among regions of change in regional yields. Crop groups labels: CERE=(soft wheat, durum wheat, barley, maize, other cereals); ROTU=(potato, sugarbeet); SEED=(soybean, sunflower, rapeseed, other oil and seed crops).

2. Farm-scale adaptations and resulting changes in agricultural supply

Each farm-type allocate optimally its resources to activities (area shares, fertilisation rates, cattle number adjustment and feeding, share of marketed vs. on-farm

consumed products) in order to maximize gross margin subject to resources typology bindings, prices, variable costs, CAP subsidies and bindings, yearly cattle demography, taxes and norms. For climate change scenarios, changes in yields generates a new farm-level optimized set of activities, assuming prices and variable costs are identical to CTL conditions. Crop management adaptations are assumed to be costless, and hence activities only result from a change in yield value and sensitivity to fertilizer input distributions among crops. Table 3 present scenario specific changes in activities and resulting supply, relative to reference CTL run. Despite significant changes in yields without crop management adaptations, mean changes over EU15 regions in land dedicated to each crop are rather small (+0±13% and -1±12% for cereals in A2 and B1 scenario; -1±31% and -4±35% for root and tuber crops; 1±13% and -1±11% for oil and seed crops) while highly variable among regions, thus hiding significant changes in regional agricultural land-use patterns.

If crop management adaptations are accounted for, gains in yields increase significantly crops marginal land profit relatively to other land-cover types implying that at European scale (mean over regions) area shares dedicated to each crop group are increased (+8±18% and +9±17% for cereals respectively in A2-adapt and B1-adapt scenarios; +15±39% and +11±35% for root and tuber crops; +5±19% and +5±16% for oil and seed crops) while meadows are significantly reduced (respectively -25±33% and -9±31% for A2-adapt and B1-adapt scenarios, compared to -2±27% and -6±26% without crop management adaptations). Total EU15 area dedicated to pastures is though reduced by 25% (A2-adapt) and 19% (B1-adapt), while area shares of cereals, root and tuber crops, and oil and seed crops are increased by respectively 7% (A2-adapt) and 9% (B1-adapt), 11% and 10%, 5% and 4%. There is a significant spatial heterogeneity in this land re-allocation since among regions standard deviation is high, indicating complex substitution patterns between different agricultural land-uses at smaller resolution.

Despite no direct effect of climate change on animal activities is included in the model we capture a few indirect effects. First while cattle populations are weakly affected (table 3), meadow area shares is significantly reduced by a lowered relative meadows marginal land productivity compared to crop activities, thus indicating a strong intensification of pasture systems (up to -25% of total EU15 meadow area share, with no significant cattle population changes). Although we do not represent direct intensification costs, this result is interesting since livestock systems are projected to be more vulnerable under climate change, and experience a reduction in production from both grassland productivity and quality reduction, and reduced digestibility from heat stress [39]. Secondly, as cereal production increases, more fodder is available and the share of marketed cereal production (not used on-farm for cattle feeding purposes) is increased at EU15 level, but its distribution over regions is highly variable and its mean over regions negative. Complex substitutions occur between fodder and different purchased feeding inputs, and mean feeding expenditures are thus increasing over regions while its EU15 aggregated value is decreasing.

Patterns in production changes follow yield and land-use redistribution, leading to high gains in mean over regions changes (at least +50% for all crop groups in both B1 and H2 scenarios) in case of crop management adaptation, highly variable among regions

(standard deviations are at least greater than mean over regions). Total EU15 production is hence increased by 52% (A2-adapt) and 54% (B1-adapt) for cereals, 61% and 58% for root and tuber crops, and +80% and +71% for oil and seed crops. Without crop management adaptation, both crop specific production changes and climate change scenarios are strongly differentiated: total EU15 of cereals and oil and seed crops are increased (of respectively 20% and 10% for A2, and 10% and 12% for B1) while root and tuber crops production is increased by 13% for A2 scenario, and decreased by 7% for B1 scenario. These gains in production could have significant impacts on agricultural good markets, hence reducing market prices and lowering land marginal productivity highlighting the need for accounting farm-scale autonomous adaptation in larger scale appraisals.

Scenario		**A2**						B1					
Activities		**no adapt**			**adapt**			**no adapt**			**adapt**		
(a) Crops		*EU*	*m*	*sd*	*EU*	*m*	*sd*	*EU*	*m*	*sd*	*EU*	*m*	*sd*
CERE	Area	1	0	±13	7	8	±18	-1	-1	±12	9	9	±17
	Production	20	17	±38	52	56	±49	10	11	±37	54	59	±46
	% marketed	4	-2	±40	8	-5	±60	4	-2	±33	10	-1	±59
ROTU	Area	5	-1	±31	11	15	±39	1	-4	±35	10	11	±35
	Production	13	5	±76	61	84	±157	-7	-2	±79	58	66	±97
SEED	Area	0	1	±13	5	5	±19	0	-1	±11	4	5	±16
	Production	10	13	±45	81	66	±74	12	8	±38	70	61	±76
(b) Cattles		*EU*	*m*	*sd*	*EU*	*m*	*sd*	*EU*	*m*	*sd*	*EU*	*m*	*sd*
Cattle pop. (LSU)		0	0	±4	0	-1	±4	0	0	±4	0	-1	±4
Meadow area		-8	-2	±27	-25	-25	±33	-5	-6	±26	-19	-29	±31
Milk production		0	0	0	±0	0	±0	0	0	0	±0	0	±0
Feeding expenditures		-2	1	±11	-2	7	±38	-2	1	±17	0	6	±36
(c) Gross margin		*EU*	*m*	*sd*	*EU*	*m*	*sd*	*EU*	*m*	*sd*	*EU*	*m*	*sd*
Gross margin		4	3	±22	19	25	±42	-1	1	±23	19	23	±34
(d) non-CO_2 GHG em.		*EU*	*m*	*sd*	*EU*	*m*	*sd*	*EU*	*m*	*sd*	*EU*	*m*	*sd*
Total (CO_2eq)		2	1	±7	7	6	±10	0	-1	±7	5	4	±9
Crop activities (CO_2eq)		7	4	±15	22	18	±24	-2	0	±17	14	14	±23
Cattle activities (CO_2eq)		0	0	±4	-2	-2	±6	0	0	±6	-2	-3	±6

Table 3 – Relative changes (to CTL reference run, in %) in regional and EU15 aggregated farm scale optimal set of crop (a) and animal (b) activities, (c) gross margin and (d) GHG emissions for A2 and B1 climate change scenarios, with and without adaptation of crop management. *EU*, *m* and *sd* denote respectively change in EU15 aggregated value, mean and standard deviation among regions of regionally aggregated values. Crop groups labels: CERE=(soft wheat, durum wheat, barley, maize, other cereals); ROTU=(potato, sugarbeet); SEED=(soybean, sunflower, rapeseed, other oil and seed crops).

Without crop management adaptation, farm scale adaptation to climate change leads to rather small aggregated EU15 and mean over regions changes in gross margin, with high variability among regions (respectively +4% and +3±22% for A2-no-adapt, and -1 and +1±23% for B2-no-adapt, see Table 4). When accounting for crop management adaptations, variability among regions is greater, but EU15 aggregated and mean over regions are greater and always positive (respectively +19% and +25±42% for A2-adapt and +19% and +23±34% for B1-adapt), with also increased variability among regions. Climate change induced rise in production with crop management adaptation may also lead to an increase in non-CO_2 GHG emissions, but in a lower proportion than total increase in cropland, mean per unit of land emissions are lowered, due to an increase in relatively low emission crops and a decrease in optimal fertilization rate. Another interesting environmental aspect would be the diagnose of irrigated volume needs for each scenario, and a further specification of locations where irrigation adoption would be possible given projected patterns, and this idea will be further developed.

CONCLUSION

Assessing climate change impact on agriculture is a complex task involving a wide range of economical and physical processes, leading to significant uncertainties. At European scale, climate change impacts on agricultural supply have been appraised to be of relatively less important driver by the end of century compared to other global. However this diagnosis is based on a incomplete diagnosis of climate change impacts, missing both spatial heterogeneity in important determinants of agricultural supply (soil, management practices, producer typology) and fine scale processes such as autonomous adaptation.

We use a modeling framework based on a spatially explicit representation of productivity and producer behavior with regard to heterogeneity in soil, climate, and producer socio-economic context to appraise climate change impacts including autonomous adaptations of EU15 agricultural supply to climate change. Our results suggest that without accounting for autonomous adaptation European agricultural supply may have interesting resilience properties at an aggregated scale, hiding significant heterogeneity at finer scales. If autonomous adaptation is accounted for, significant gains in yields may lead to (i) a significant increase in the relative profitability of crops compared to other land-covers, thus possibly increasing its agricultural land-use share over meadows, and (ii) significant increase in total European production which may have impacts on agricultural markets, thus highlighting the need for integrating fine scale processes such as autonomous adaptation.

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