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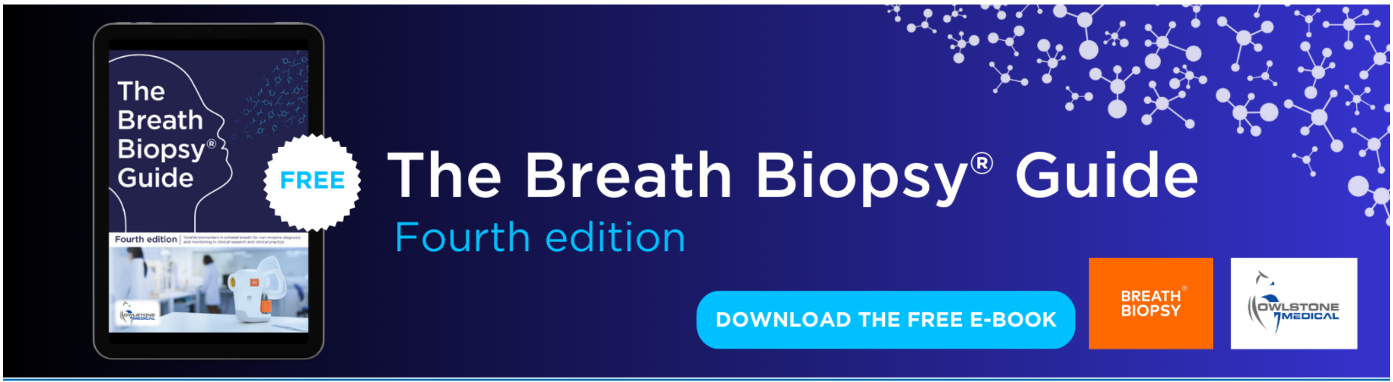

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Climate change induced transformations of agricultural systems: insights from a global model

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Abstract

Climate change might impact crop yields considerably and anticipated transformations of agricultural systems are needed in the coming decades to sustain affordable food provision. However, decision-making on transformational shifts in agricultural systems is plagued by uncertainties concerning the nature and geography of climate change, its impacts, and adequate responses. Locking agricultural systems into inadequate transformations costly to adjust is a significant risk and this acts as an incentive to delay action. It is crucial to gain insight into how much transformation is required from agricultural systems, how robust such strategies are, and how we can defuse the associated challenge for decision-making. While implementing a definition related to large changes in resource use into a global impact assessment modelling framework, we find transformational adaptations to be required of agricultural systems in most regions by 2050s in order to cope with climate change. However, these transformations widely differ across climate change scenarios: uncertainties in large-scale development of irrigation span in all continents from 2030s on, and affect two-thirds of regions by 2050s. Meanwhile, significant but uncertain reduction of major agricultural areas affects the Northern Hemisphere's temperate latitudes, while increases to non-agricultural zones could be large but uncertain in one-third of regions. To help reducing the associated challenge for decision-making, we propose a methodology exploring which, when, where and why transformations could be required and uncertain, by means of scenario analysis.

S Online supplementary data available from stacks.iop.org/ERL/9/124018/mmedia

Keywords: agriculture, climate change, adaptation, transformational change, uncertainty, robust adaptation, agricultural systems

1. Introduction

Climate change ranks highly among threats to the ability of food supply systems to meet growing demand through 2050 and could have major effects on food prices [1–6]. It is already depressing the productivity of major crops [3, 7, 8], and recent results confirm future climate changes will greatly affect agricultural supply. Yields of major crops will decrease in low latitude areas even under a local increase in temperature below 2 °C, and world-wide losses are expected for larger temperature increases [3, 9–11]. This will precipitate significant adjustments throughout the global food supply chain. Starting at field level with alternative crop management practices [11, 12] and adjustments to the location and specialization of agricultural activities, climate change adaptations will affect international trade flows and consumption levels and spur targeted research and development efforts [3, 6, 13].

Changing climate necessitates in-depth, or transformational, changes in agricultural production systems that pose specific challenges to decision-making [14–16]. As opposed to more incremental forms of adaptations, they imply large changes to either the location or the structure of regional food production capacity. Examples include the large development of irrigation in a region, extension of a rail system into a new cropping region, or the relocation of a major processing facility following a shrink in surrounding production level [15]. However, previous literature focuses on conceptual definitions and illustrative examples, and the extent to which such adaptations are required remains unclear. Furthermore, such adaptation options can be long-lived, investment-intensive or of limited reversibility and need to be anticipated and planned. However, such deliberateness is limited by large uncertainties on the aptness of specific transformations [17], which compound along a chain of assumptions regarding future emissions, climate response, crop response, and economic response [18]. Due to their limited reversibility, transformations subsequently revealed to be inadequate or wrongheaded could lock agricultural systems into a maladaptive pathway, increasing vulnerability to changes in climate and turning investments into sunk costs [19]. In addition, the potential future value of better information provides an incentive to postpone transformations.

A growing body of literature is developing strategies to overcome this challenge [20–22]. Some approaches seek to minimize regret or maximize flexibility by incorporating safety margins and reduced lifetime into the design of adaptations, while others promote soft adaptations such as incorporation of robust decision-making methods into existing decision frameworks. Given the uncertain but potentially large transformations required from agricultural systems, it is critical to map and understand the various uncertainties at stake, thereby ‘disempowering impacts of uncertainty by disaggregating the decision-making process into actionable steps’ [23]. It has been suggested that impact assessment modelling frameworks—combining general circulation models (GCMs), global gridded crop models (GGCMs) and global economic models (GEMs) of the agricultural sector—could be used to achieve this goal [24] in a signal-to-noise type of analysis.

In this study, we use the EPIC GGCM and the GLOBIOM high-resolution GEM of the agricultural sector to extend previous literature with global insights into the transformations required of agricultural systems to face climate change. Our study addresses the following questions:

- How the notion of transformation can be operationalized from GLOBIOM outputs?
- What transformations are required from agricultural systems to buffer climate change impacts?
- How robust are these transformations across scenarios?

2. Methods

2.1. Modelling of impacts and adaptations for contrasted scenarios

We use simulations from the EPIC GGCM [25, 26] to estimate yield, input level, and cost coefficients for 17 crops and 4 crop management systems spanning main input intensity gradients (rain-fed and irrigated high fertilization, rain-fed low fertilization, and subsistence farming) in the present climate and nine climate change scenarios. These scenarios span major uncertainties along the impact assessment chain along one central scenario (table 1), including anthropogenic perturbation of the climate system using four representative concentration pathways RCPs [27]; the response of the climate system using five GCMs selected to capture major uncertainties in the climate response [28]; and a scenario without the effects of increased atmospheric carbon dioxide concentration (CO_2) on plants, as a pessimistic boundary of this major uncertainty (SOM section 1.1.2). Simulations were performed in the frame of the Inter-Sectoral Impact Model Inter-comparison Project [10, 28], over more than 200 000 pixels of potential cropland on a regular 0.5° latitude–longitude grid intersected with classes of homogeneous soil, altitude, and slope and country boundaries. We re-aggregated the simulated values from 0.5° to 2° and implemented them into GLOBIOM (SOM section 1.2).

We model adaptations in the agricultural sector with GLOBIOM [29], a bottom-up global recursive dynamic partial equilibrium model of the agricultural, bio-energy and forestry sectors. Its simultaneous modelling at global scale of both regional market interactions and bottom-up evolution of production systems makes it well suited among other global models for assessing climate change induced changes to production systems. It determines prices, production, consumption and bilateral trade flows endogenously for 30 aggregated regions over 10 years time steps, and we therefore hereafter refer to time horizons as decades (e.g., ‘2050s’ to be understood as ‘the decade from 2050 on’). Demand, trade and market equilibrium are modelled at regional level, while production is modelled at the scale of agricultural production systems, defined at the above mentioned spatial resolution by combination of activities and management systems. Market prices adjust so that total production equals demands for food, feed, and energy. The ‘Middle of the Road’ shared socio-economic pathway SSP2[5]. Reference [30] is used to generate the baseline simulation including demand behaviour and

[5] It projects a population increase up to 9.2 billion individuals by 2050, and more than a doubling of income per capita compared to 2000—see http://secure.iiasa.ac.at/web-apps/ene/SspDb/dsd?

Table 1. Scenario assumptions.

Scenario	Climate change assumption: RCP	GCM	CO_2 effects	Socio-economic assumption
Baseline				
	Constant present climate and CO_2 level			SSP2
Central scenario				
	8.5	HadGEM2-ES	Yes	SSP2
Radiative perturbation uncertainty {RCP}				
	2.6 4.5 6	HadGEM2-ES	Yes	SSP2
Climate response uncertainty {GCM}				
	8.5	IPSL-CM5A-LR GFDL-ESM2M MIROC-ESM-CHEM NorESM-1 M	Yes	SSP2
CO_2 effects uncertainty {CO_2}				
	8.5	HadGEM2-ES	No	SSP2

Note: The specific effect of climate change is diagnosed by comparing nine different climate change assumptions to the baseline, incorporating SSP2 socio-economic assumptions common to all scenarios. The nine climate change scenarios consist in a central scenario (in grey) and variations around the choice of the emission pathway (RCPs, three alternative scenarios), the climate model (GCMs, four alternative scenarios) and increasing CO_2 effects on crops (CO_2 effects, one alternative scenario).

production possibilities (e.g., technological progress) from 2000s to 2050s under present climate.

We define adaptations to climate change scenarios as the changes in endogenous variables occurring under these scenarios relative to the baseline. This definition allows representing difference in decisions of agents due to the sole effect of changes in climate, and is consistent with IPCC definition of '*the process of adjustment to actual or expected climate and its effects*' [31], as well as with common definitions in earlier studies using modelling tools (e.g., [2, 5]). At regional scale, consumers modify their consumption level by product, and alter their origin between regional production and imports from various regions. As summarized in table 2, at high spatial resolution producers adapt by altering field-scale crop management practices (as simulated by EPIC, see SOM section 1.1). They also alter existing cropland allocation to various crops and managements within limits set by maximal conversion rates per time step. This includes shifts from rainfed to irrigated production at high resolution with maximal expansion rates, while accounting for current regional water scarcity (SOM section 1.5). Producers can also alter the extent of cropland within the limits imposed by land use change costs, competition with other uses, a maximum per time-step conversion rate and regional land scarcity costs (SOM section 1.4). Overall, producers thus adapt to changes in local production possibilities and costs (affected by climate change through inputs from EPIC) and to market forces of demand and competition. Technological progress is exogenous, and we do not include adaptations such as introduction of crops not initially present in a spatial unit, changes in cultivars, or endogenous directed technological progress. We do not account for future changes to the availability of water resource for irrigation purposes.

2.2. Defining transformational change at the scale of agricultural systems

There is no clear operational definition of transformational adaptations in agriculture beyond the idea of significant change either to the rationale for using land within system or to the location of a system to pursue the same goal [15, 16]. Criteria include the depth, generality, extent or permanence of changes within a system, or of impacts outside the system [15], but also pro-activeness, knowledge and financial investment as well as lifetime of adaptations [23, 32, 33]. Examples range from land acquisition in a remote location by producers in Australia either in reaction or in anticipation of changes in climate [34], to the historical paradigm shifts in farming activities in developed countries throughout the 20th century [16]. Our modelling framework cannot diagnose endogenously paradigm shifts in the use of cropland by producers since they are assumed to always react to on-going changes in local biophysical (e.g., yield) and market conditions to maximize profits. It is better suited to investigate the notion of transformation based on large changes to the use of land and water resource. To separate classes of agricultural systems adaptations in our model, we compiled qualitative and quantitative estimates regarding their lifetime, irreversibility, and knowledge and financial investment requirements

Table 2. Classification of modelled adaptations at the scale of agricultural systems, from incremental to transformational.

Adaptation options	Example	Lifetime[a]	Investment level		Irreversibility level	Type	Representation in the modelling framework
			Financial	Knowledge			
Existing crop management practices	Alter sowing date, crop cultivar precocity or input level	5 years	Low	Low	Low		
Allocation of existing resources to activities	Reallocate existing cropland or irrigation facilities to different crops	5 years	Low	Low	Low	Incremental	Choice of sowing and harvesting dates, input level by systems and crops in EPIC
Acquisition of new equipment	Invest into new irrigation or fertilization equipment	20–30 years	High	Medium	Medium	Systemic	
Large development of irrigation	Large increase in irrigated water use requiring new water infrastructure	50–75 years	High	High	High		Choice of acreage by crop and management system within cropland in GLOBIOM
Abandon or convert cropland in existing agricultural zones	Switch to forest plantations, farm exit and land abandonment	30 years	High	High	High	Transformational	
Development of agricultural activity in non-agricultural zones	Expansion of cropland over other land covers	10 years	High	High	High		Competition between cropland, grassland, and other land covers in GLOBIOM

[a] Estimated from Reilly and Schimmelpfennig, (2000), Smith, Horrocks and Hamilton (2011), Jones and McInnes (2004).

(table 2) from various sources [23, 32, 33], with a particular focus on changes in the use of land and water resources.

One class consists of incremental adaptations, including adjustments in crop management practices (altering crop calendar or nutrient and water input levels), or in cropland allocation among existing crops. These are tactical choices requiring minimal financial investment, few cropping seasons for the mastery of associated managerial skills, and can be reversed from one cropping season to another. They can be routinely implemented by farmers in anticipation of changes in yields and prices over short time periods [12, 35–38].

Adaptations become systemic and then transformational in proportion to their irreversibility, capital requirements, lifetime, and impact. For example, shifts from rainfed to irrigated systems are systemic due to estimated lifetimes of 20–30 years and significant capital requirements (table 2). Irrigation expansion becomes transformational when undertaken on a scale which exacerbates competition for water resources, affecting other users and potentially prompting large additional investments in long-lived water storage and distribution infrastructures (table 2). Similarly, we use the density of agricultural areas to trace transformational change because of underlying significant level of irreversibility and investments assumed in the literature (table 2). Expensive investment into transport and processing infrastructure would be required to build production capacity in new areas, while losses in the production capacity of established (i.e., dense) cropland areas may be lost over long time due to workforce migration and infrastructure degradation. For each time step we classified pixels into either agricultural or non-agricultural zones within each region: we compute in each pixel the cropland density as the share of cropland over total land available in the baseline scenario. In each region, pixels which fall above (respectively below) the third quartile in cropland density are classified as part of agricultural (respectively non-agricultural) zones. This definition does not distinguish underlying reasons between biophysical (e.g., unsuitable land) or socio-economic (e.g., protection policies, low access to market) factors although GLOBIOM accounts for both (SOM section 1.4). We thus focus on three different transformational adaptations of agricultural systems in a region: large increase in irrigated area (>25%, assuming large investment and lifetime related to a change in water resource), large cropland increase (>20%) in non-agricultural zones (i.e., pixels whose share of cropland is relatively low compared to other pixels in the same region, and where a large investment need is assumed in order to increase sectoral production capacity) and large cropland reductions in agricultural zones (>10%, large irreversibility related to loss in sectoral production capacity).

2.3. Exploring the robustness of transformations in agricultural systems

Uncertainty in the magnitude and the direction of appropriate transformational change is problematic, as ex-post adjustment of decisions will often be financially and politically very costly [23]. In this context, any transformational adaptation is a risky choice and the hope of more accurate information in the future acts as an incentive to postpone it. From a decision-making perspective, it is crucial to know when transformations are required, but also whether they are robust across plausible scenarios, as well as the extent to which robustness could be improved by uncertainty reduction. To quantify the robustness of a transformational change over a set of scenarios, we propose a signal-to-noise type of scenario analysis. On the one hand, we define the *signal* as the largest magnitude of an adaptation (e.g., increase in irrigated area) across scenarios[6], and compare it to a threshold to indicate whether a transformational change is required or not. On the other hand, we define the *noise* as the range of the adaptation across all scenarios: a noise larger than the signal indicates non-robustness, i.e., either uncertainty in the need for transformational change or very large uncertainty in extent.

By varying the time horizon of the analysis (2020s, 2030s, 2040s and 2050s), we derive when the need for a transformation arises and whether this need is robust or not across scenarios. By varying the set of scenarios considered, we diagnose whether the need for a transformation could be more robust while assuming lower uncertainty, and whether one scenario dimension can be identified as crucial to reduce uncertainties in required transformations.

3. Results

3.1. Direct biophysical impacts and their uncertainties

By mid-century, climate change will have large biophysical impact on crops yields, equivalent to a −18% to +3% change in global vegetal calorie supply compared to the baseline scenario (first column of figure 1). However, impact varies among regions, crops, and management systems, thereby providing opportunities for targeted adaptations. Firstly, biophysical impacts greatly differ at large scales: when the world is split in ten macro regions (SOM section 1.3), the impacts vary not only in magnitude but also in direction (except for one scenario, SOM section 2.1, table ST2). This large-scale spatial variability of the impacts of climate change is a robust finding in the literature [3, 5, 10, 39], and invites world-wide redistribution of production systems. Secondly, impacts vary across crops (from −24% for oil palm to +17% for barley) and management systems (from −7% for irrigated high input systems to −2% for rainfed low input systems, table ST3 in SOM). Such a range is also consistent with literature [3, 10, 40] and allows for adaptation through local changes in the specialization and management of agricultural systems.

Several assumptions regarding underlying phenomena contribute to each climate scenario and each of these affects impact patterns—and by extension adaptation opportunities—differently. Increasing atmospheric carbon dioxide concentration, for example, increases plant light and water-use

[6] Standard definition of signal relies on most likely values. However, given the limited number of scenarios and the ambiguity characterizing their distribution, maximum value provides a more meaningful way to delineate potential transformations.

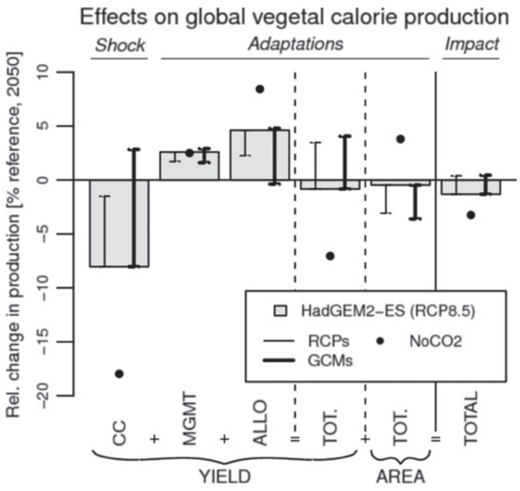

Figure 1. Climate change shocks, adaptations, and final impacts on global vegetal calorie supply, in percentage of change relative to the reference supply without climate change in 2050. From the left to the right, the figure displays the initial climate change biophysical effects on productivity (Shock), effects of subsequent adaptations through various mechanisms (Adaptations), and final impact on supply (Impact). Changes in the allocation of crop management systems (MGMT), and production relocation (ALLO) sum up with the biophysical effects to modify global cropland productivity (TOT. YIELD). In addition, production is also affected by a change in global cropland extend (TOT. AREA). Bars present the climate change scenario for GCM HadGCM2-ES under RCP 8.5, while solid error bars denote the range for four other GCMs under the same RCP (thick) or three other RCPs under the same GCM (thin). Dots represent values for HadGCM2-ES GCM under RCP 8.5 without increasing [CO_2] effects.

efficiencies [41], but crop models such as EPIC could be optimistic [42]. Assuming no CO_2 effects worsen biophysical impacts on yields by about 10% at global scale (figure 1), but do not alter much the ranking of impacts across regions, crops and crop management systems (section 2.1 of SOM). The range associated with climate responses (using alternative GCMs) on a global scale is similar (11%), but in this case the effects of each climate response vary greatly across regions, crops, and crop management systems (section 2.1 of SOM), probably due to a large disagreement on changes in rainfall patterns [43, 44]. Alternative emissions pathways have similar effects but with overall lower amplitude (section 2.1 of SOM). This might be particular to the 2050 time horizon; emission pathways are expected to dominate over longer time scales due to divergence in cumulative emissions [45–47]. Finally, not all macro regions show similar sensitivity of impacts to the various scenario dimensions: high latitude temperate regions show greater variability in biophysical impacts, while tropical to subtropical regions face more systematically negative impacts (section 2.1 of SOM).

3.2. The role of supply-side adaptations and indirect effects through markets

After accounting for adaptations, global vegetal calorie supply is reduced by only 3% at worse (last column of figure 1). This is consistent with earlier estimates, which reported final climate change impacts on global food consumption of a few percent by 2050s, with however significant spatial variability [3, 5]. Several supply-side adaptations combine to mitigate the effects of climate change. Using a decomposition method (section 2.2 in SOM), we estimate that global-wide shifts in management systems compensate for negative yield impacts by an equivalent of 2–3% of baseline global vegetal supply (second bar from the left). Underlying changes in management are crop, region and scenario specific but global scale irrigation development plays a significant role (SOM section 2.3). Crop substitution and relocation of production systems further compensates by up to 8% of baseline global vegetal supply (third bar from the left), with about one third of simulated cropland reallocations occurring trans-regionally (section 2.2 of SOM). This highlights the important role of trade at facilitating production reallocations between regions [5, 48–50]. After these adaptations (and including CO_2 effects), climate change results in yield gains of up to +4% (third bar from the right), while global cropland is reduced by up to 4% (last bar).

The various scenario dimensions modulate adaptation portfolios. Negation of CO_2 effects (figure 1, black dots compared to grey bars) almost doubles gains from reallocations, with small effects on the share of land reallocated within and among macro regions (SOM section 2.2). Overall, the final yield effect is negative and new land needs to be put into cultivation while the impact on final supply is twice worse. Climate model assumptions have the highest impacts on reallocation effects (thick error bars in figure 1), but only weakly affect gains from crop management system switches. Emissions pathways (thin error bars in figure 1) have a similar effects over smaller ranges.

Market interactions are another important, if indirect, driver of adaptations, as has been reported in the literature [1, 2, 49–52]. For example, despite the negative yield impacts of the HadGEM2-ES climate model (RCP 8.5 with CO_2 effects) in Latin and Central America (LAM), final supply, agricultural area, and net exports grow in this scenario relative to the baseline (figure 2). This occurs in most scenarios, due to heightened competitiveness of producers in LAM over those in Northern America (NAM, see SOM sections 2.2 and 2.5). Such effects are highly region-specific: the Middle East and Northern African regions (MNA) almost always become more competitive, while comparative advantage tends to decrease in the Commonwealth of Independent States (CIS) and Oceanic (OCE) regions. The effect on European regions (EUR) varies among scenarios without a clear trend. Sub-Saharan Africa (SSA) displays consistently weak adaptation due to world-high demand elasticity through 2050s as well as the predominance of subsistence production systems, for which reallocations are restricted. These regions contrast with Asian regions (EAS, SAS and SEA), where adaptation is facilitated by less elastic demand and larger ability to reallocate production systems internally. This illustrates a form of adaptive capacity implicitly embedded in region-specific model (e.g., demand, trade and land use change specifications), and socio-economic scenario (e.g., GDP and population trajectories) assumptions.

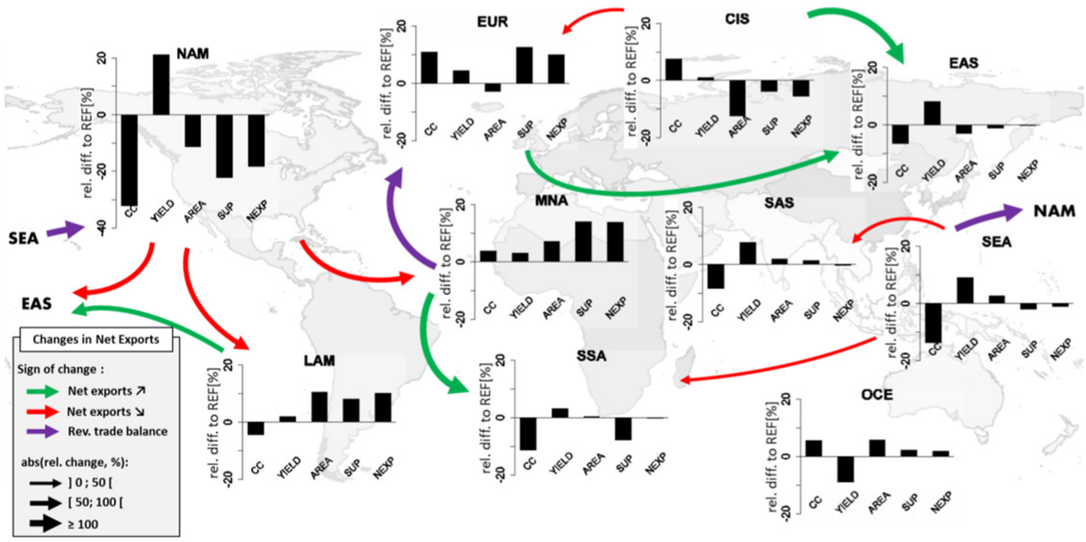

Figure 2. Continental scale impacts of and adaptation to climate change by 2050 for HadGEM2-ES climate model under RCP 8.5 (incl. CO_2 effects). Individual graphs show for each continental region the biophysical shock on total vegetal calorie supply (CC), and changes in four other variables, all expressed in percentage relative to the supply in the reference scenario without climate change. These variables are: gains in supply through internal changes in yield by altering cropland allocation and management (YIELD) and changes in cropland total area (AREA), final effect on supply (SUP), and changes in net export flows (NEXP). Arrows display qualitative information on the main changes in net trade flows between regions, relative to the baseline. Green, red and purple colours indicate respectively increased, decreased, and reversed net exports flows between two regions. Thickness of arrows indicates the amplitude of change in net exports.

3.3. Implied transformations at the scale of production systems

Changes in the management, location and specialization of production systems translate at the scale of agricultural systems into different categories of adaptations. We illustrate with three individual countries how we distinguished those of a transformational nature (figure 3). Adjustment of cropland allocation among existing crops is of incremental nature. In the HadGEM2-ES/RCP 8.5 scenario (figure 3, 6–9th bars from the top in each panel), the area occupied by soybean increases by an equivalent of 7% of total cropland in Brazil at the expense of dry beans (−2%), rice (−2%), and other crops (−3%). In Mexico, sorghum partially supplants dry beans and corn, while in the USA corn replaces wheat and cotton.

Larger changes to resource use imply transformational change for agricultural production systems. Relative to the baseline, cropland expands +26% in Mexico and decreases by 14% in the USA under the HadGEM2-ES (RCP8.5 with CO_2 effects) climate model by 2050s (figure 3, 2nd bar from the top). Cropland decreases by 13% in agricultural zones of the USA (figure 3), above the threshold defining transformational change and implying sectoral capacity loss not easily reversed. Similarly, for Mexico cropland increases in non-agricultural zones are three times greater than in agricultural zones (respectively +36% and +12%) and reaches a transformational extent implying significant infrastructural investments. The rationale for these changes lies in complex interactions between local biophysical properties, the opportunities offered by reallocations, and changes to comparative advantages across regions. For example, in the USA for this scenario the biophysical impacts are negative while the yield differential between agricultural and non-agricultural zones is halved (SOM section 2.5). Exports are cut and USA production capacity is reoriented towards domestic demand: remote climate change impacts induce in this scenario a loss in comparative advantage on international markets, while demand is rather inelastic. At the same time, Mexico reduces its net imports and increases its production capacity through cropland expansion into non-agricultural zones, but demand is strongly affected by competition with American consumers.

Lastly, irrigated areas increase in this scenario by 28%, 31%, and 33% by 2050s in respectively Mexico, the USA, and Brazil (figure 3, 5th bar from the top in each panel) where it is an important adaptation lever (SOM section 2.3). However, water use for irrigation increases by more than 20% in already water limited regions such as Mexico and the USA, where a doubled water scarcity cost limits irrigation expansion (section 2.4 in SOM).

3.4. Exploring transformation robustness across scenarios, time and space

Through scenario analysis, we diagnose *where* transformations are required, their *robustness*, as well as the factors shaping this robustness. For example, the maximum cropland decrease in agricultural zones across scenarios (figure 4(b)) is larger than −10%—and thus in the transformational range—in one third of regions by 2050s (red and green colours) but the amplitude of change is large in all these regions (red colour, non-robust) but CIS (green colour, robust). Similarly, in another third of regions, transformational cropland development (i.e., >+20%) in non-agricultural zones is expected although robust in only two regions (figure 4(c)). Most of the former cases are located in temperate latitudes of the Northern Hemisphere with significant uncertainty in yield impact (figure 4(a)), while the later are geographically scattered.

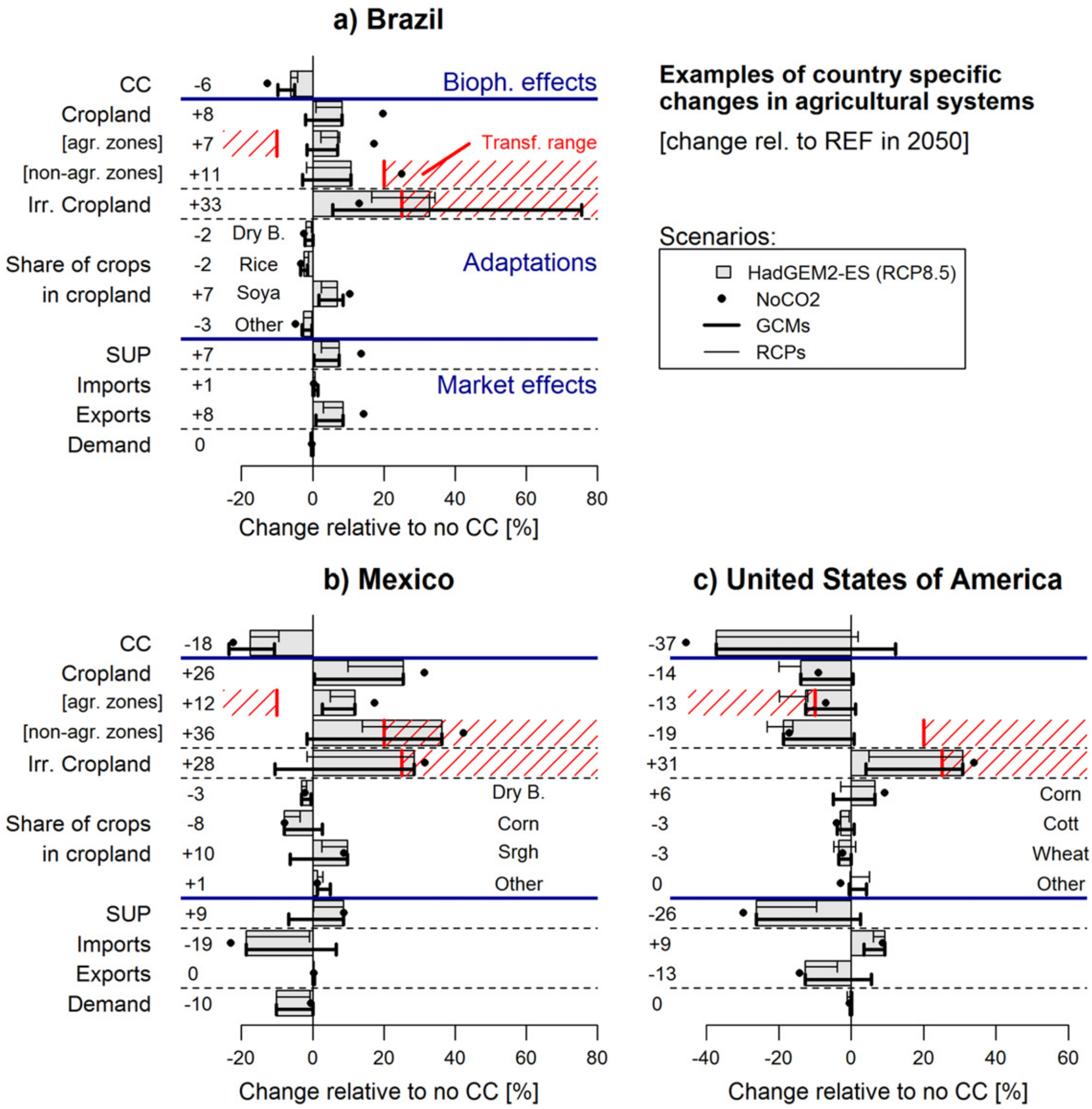

Figure 3. Adaptations at the scale of agricultural systems in Brazil, Mexico, and the USA by 2050. Panels display in individual regions climate change effects and adaptations of agricultural systems for the central scenario (HadGEM2-ES × RCP 8.5 × CO_2, and figures) and their spread across different climate models under RCP 8.5 (thick error bars), across different emission pathways for HadGEM2-ES (thin error bars), and the effect of not accounting for CO_2 effects (dots). In each panel, bars display the aggregated biophysical effect (CC), systems' adaptations (relative differences to the no climate change reference for cropland area in total as well as in agricultural and non-agricultural zones, irrigated cropland, and the share of various crops within total cropland—in % cropland area), as well as market effects (final supply, trade flows and final demand). For three adaptations options of systems, red hatched areas display the range above which they are considered as transformational (as delimited by thresholds, see section 2.2).

Uncertain market indirect effects add to biophysical uncertainties (SOM section 2.2 table ST5): for example productivity gains in CIS or EUR do not necessarily translate to increased competitiveness due to sometimes limited export possibilities, leading to cropland losses. Similarly, the development of non-agricultural zones in Brazil under most (but not all) climate change scenarios despite robustly negative impacts (figure 4(a)) stems from non-robust opportunities of increased export to the USA (SOM section 2.2 table ST5). Overall, almost none of these transformations are robust across scenarios: this is also the case for large development of irrigation, the most wide-spread transformation. For about 70% of regions by 2050s, such a transformation could be relevant although not robust across all scenarios (figure 4(d)). This owes to the large uncertainties in future rainfall patterns and crop water-use efficiency, and would be worsen if we had accounted for the very uncertain projected changes to the availability of water resource for irrigation purposes [53] due to an increasing competition with other usage and climate change [54], and depletion of unsustainably used water resource [55].

In such a context, knowing *when* transformations could be required, and their robustness over time are crucial information. Table 3 summarizes the information contained in figures 4(b)–(d) but repeated for various time horizons for all scenarios (ALL columns, see SOM section 3 for individual maps), the numbers indicating for each macro regions and time horizon (rows) and type of transformation (column

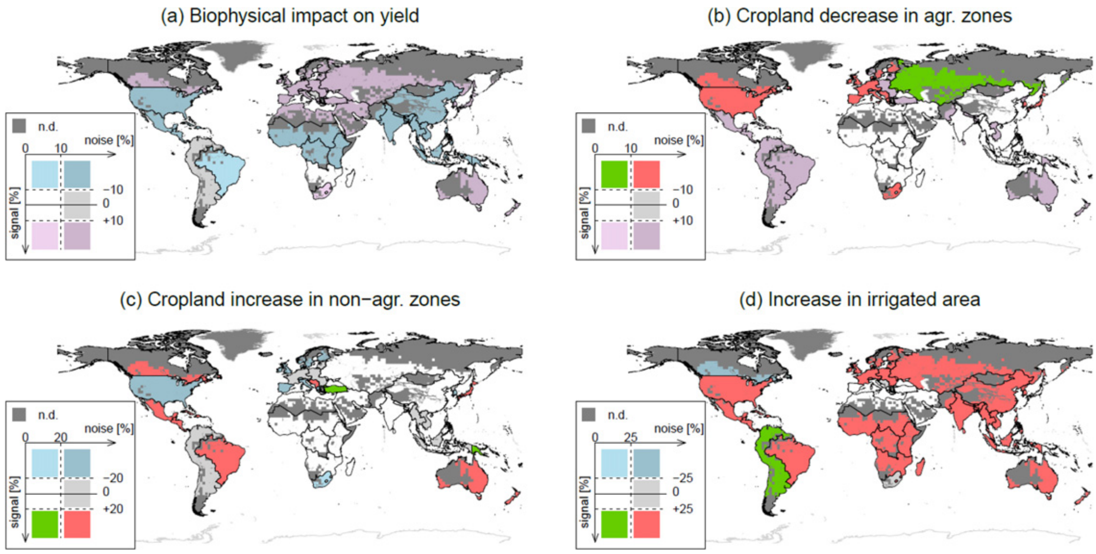

Figure 4. Map of signal to noise ratio for biophysical impacts (a) and induced transformations (b)–(d) of agricultural systems by regions in 2050s. Panel (a) displays the biophysical effect of climate change on crop yields (aggregated over crops, in calories). Panels (b)–(d) display changes at the level of GLOBIOM regions in various adaptation responses to climate change (change relative to the baseline by 2050): cropland area in respectively agricultural and non-agricultural areas (see section 2.1 for definition), and irrigated area. For panel (a), colour tones indicate whether the signal (value in most extreme case across scenarios) is strongly negative (light and dark blue, value inferior to a threshold), strongly positive (light and dark purple, value superior to a threshold) or less strong (white and light grey, absolute value inferior to a threshold). Light (respectively dark) colours indicate robustness, i.e., whether the noise (range of impact/response across scenarios) is lower (respectively larger) than the threshold. In panels (b)–(d), the same colour code prevails except that for each panel, we highlight robust and non-robust transformations in respectively green and red colours. Thresholds for adaptation response separate potentially transformational response, and are 25%, 20% and 10% for change in respectively irrigated area, marginal cropland, and dense cropland. Similarly, a threshold of 10% indicates strong biophysical impact.

groups) the number of regions within a macro region for which a transformation could be required (i.e., signal larger than threshold, either red or green colour in figure 4), and the number of these cases being robust across scenarios in parenthesis (green colour in figure 4). Transformational cropland decrease in agricultural zones could develop as early as 2020s in the USA and Southern and Eastern EUR where it would remain non-robust, whereas in other regions such a transformation would potentially occur only by 2040s, and would even be robust by 2050s for CIS. Similarly, developments of non-agricultural zones would not be required until 2040s for most concerned regions (except for Canada), but would generally remain non-robust across scenarios (except for Turkey by 2050s). On the contrary, transformational developments of irrigation could occur as early as 2020s in regions like Mid-Western Europe, Brazil, India, Australia or Southern Africa, and would quickly expand to Asian and Sub-Saharan regions from 2030s onwards. While the potential such transformation rapidly expands, it also remains largely non-robust across scenarios. In addition, columns ALL-{GCM}, ALL-{RCP} and ALL-{$n\mathrm{CO}_2$} in table 3 present the same information as above, but if removing from the set of scenarios considered respectively GCMs other than HadGEM2-ES, RCPs others than RCP8.5, or the no-CO_2 scenario. For example, assuming the climate response would be much closer to that simulated by the HadGEM2-ES model than by other GCMs (ALL-{GCM} column) would remove the need for transformational increases in irrigated area by 2040s in five regions (from 17 to 12) and make it robust in three other regions (2–5). Two main results can be highlighted: first, uncertain reductions in a single scenario would only weakly reduce cases of non-robust need for cropland increase in non-agricultural zones, but could reduce up to two thirds of cases of non-robust need for transformational either increased irrigation or decreased cropland in agricultural zones. Secondly, over most time horizons and transformations, a more accurate climate response would best clarify the need for and robustness of transformations, as compared to other scenario dimensions.

4. Discussion and conclusions

To our knowledge, we provide the first global scale attempt to separate transformational change from other adaptations required from agricultural production systems to cope with climate change. We use the GLOBIOM model to investigate three transformational adaptations, based on literature: a large development of irrigated area as a proxy for changes to water resource management infrastructures, and a large increase (respectively decrease) in cropland area in places where cropland is occupying a small (respectively large) area share as a proxy for changes to transport and processing infrastructures and employment. Our results show that by 2050s established agricultural zones could decrease significantly in mid- to high-latitudes of the Northern Hemisphere, triggering migration of labour out of the agricultural sector and disappearance of processing activities. Cropland could increase

Table 3. Development through time of uncertain transformations, and effects of uncertainty reduction in various scenario dimensions.

			Cropland reduction in agr. zones				Cropland increase in non-agr. zones				Increase in irrigated area			
			Scenarios				Scenarios				Scenarios			
Time Horizon	Group of regions	(#)	ALL	ALL -{GCM}	ALL -{RCP}	ALL -{nCO_2}	ALL	ALL -{GCM}	ALL -{RCP}	ALL -{nCO_2}	ALL	ALL -{GCM}	ALL -{RCP}	ALL -{nCO_2}
2050s	**ALL**	[30]	**10 (1)**	**5 (1)**	**9 (1)**	**11 (2)**	**9 (2)**	**7 (2)**	**9 (2)**	**6 (2)**	**22 (1)**	**19 (3)**	**22 (2)**	**21 (1)**
	LAM	[4]	—	—	—	—	3	3	3	1	4 (1)	4 (2)	4 (1)	4 (1)
	NAM	[2]	2	1	1	2	1	1	1	1	1	2	1	1
	SSA	[5]	1	1	1	1 (1)	—	—	—	—	4	4 (1)	4 (1)	4
	MNA	[2]	—	—	—	—	1 (1)		1 (1)	1 (1)	—	—	—	—
	EUR	[7]	4	1	4	5	1	1	1	—	5	4	5	4
	CIS	[1]	1 (1)	1 (1)	1 (1)	1 (1)	—	—	—	—	1	—	1	1
	EAS	[3]	2	1	2	2	1	1 (1)	1	1	2	—	2	2
	SAS	[2]	—	—	—	—	—	—	—	—	2	2	2	2
	SEA	[2]	—	—	—	—	—	—	—	—	2	2	2	2
	OCE	[2]	—	—	—	—	2 (1)	1 (1)	2 (1)	2 (1)	1	1	1	1
2040s	**ALL**	[30]	**9**	**3 (1)**	**8 (1)**	**9 (1)**	**3**	**2 (1)**	**3**	**2**	**17 (2)**	**12 (5)**	**16 (2)**	**17 (3)**
	LAM	[4]	—	—	—	—	1	1 (1)	1	—	3 (1)	2 (2)	2	3 (1)
	NAM	[2]	1	1 (1)	—	1	1	1	1	1	—	—	—	—
	SSA	[5]	1	1	1 (1)	1	—	—	—	—	5	3 (1)	4 (1)	5
	MNA	[2]	—	—	—	—	—	—	—	—	—	—	—	—
	EUR	[7]	6	1	6	6	—	—	—	—	3	2	3	3
	CIS	[1]	1	—	1	1 (1)	—	—	—	—	—	—	—	—
	EAS	[3]	—	—	—	—	—	—	—	—	1	—	2	1
	SAS	[2]	—	—	—	—	—	—	—	—	2 (1)	1 (1)	2 (1)	2 (1)
	SEA	[2]	—	—	—	—	—	—	—	—	2	2	2	2 (1)
	OCE	[2]	—	—	—	—	1	—	1	1	1	1	1	1
2030s	**ALL**	[30]	**6 (1)**	**5 (2)**	**4 (1)**	**6 (1)**	**1**	**1 (1)**	**1**	**1**	**12**	**8 (5)**	**12 (1)**	**11**
	LAM	[4]	—	—	—	—	—	—	—	—	1	1 (1)	1	1
	NAM	[2]	1	1 (1)	—	1	1	1 (1)	1	1	—	—	—	—
	SSA	[5]	1	1	—	1	—	—	—	—	4	2 (1)	4 (1)	3
	MNA	[2]	—	—	—	—	—	—	—	—	—	—	—	—
	EUR	[7]	4 (1)	3 (1)	4 (1)	4 (1)	—	—	—	—	3	2	3	3
	CIS	[1]	—	—	—	—	—	—	—	—	—	—	—	—
	EAS	[3]	—	—	—	—	—	—	—	—	1	—	1	1
	SAS	[2]	—	—	—	—	—	—	—	—	1	1 (1)	1	1
	SEA	[2]	—	—	—	—	—	—	—	—	1	1 (1)	1	1
	OCE	[2]	—	—	—	—	—	—	—	—	1	1 (1)	1	1

Table 3. (Continued.)

			Cropland reduction in agr. zones				Cropland increase in non-agr. zones				Increase in irrigated area			
			Scenarios				Scenarios				Scenarios			
Time Horizon	Group of regions	(#)	ALL	ALL -{GCM}	ALL -{RCP}	ALL -{$n\mathrm{CO}_2$}	ALL	ALL -{GCM}	ALL -{RCP}	ALL -{$n\mathrm{CO}_2$}	ALL	ALL -{GCM}	ALL -{RCP}	ALL -{$n\mathrm{CO}_2$}
	ALL	[30]	**5 (1)**	**3 (2)**	**4 (1)**	**2**					**7 (3)**	**4 (2)**	**7 (3)**	**7 (3)**
	LAM	[4]	—	—	—	—	—	—	—	—	1 (1)		1 (1)	1 (1)
	NAM	[2]	1	1 (1)	—	—	—	—	—	—	—	—	—	—
	SSA	[5]	—	—	—	—	—	—	—	—	1	1	1	1
	MNA	[2]	—	—	—	—	—	—	—	—	—	—	—	—
2020s	EUR	[7]	4 (1)	2 (1)	4 (1)	1	—	—	—	—	3	2 (1)	3	3
	CIS	[1]	—	—	—	—	—	—	—	—	—	—	—	—
	EAS	[3]	—	—	—	—	—	—	—	—	—	—	—	—
	SAS	[2]	—	—	—	—	—	—	—	—	1 (1)	1 (1)	1 (1)	1 (1)
	SEA	[2]	—	—	—	—	—	—	—	—	—	—	—	—
	OCE	[2]	—	—	—	—	—	—	—	—	1 (1)		1 (1)	1 (1)

For different time horizons, values in the three groups of columns indicate the number of GLOBIOM regions (within macro regions in rows) that are affected by three transformational adaptations in the most extreme scenario: respectively decrease of cropland in agricultural zones larger than −10%, cropland increase in non-agricultural zones larger than +20%, or increase in irrigated area larger than +25% (either red or green colours of figure 4 for panels respectively (a)–(c)). Values in parenthesis indicate the number of these cases for which the change is robust across the subset of scenarios (green colour in figure 4). For each group of columns, values are displayed for all scenarios (*ALL*), and subset of scenarios if removing scenarios corresponding to one scenario dimension: respectively climate models (*ALL*-{*GCM*}, i.e., leaving only four scenarios differing by RCPs, and one by CO_2 effect), emission pathways (*ALL*-{*RCP*}), and CO_2 effect (*ALL*-{nCO_2}).

substantially in non-agricultural zones of other regions of Northern, Central and Latin America, Australia, Turkey, Balkan countries as well as in Japan, requiring anticipatory investments in processing chains and physical infrastructure. Lastly, in most of the world, irrigated areas could greatly increase due to climate change, requiring investment into irrigation equipment and water resource management infrastructures. These definitions have limitations: first they are only proxies for adaptations of limited reversibility and high investment requirements, which are only implicitly modeled. In addition we did not address certain sustainability aspects such as greenhouse gas balance, soil and biodiversity degradation or groundwater depletion: it could make certain of the diagnosed transformations less desirable. Nonetheless, our contribution provides a global view on transformational adaptations that is complementary to previous literature focused on conceptual definitions combined with illustrative examples [15, 16, 24]. Adaptation research is still an emerging field [56, 57] and further work is required to acquire data and develop appropriate modelling approaches [58, 59], in particular concerning the sustainability criteria of transformations, and decisions related to options of limited reversibility and high capital and knowledge requirements.

In addition, we assess the strength of trends toward particular transformative adaptations in agricultural systems, and explore their link to various mechanisms and scenario dimensions. We find most of the above-mentioned transformations to be of largely uncertain magnitude and often direction across scenarios. We highlight the main factors shaping this non-robustness: first, the various scenario dimensions have distinct effects. Spatial patterns of direct biophysical impacts vary among climate models on both large and smaller scales leading to scenario-specific relocations of production systems across and within mains regions, while uncertainties with respect to CO_2 effects inflate everywhere the range of potential cropland increases. Secondly, socio-economic assumptions further stratify regions according to their response to variable biophysical shocks through indirect market effects. For example, price and demand elasticity differentials across regions drive large-scale decommissioning of cropland in Northern America and Europe while boosting output in LAM. Many of the baseline scenario assumption and model features contributing this effect relate to the notion of adaptive capacity and this link should be further investigated. Finally, uncertainties concerning changes in precipitation regimes and crop water-use efficiency inflate the potential need for large developments of irrigation. Overall, all these uncertainties should systematically be included in any impact and adaptation assessment unless their range is fundamentally reduced.

We did not include all sources of uncertainty in the climate change impact and adaptation assessment chain. Importantly, for the same climate change scenarios, estimates of direct biophysical impacts greatly differ across crop models [10], and do not yet include the impacts of sea-level rise, changes in pest, weed, and disease pressures, and tropospheric ozone [9]. Some adaptation measures are not accounted for (e.g., directed technological change or implementation of crops new to a region). Indirect market effects and region- and scenario-specific adaptation portfolios also depend on the chosen economic model and baseline scenario [5]. As a result, we do not claim to provide an exhaustive view of the range of considered transformations required from agricultural systems to cope with climate change. Yet, our results emphasize that uncertainties in required transformation of agricultural production systems are already large enough to challenge their adequate achievement. The risk of maladaptive decisions or delayed action could be high, thereby potentially shifting upward current impact estimates. This calls for a more intensive research effort to investigate such cases in the historical record, and estimate costs and institutional frameworks associated to maladaptative behaviour.

Lastly, although actual guidance to adaptation decision would require country-specific in-depth analysis, we propose a methodology providing practice-relevant information [17, 60] by using signal-to-noise type of scenario analysis for various time horizons and subsets of scenarios. Firstly, this could help evaluating the rationale for postponing actions of limited reversibility, by identifying which and when option are of non-robust sign or extent, and what the related key uncertainties to be reduced. This however needs to be confronted with the rate of uncertainty reduction, which is typically very low for precipitation changes, a crucial component of GCM uncertainty [61]. Secondly, the global overview clearly suggest that with respect to water and agriculture, a global effort to adopt principles of decision under high uncertainty—such as investing in no-regret and soft options, incorporating flexibility and reduced lifetime in the design of infrastructures—could be highly rewarding. This represents an important step towards delivering practice-relevant information [17, 59], which would be most valuable when associated to large stakeholder involvement and embracing broader aspect such as paradigm shifts and sustainability issues [62, 63].

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