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Assessing Market Stability under Climate-Induced Production Shocks: Agricultural Trade and Storage as Adaptation Mechanisms

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Agricultural trade and storage as adaptation mechanisms.

Abstract

Climate change and extreme weather events lead to short-term variability and shocks to agricultural supply, impacting the entire food system and posing threats to food security. Furthermore, instability in the food system may disturb other systems such as energy and water. Studies into the interdependent demand and supply relationships in these systems require a framework that can take stock of both the climate-induced deviations between expected and observed prices and yields, the impacts on the food commodity market, as well as different adaptation mechanisms that may serve as market stabilization policies, such as storage and different trade-liberalization mechanisms.

This study develops a non-stationary model for market stabilization policy design, called GLOBIOM-X. GLOBIOM-X aims to analyze the impact of climate-induced yield shocks on market stability and how market instability can be contained through the adaptation mechanisms of stockholding and trade liberalization. The model is based on the bio-economic land use model GLOBIOM. GLOBIOM-X runs in annual time steps and can address agricultural land use from the producers' perspective based on expected prices. Stockholding is incorporated in the model by allowing producers to temporarily stock their products and consumers to take-up products from storage facilities.

For the assessment of the effectiveness of trade policies and stockholding options in reducing price spikes and improving food availability, shortfalls in production based on realistic weather events have been quantified. Three types of storage scenarios; baseline-level storage, unlimited storage and storage including intervention prices and a trade reduction and complete trade liberalization scenario are implemented in order to assess their impact on market stability. Results are assessed in terms of their environmental impacts, equality and profitability. Thereby, this paper helps to give insight to what extent different types of policy measures reduce the negative impacts that yield shocks due to extreme events have on the environment, equitability amongst consumer systems and competitiveness. Both storage and trade liberalization help reduce the increase in greenhouse gas emissions, storage facilities may lead to a more equitable food system on the consumer side, whereas trade liberalization leads to more competitiveness in the EU agri-food business.

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Introduction

There is growing evidence that both the frequency and intensity of weather extremes has increased due to climate change (IPCC 2013; Schleussner et al. 2016). About a decade ago, the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) anticipated that “projected changes in the frequency and severity of extreme climate events will have more serious consequences for food and forestry production, and food insecurity, than will changes in projected means of temperature and precipitation” (IPCC 2007). Recently, the World Economic Forum considered extreme weather events amongst the top risks facing the world (World Economic Forum 2018).

Climate change alters both trend and fluctuations in daily, seasonal and annual temperature and rainfall and, thereby, agricultural production. There has been a vast amount of literature assessing long-term climate change impacts on agricultural production, mainly focusing on 50-100 year mean climate change effects on average levels of crop yields (Chen, McCarl, and Schimmelpfening 2004; Challinor et al., 2014). However, research into the impact of the variance in climate has so far lagged behind the analysis of the impact of means of climate on agricultural production and food security (Chen, McCarl, and Schimmelpfening 2004). Extreme weather events affect harvests and motivate policymaking, both in the form of disaster-relief and in the form of adaptation measures. This leads to a wedge between the increased understanding of the influence of steady weather patterns on agricultural production and the economy as a whole and the lack of knowledge on the immediate impacts of individual weather events (Frieler et al. 2017). Willenbockel (2012) analyzed the impact of possible extreme weather events on price fluctuations, and Thornton et al. (2014) reviewed impacts of climate variability and extreme events on biological and food systems in the developing world. These studies are amongst the few focusing on the variance instead of the trend in climate change. The extent to which the intensity and frequency of extreme weather events in different regions of the world will change in the short and longer-term therefore requires further investigation.

The aim of this paper is to analyze the effect of likely future yield shocks caused by extreme climate events on the agricultural sector, and how potential adaptation mechanisms storage and trade liberalization can reduce the negative impacts on the agricultural sector.

Global-climate research projects use climate models to study how climate responds to natural and anthropogenic changes to the Earth's natural systems. Anthropogenic influences on the climate system are often assessed by including greenhouse gas concentrations, pollution, and changes in land use and land cover (Bjørnæs 2011). Because GCMs differ in terms of how they model atmosphere, land, and ocean dynamics, the model differences represent uncertainties in these dynamics as well as model uncertainties (Lobell and Burke 2008). Different climate scenarios result in different probabilities and magnitudes of weather variability. To analyze their effects on the agricultural sector, we first need to quantify the effect of such climate variabilities on crop yields. The impacts of climate change on yields can be assessed using process-based crop models and their global implementations, also referred to as Global Gridded Crop Models (GGCM) and statistical models. Process-based crop models simulate a wide range of exogenous variables such as weather, plant genotypes, environmental factors and management styles on plant growth.

Together with the information on human and environmental processes, climate change and its impacts can be studied, leading to the evaluation of emission scenarios, potential economic impacts of climate change, climate mitigation and adaptation costs, feedback loops and uncertainties. It, therefore, makes the chain of climate- crop and PE and CGE models central to the study of climate change, including extreme events, as well as the study of policy adaptation measures (Moss et al. 2010). Examples of studies using such a chain include Nelson et al. (2014), Wolf et al. (2015), Leclère et al. (2014), Hertel, Burke, and Lobell (2010), Hasegawa et al. (2018).

This paper uses this chain of modelling where biophysical models estimate the impact of yield losses caused by extreme climate events. The literature and efforts on including short-run volatility in equilibrium models is scarce. Fuss et al. (2015) assessed the effects of yield variability in GLOBIOM by running the model across a finite range of yield scenarios. To distinguish between decision making based on expected yields and the outcomes of eventual yields, the various states of nature of yields are only assessed over second-stage variables such as quantity demanded, traded and processed, and not over first-stage variables such as area allocation, land use and land cover change, and livestock activities. Ermolieva et al. (2016) expand on this model by including storage capacities.

In this paper, a non-stationary partial-equilibrium model for market stabilization policy design, called GLOBIOM-X, is developed in order to assess the effect of yield losses on the agricultural sector. The model is based on the Global Biosphere Management Model (GLOBIOM).

GLOBIOM is a bottom-up recursive-dynamic, partial-equilibrium, price-endogenous model running at the level of major countries and world regions on an annual basis. Trade is modelled in a bilateral way between individual regions. GLOBIOM-X is adjusted in such a way that it can run in annual time steps and can address agricultural land use from the producers' perspective based on expected prices. GLOBIOM-X is adapted to accommodate for the differences between expected prices based on which the producer makes his decisions and realized prices and yields that are an outcome of those decisions. Stockholding is incorporated in the model by allowing producers to temporarily stock their products and consumers to take-up products from storage facilities.

For the assessment of the effectiveness of trade policies and stockholding options in reducing price spikes and improving food availability, we quantify shortfalls in production that are based on realistic weather events. Climate model forecasts in combination with process-based crop model results are used to estimate the climate-induced magnitude and likelihood of yield losses in the four main staple crops wheat, rice, maize and soybeans.

Methodology

According to Ricardian theory, the economic rent of a piece of land represents the revenues obtained from the land in its most productive use. The most profitable farming activity at any particular location is dependent on the local climate and biophysical context. Climate change may alter the relative productivity of crops in certain regions, making the crop more favourable (unfavourable) if, on average, climate moves closer to (further away from) the optimum. Under a Ricardian approach, farmers are assumed to have complete foresight, meaning that they are able to quantify the impacts of climate change in monetary terms and adjust their farming activities if another activity is more profitable over the longer term, provided costs of adjustment are inexpensive.

It is however unreasonable to assume that farmers have complete foresight and can autonomously adapt to changing weather patterns. Yield fluctuations may therefore lead to over- and under-supply. First formalized by Ezekiel in 1938, the cobweb model is the most well-known model dealing with these supply fluctuations away from the equilibrium. It assumes that producers are naive and believe that the current market price of the previous time-period will also prevail in the next time-period, thereby making errors in their expectations that can aggregate over time and generate endogenous fluctuations in market prices. These price fluctuations can either converge to an equilibrium, diverge to infinity or exhibit periodic movements (Femenia 2015).

Crop yield variability does not only depend on variability in weather, as human behaviour is also an influencing factor. To take producer and consumer's reactions to crop yield changes into account, as well as the feedback effects to other natural systems and economic sectors, simulation models covering the agricultural sector can be used (Nelson et al. 2014; Hasegawa et al., 2018). A producer's reaction to shocks can be imposed on different elements. Generally, the introduction of stochastic elements in models is partial in its nature, meaning that it only includes uncertainty in some parameters. These do not only have to relate to yield fluctuations. Price volatility can be introduced for two main reasons. First, the time lag between production decisions and observed yields introduces

short-term rigidity in agricultural supply. Second, because the demand for agricultural products is inelastic, a decrease in supply caused by an exogenous shock will lead to a large price increase. Verma and Hertel (2009) analyse the interplay between trade policies and calorie consumption in the presence of commodity price volatility. To this end, a stochastic simulation approach is applied to simulate endogenous price reactions on output volatility. Furthermore, impacts on the nutrition status of poor people are estimated by accounting for behavioural responses of low-income households to changing prices and incomes. Additional stochasticity may be introduced in models by implementing a range of values according to a certain distribution of a parameter. The most common way of doing this is by varying the yield and/or expected prices. However, different specifications of the demand (intercept, slope, elasticity), trade cost (intercept, slope, elasticity), physical storage cost, storage capacity and transportation and handling costs or macroeconomic variables may also lead to the necessary variability.

Conventional models covering the agricultural sector typically find a unique pathway for the agricultural production under climate change. With their economy-wide structure, the current CGE models can not only assess the effect on land-based sectors that are primarily affected by climate change but also the other sectors via indirect income and price effects. For example, a climatic shock on agricultural yields may affect consumption not only through a loss of production but also through a loss of GDP. PE models focus on the land-based sectors only, but with more detail and a larger number of endogenous variables. The main focus of these models to date has been on medium to long-term productivity changes and studies have not analysed inter-annual price fluctuations, e.g. from extreme weather events. There has also been less coverage of what happens when yields and prices diverge away from market equilibria.

GLOBIOM-X

This paper develops a novel model, called GLOBIOM-X, that aims to analyze the effects of short-term yield losses on the agricultural sector. The model is based on the bio-economic land use model GLOBIOM. GLOBIOM represents the world's agricultural and forestry sectors and most relevant economic and demographic indicators and trade relations in 37 world regions. GLOBIOM is a partial-equilibrium model, meaning that the supply and demand sides of the agricultural and forestry sectors are represented, with supply and demand being equal at a certain price level. The model is recursive dynamic and able to model changes over periods of time, where the outcomes of the previous time step are given as starting values for the subsequent time step. GLOBIOM is bottom up, because the supply side of the model is built up from field (land cover, land use, management systems) to farm (production/markets). The model computes the global agricultural and forest market equilibrium by choosing land use, processing activities, and international trade flows to maximize the sum of producer and consumer surplus, subject to resource, technological and policy constraints. The level of production in each area is determined by the agricultural or forestry profitability in that area (depending on suitability and management), market prices (reflecting the level of demand) and the conditions and costs associated with conversion of the land, expansion of production and, where relevant, to international market access. Trade is modelled as bilateral trade flows between individual regions.

GLOBIOM is adjusted to run on an annual basis and take the difference between producer's decision making between expected prices and yields and the outcome of those decisions based on actual yields and prices into account. To allow for short-term analysis using GLOBIOM, we alter the model so that it solves in annual instead of 10-year time steps. To do so, we have adjusted the following areas: (1) changes to the exogenous model parameters, (2) changes to the coefficients of expansion and reduction for crops and livestock.

Exogenous model parameters

In the model, changes in final demand for agricultural products are explained by the combination of three exogenous factors - population, GDP and income elasticities, which lead to a change in food diets and target demand by product- and one endogenous factor -the evolution of the market price. Total domestic demand for a crop in a region depends on the evolution of demand for food, feed and other use, as many crops are used for human consumption, to feed the animals and to accommodate the biofuel sector. Changes to the exogenous factors are based on the Shared Socio-economic Pathways (SSP's) which have been developed for the 5th Assessment Report of the IPCC (AR5). These exogenous factors are re-calculated based on a linear interpolation of the 10-year time steps.

An increase in production of crops can be achieved through three mechanisms in the model: an increase in the total area cultivated, exogenous technological change or endogenous productivity increase through the adoption of more productive systems or a relocation of production to more productive areas. The exogenous yield growth rate is applied on future yields to represent technological change and depending on the evolution of prices and land availability. The exogenous crop productivity growth is computed based on FAO historical trends from 1990 to 2010. In the annual version of GLOBIOM, this factor is also annualized by means of linear interpolation.

Land conversion and conversion of land use

The endogenous intensification mechanism is the fact that the model might re-allocate land to different management systems (for crops: subsistence, low input, high input, irrigated). A linear partial-equilibrium model such as GLOBIOM applies maximum constraints on expansion and reduction of crop and livestock activities, as well as the re-allocation of management activities. The value over the 10-year periods of these constraints are multiplied by the factor 0.1 as this allows the intensity of the expansion / reduction to be similar after a 10-year period in the 10-year version (x) and the annual version (y). That is, $x^{0.1} = y$, because $(x^{0.1})^{10}$ equalizes the limit on expansion/contraction of the 10-year version.

Non-linear land conversion costs represent the rising cost for every additional unit of conversion. To arrive with a similar amount of conversion after ten annual steps as we would in the standard version of GLOBIOM, we increase the slope of the function describing non-linear land conversion costs. We increase the parameter of the non-linear function for land conversion costs by factor 10 based on the following reasoning:

The function describing land conversion costs is a quadratic function of the form

$$f(x) = \frac{1}{2} Aq^2 + Bq \quad (A, B > 0^1).$$

Let: - q be the total quantity of land converted over the 10-year time period, c through l be the quantity converted in each subsequent annual time step ($c+d+e+f+g+h+i+j+k+l=q$)

- A_{10} and A_1 be the slope coefficients in the 10-yr and annual versions respectively.

- B_{10} and B_1 be the intercept coefficients in the 10-yr and annual versions respectively.

$$0.5A_{10}q^2 + B_{10}q = (0.5A_1c^2 + B_1c) + (0.5A_1d^2 + B_1d) + (0.5A_1e^2 + B_1e) + (0.5A_1f^2 + B_1f) + (0.5A_1g^2 + B_1g) + (0.5A_1h^2 + B_1h) + (0.5A_1i^2 + B_1i) + (0.5A_1j^2 + B_1j) + (0.5A_1k^2 + B_1k) + (0.5A_1l^2 + B_1l)$$

¹ The function implies linearly-increasing marginal costs: $f'(x) = A.q + B$. It reflects the fact that the more land is converted, the higher the unitary cost of conversion. In other words, the land which is least expensive to convert is converted first.

$$0.5A_{10}q^2 + B_{10}q = 0.5A_1(c^2, d^2, e^2, f^2, g^2, h^2, i^2, j^2, k^2, l^2) + B_1(c, d, e, f, g, h, i, j, k, l)$$

$$0.5A_{10}q^2 + B_{10}q = 0.5A_1(0.1q^2) + B_1(0.1q)$$

Assuming equal intervals:

$$0.5q^2(A_{10}-0.1A_1) + q(B_{10}-0.1B_1)$$

$$A_{10}=10A_1 \text{ and } B_{10}=10B_1$$

Trade, demand and resource supply

There are two trade cost functions in GLOBIOM: (1) An exponential trade cost function when trade flows are observed in previous time-period; (2) A quadratic trade cost function when there is no trade observed in the previous time-period, as well as a few other non-linear functions in GLOBIOM, representing the demand function for final products and the resource cost function for water and land. The latter ones are isoelastic functions where prices (p) are expressed as functions of quantities (q) demanded or used: $p=p_0 \cdot (q/q_0)^{1/\varepsilon}$ where ε is the price-elasticity of demand or resource use. Resource use equations represent a form of absolute scarcity of land and water which is independent of time. We assume that the reactions to price and cost changes remain similar, independent of whether the price change occurs over a 10-year period or over an annual period.

Including expectations

The objective function of GLOBIOM focuses on the maximization of global consumer and producer surplus. However, a producer bases his production decisions on expected instead of actual prices and on expected yields. To accommodate for the differences between expected and realized prices and yields, the default objective function is adapted by replacing the part of the constant elasticity demand function belonging to crop production with the expected revenues obtained from crop production. More formally, GLOBIOM's objective function is defined as the sum of global consumer and producer surplus. In GLOBIOM, this is defined as the integral under the demand functions minus the sum of all production, resource and trading costs (Havlik et al., 2011):

$$\begin{aligned} \text{MaxOBJ}_t = & \sum_{r,y} \left[\int \{ \phi_{r,t,y}^{\text{dem}} (D_{r,t,y}) d(.) \right] - \sum_r \left[\int \{ \phi_{r,t}^{\text{splw}} (W_{r,t}) d(.) \right] - \sum_{r,m} (\tau_{r,m}^{\text{proc}} \cdot P_{r,t,m}) \\ & - \sum_{r,l,l} \left[\int \{ \phi_{r,l,t}^{\text{lucc}} \left(\sum_{c,g} Q_{r,t,c,g,l,l} \right) d(.) \right] - \sum_{r,c,g,l,s,m} (\tau_{c,g,l,s,m}^{\text{land}} \cdot A_{r,t,c,g,l,s,m}) \\ & - \sum_{r,c,g,l,s,m} (\tau_{c,g,l,s,m}^{\text{calib}} \cdot A_{r,t,c,g,l,s,m}) - \sum_{r,c,g,a,m} (\tau_{c,g,a,m}^{\text{calib}} \cdot B_{r,t,c,g,a,m}) \\ & - \sum_{r,r,y} \left[\int \{ \phi_{r,r,t,y}^{\text{trade}} \left(T_{r,r,t,y} \right) d(.) \right] \end{aligned} \quad (1)$$

Where MaxOBJ represents the sum of consumers and producers' surplus, ϕ^{dem} the constant elasticity demand function, d the final demand, ϕ^{splw} represents the constant elasticity water supply function, W represents the water use, τ^{proc} : the processing cost by unit of primary product, P the processed quantity, ϕ^{lucc} the land use/cover change cost function with rising marginal costs, Q the amount of land use/cover change, τ land the management cost per hectare of land use (except for water), A the land use activities, τ^{calib} : the calibrated production cost per hectare of land use activities or per livestock unit, B the livestock numbers, ϕ^{trade} the constant elasticity international trade cost function, T the international shipments. The indices r represent the region, t the period, c the country, g the

spatial grid, l the land use type, s the primary product, a the animal type, y the final product and m the management system.

For a producer, the resulting shadow prices of land derived from solving equation (1) represent the land's marginal contribution to profit. If a producer has no constraints on land use, profit maximization occurs at the point where shadow prices are equal among all alternative land uses. However, the equality of shadow prices among land uses only accounts for expected output prices because producers do not know output prices at the time they choose their production activities, and must base their expectation on past experience. This causes uncertainty for the producer about the difference between the actual and expected output price, which may differ per activity and through time. To accommodate for the differences between allocation decisions based on expected prices and the outcomes of these decisions, we solve equation (1) first by replacing the part of the constant elasticity demand function belonging to crop production in equation (1) by the expected revenues obtained from crop production:

$$\begin{aligned}
 MaxPOBJ_t = & \sum_{r,a} \left[\int \{ \xi_{r,t,a}^{dem} (D_{r,t,a}) d(.) \right] + \sum_{r,c,g,l,i,m} (p_{r,t,i}^* \cdot A_{r,t,c,g,l,i,m}) \\
 & - \sum_r \left[\int \{ \xi_{r,t}^{splw} (W_{r,t}) d(.) \right] - \sum_{r,m} (\xi_{r,m}^{proc} \cdot P_{r,t,m}) \\
 & - \sum_{r,l,\tilde{l}} \left[\int \{ \xi_{r,l,\tilde{l}}^{lucc} \left(\sum_{c,g} \varrho_{r,t,c,g,l,\tilde{l}} \right) d(.) \right] - \sum_{r,c,g,l,s,m} (\xi_{c,g,l,s,m}^{land} \cdot A_{r,t,c,g,l,s,m}) \\
 & - \sum_{r,c,g,l,s,m} (\xi_{c,g,l,s,m}^{calib} \cdot A_{r,t,c,g,l,s,m}) - \sum_{r,c,g,a,m} (\xi_{c,g,a,m}^{calib} \cdot B_{r,t,c,g,a,m}) \\
 & - \sum_{r,r,y} \left[\int \{ \xi_{r,r,t,y}^{trade} \left(T_{r,r,t,y} \right) d(.) \right]
 \end{aligned} \tag{2}$$

Where *MaxPOBJ* represents the producers' surplus based on expected prices of crop production and the consumers surplus of animal and forest products, p^* represents the expected price of crop production, and the index i represents crop products.

Storage

In GLOBIOM, production can be altered along the supply curve in order to meet expected demand. In the long run, the supply curve may be altered via e.g. technological change and farm structural change, and the demand curve can be altered through e.g. GDP and population changes, leading to a new equilibrium price. For inter-annual changes however, producers cannot change the production quantities of a certain crop anymore, and the adaptive capacity of changing production quantities must come from e.g. storage instead of altering land allocation or changing management styles. Without storage, a yield shock will lead to a shift in the supply curve, and a corresponding shift in the price. Storage may therefore be able to mitigate part of the price-effect caused by a yield shock. Below we explain how storage is implemented in GLOBIOM. Storage is directly included in the MaxOBJ of equation (1).

We first solve *MaxPOBJ* as depicted in equation (2), where producers maximize their expected revenues based on expected prices of crop production. Upon solving equation (2), we fix the allocation of $A_{r,t,c,g,l,i,m}$. After the producer's land allocation and management decision based on expected prices has taken place, production has an upper bound: it's defined as the goods harvested based on the

land allocation and the outcome of the yields plus any crops left in storage from previous harvests. With the fixed allocation we solve MaxOBJ in equation (1), where storage is now directly included.

$$\begin{aligned} \text{MaxOBJ}_t = & \sum_{r,y} \int \varphi_{r,t,y}^{dem} (D_{r,t,y}) d(\cdot) - \sum_r \left[\int \varphi_{r,t}^{splw} (W_{r,t}) d(\cdot) \right] - \sum_{r,m} (\tau_{r,m}^{proc} \cdot P_{r,t,m}) - \\ & \sum_{r,l,l^*} \left[\int \varphi_{r,l,l^*,t}^{lucc} (\sum_{c,g} Q_{r,t,c,g,l,l^*}) d(\cdot) \right] - \sum_{r,c,g,l,s,m} (\tau_{c,g,l,s,m}^{land} \cdot A_{r,t,c,g,l,s,m}) - \sum_{r,c,g,l,s,m} (\tau_{c,g,l,s,m}^{calib} \cdot \\ & A_{r,t,c,g,l,s,m}) - \sum_{r,c,g,a,m} (\tau_{c,g,a,m}^{calib} \cdot B_{r,t,c,g,a,m}) - \sum_{r,r^*,y} \left[\int \varphi_{r,r^*,t,y}^{trade} (T_{r,r^*,t,y}) d(\cdot) \right] - \sum_{r,y} (\beta_{r,y}^{p*} \cdot \\ & S_{r,y}^{p*}) - \sum_r (\beta_{r,y}^{d*} \cdot S_{r,y}^{d*}) \end{aligned} \quad (3)$$

Where MaxOBJ_t represents the sum of consumers' and producers' surplus including storage, $S_{r,y}^{p*}$ the producer-side storage, i.e. the final products that the producers decide to sell to stock-holders in the specific year, $S_{r,y}^{d*}$ the consumer-side storage; i.e. the final products that the consumers decide to take-up from inventories in that specific year. $\beta_{r,y}^{p*}$ and $\beta_{r,y}^{d*}$ represent the cost for stocking and taking up products from storage respectively.

The new product balance, the equation ensuring that total production, stocking and exports equals total consumption, storage-uptake and imports, will then equal:

$$\begin{aligned} D_{r,t,y} \leq & \sum_{r,c,g,l,s,m} (\tau_{c,g,l,s,m}^{land} \cdot A_{r,t,c,g,l,s,m}) + \sum_{r,m} (\tau_{r,m}^{proc} \cdot P_{r,t,m}) + \\ & \sum_{r,r^*,y} \int \varphi_{r,r^*,t,y}^{trade} (T_{r,r^*,t,y}) d(\cdot) - \sum_{r,r^*,y} \int \varphi_{r,r^*,t,y}^{trade} (T_{r^*,r,t,y}) d(\cdot) + S_{r,y}^{d*} - S_{r,y}^{p*} \end{aligned} \quad (4)$$

Subject to the following two constraints:

$$S_{r,y,t}^{p*} \leq S_{r,y,t}^{max} - SH_{r,y,t} \quad (5)$$

$$S_{r,y}^{d*} \leq SH_{r,y,t} \quad (6)$$

$$, \text{ with } SH_{r,y,t} = SH_{r,y,t-1} + S_{r,y,t}^{p*} + S_{r,y}^{d*}$$

Where $SH_{r,y,t}$ are carry-over stocks from the previous time-step. Equation (5) specifies that the quantity put in storage may not exceed the difference between the maximum capacity and the carry-over stocks of last year. Equation (7) specifies that the uptake of storage must not exceed the carry-over stocks of last year. Production directly consumed will not go via the storage-holder channel, but through trade or direct consumption in the region itself, as defined in the product balance.

To test the implementation of storage in GLOBIOM-X, we assume the following values for the parameters. For the purpose of model testing, stocking is only possible for wheat and for Europe. Stocking capacity is assumed to be 150% of the 2000/2010 stocks reported by the European Commission for Europe and weighted by the five GLOBIOM-EU regions based on the total production in 2000 (European Commission, 2011). 2009/2010 was the year closest year to GLOBIOM's base-year (2000) reported online but given that GLOBIOM's production in 2000 and the reported 2009/2010 production are very similar, we assume that capacity has remained similar as well. Storage costs for both producers and consumers are initially set at 10% of last year's price of the respective crop. The values of these exogenous parameters can be found in Table 1 below.

Table 1: Initial stocks, stocking capacity and costs of storage for wheat in Europe.

Region ²	Initial storage (1000 tons)	Storage capacity (1000 tons)	Cost of storing (producer and consumers) (USD 2000/ton)
EU_Baltic	285.07	427.6	12
EU_CentralEast	4785.9	7178.91	11
EU_MidWest	10633	15949.36	11
EU_North	3950.2	5925.25	10
EU_South	2745.9	4118.89	16

GLOBIOM-X thus first solves equation (2), representing producers' expected revenues. Upon solving equation (2), we fix the allocation of $A_{r,t,c,g,l,i,m}$ and with the fixed allocation we solve producers' profits and consumers' utility including the possibility of storage in (3), under the new product balance and constraints in equations (4)-(6). This two-step system implies that within an agricultural season, an unanticipated change in yields will lead to a change in supply of products, which will lead to a change in the corresponding prices and demand of the product. Only in the next period, a change in resource costs will allow producers to shift the supply and reconsider their crop allocation decisions. Storage can however mitigate the shortage of supply and (part of) the resulting price increase. In the next period, a change in expected revenues will allow producers to shift the supply and reconsider their crop allocation decisions. Figure 1 below schematically shows the steps and intermediate and final outputs.

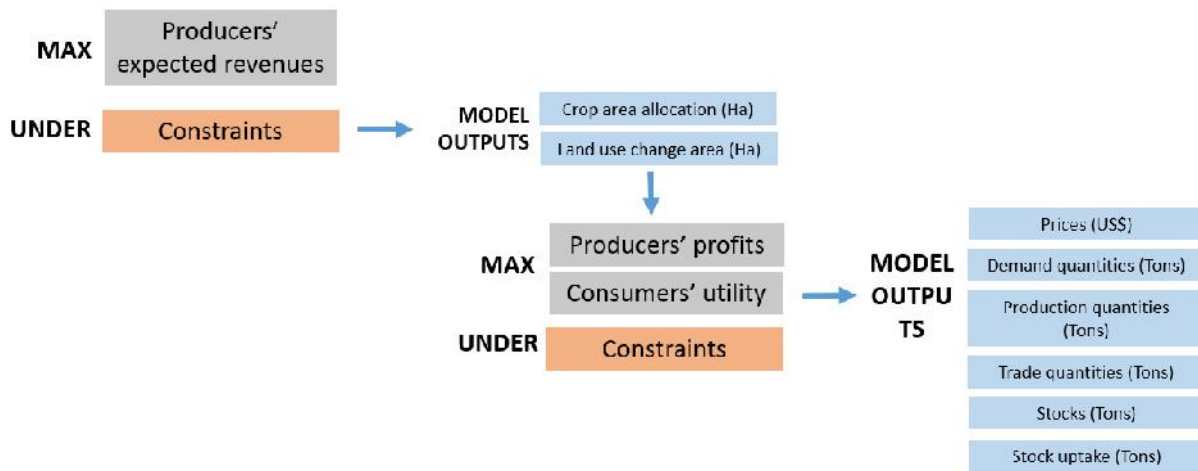


Figure 1: Schematic overview of steps in GLOBIOM-X

Data

Extreme events are often only signaled after they took place, making it difficult to define them. However, the existing literature has made a few attempts to classify extreme events. Stephenson (2008) characterizes extreme events based on their severity (large losses), rarity (low probability of

² Where EU_Baltic represents Estonia, Latvia and Lithuania; EU_CentralEast represents Bulgaria, Czech Republic, Hungary, Poland, Romania, Slovakia and Slovenia; EU_MidWest represents Austria, Belgium, France, Germany, Luxembourg and the Netherlands; EU_North represents Denmark, Finland, Ireland, Sweden, and the UK; EU South represents Cyprus, Greece, Italy, Malta, Portugal and Spain.

occurrence) and whether they are acute (e.g. a major hurricane) or chronic (e.g. a major drought spell). The threshold on severity and rarity can be chosen based on an absolute or relative value that is in the tails of the distribution. It is important to differentiate between weather and climate extremes. Both weather and climate extremes may lead to extreme events; however, weather extremes have a short-term nature (e.g. heavy floods), whereas climate extremes are longer in nature (e.g. drought spells). For the assessment of the effectiveness of market stabilization policies in reducing price spikes and improving food availability, we first quantify shortfalls in production that are based on realistic weather events. For this, we use the impact of droughts on crop production. To identify the impact of droughts on yield and production changes, we use the Standardized Precipitation Evapotranspiration Index (SPEI), calculated for the most important rainfed crops in Europe at a 1x1 km resolution over the past 22 to 25 years. The SPEI is a meteorological drought index that measures the onset, duration and magnitude of drought conditions with respect to normal conditions at every location (Vincente-Serrano et al. 2010). The SPEI is calculated based on long-term frequency distribution of water deficit defined as precipitation minus potential evapotranspiration with monthly time steps, from 1990-1995 to 2017. The values are obtained from the CGMS25 database and, therefore, starting years vary between 1990 and 1995. Based on the SPEI value and the historic data, various drought scenarios can be composed. The SPEI value quantifies how rare a given water deficit is with respect to the frequency distribution. Potentially hazardous months in terms of droughts are those with a negative SPEI value, e.g. less than -1 or -2; potentially hazardous months in terms of wetness are those with positive SPEI values, e.g. higher than 1 or 2. The SPEI is available for all months and as the average of the growing season.

To calculate the effects of droughts on crop yields, drought scenarios are created. We identify years for which the mean European growing season SPEI ranging from April to September, is below a certain threshold, indicating drought. Considering the different drought characteristics such as frequency, severity, duration or extend, we create different drought scenarios: (i) area under drought as percentage of European cropland with $\text{SPEI} \leq -1$ (ii) area under severe drought as percentage of European cropland with $\text{SPEI} \leq -1.5$ (iii) most severe drought over Europe as aggregated SPEI index. In combination with the process-based crop model EPIC, this will lead to a yield shock defined as the ratio of a crop yield under the selected SPEI drought shock to a crop yield based on normal (average) conditions. To be able to use the yield shocks further down in the analysis within the model, we aggregate the data to a 200x200km resolution. Zero yield values, which are artefacts of the EPIC modelling process, are excluded. Figure 2 shows the yield shock defined as the ratio of a crop yield under the selected SPEI drought shock to a crop yield based on normal (average) conditions for the simulated crops wheat, maize, rapeseed, potatoes, sunflower and soybean.

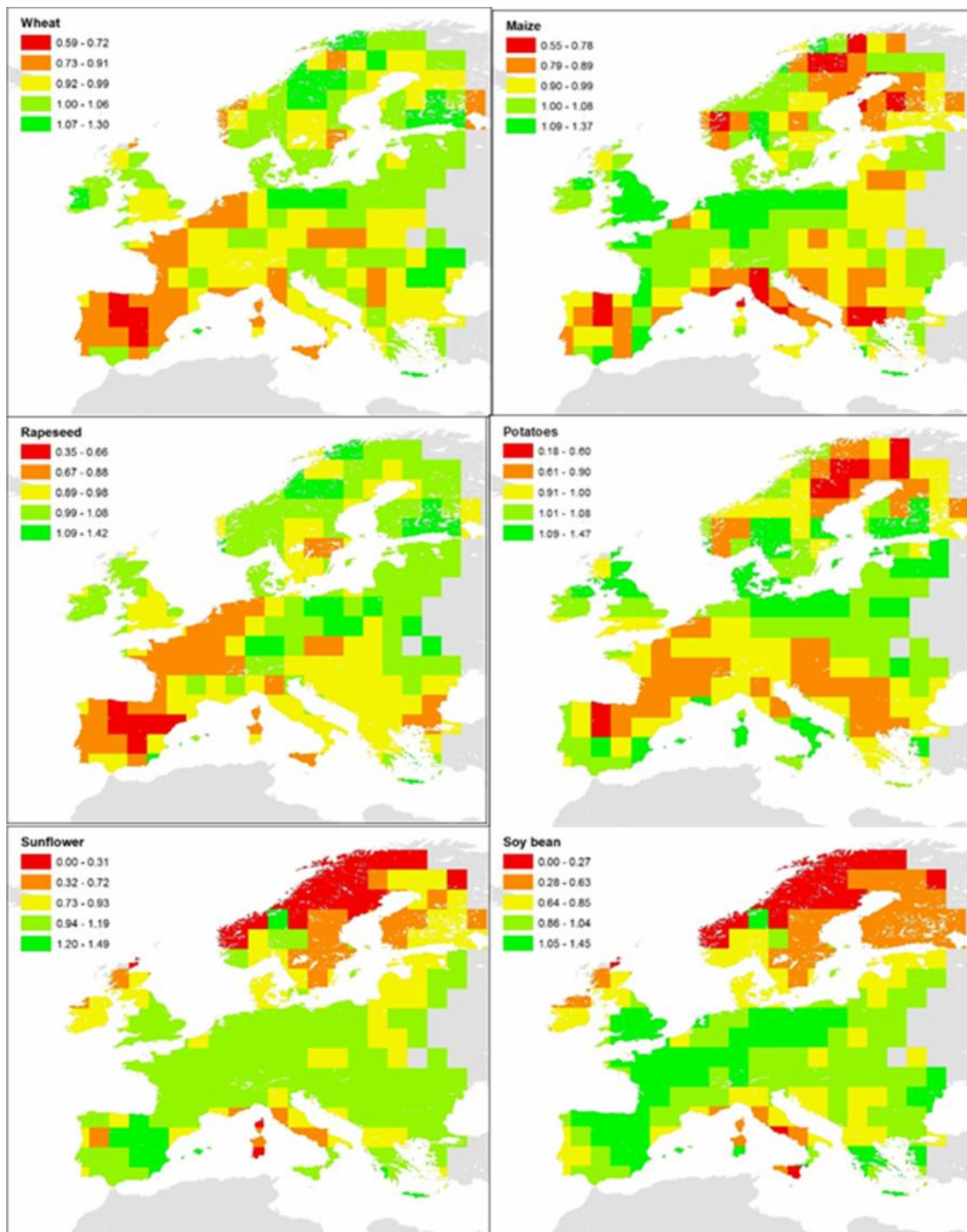


Figure 2: Yield shock defined as the ratio of a crop yield under the selected SPEI drought shock to a crop yield based on normal (average) conditions for the simulated crops wheat, maize, rapeseed, potatoes, sunflower and soybean

Scenarios

Extreme climate events motivate policymaking, both in the form of disaster-relief and adaptation measures. The integration of extreme weather events in climate scenarios and climate-induced crop yield impacts in integrated assessment and simulation models provides a unique opportunity to establish a baseline against which potential climate adaptation policies can be analyzed. Adaptation

measures are decisive in determining the extent to which agricultural production and food security will be impacted by extreme weather events. A broad exploration of policies under the uncertainty of both climate and socioeconomic conditions is necessary for informing policy strategies on climate change mitigation and adaptation.

Different strategies to reduce yield vulnerability and to mitigate the negative effects of production shocks on output prices and food availability can be envisaged. Based on the 2013 CAP reform and recent policy debates we can distinguish three main themes that directly lead to potential stabilization policies: (1) The increased need for crisis risk management under the expectation that extreme climatic events will become more frequent and of a more severe magnitude; (2) the increase in storage facilities that is observed over the past decade, mostly privately organized; (3) the decrease in market support measures such as intervention schemes. Furthermore, we distinguish two trade scenarios; a trade liberalization scenario where tariffs get gradually phased out until 2050 and a trade reduction scenario, where tariffs get enhanced until 2050.

Base: the baseline scenario, where yield variability on a 200x200 km resolution caused by a severe drought is introduced as of 2020. There are no specific policies introduced, meaning that any adaptation to the yield variability must come from autonomous market-based incentives that do not directly require government action, such as a change in management systems, increase in the area allocated to a certain crop, or a change in the demand for food or feed production.

Store: In the store scenario, we allow storage in the EU for all crops that are simulated to be affected by droughts. Storage facilities are modelled according to their 2000 capacity and initial stock level. We choose to follow the USDA storage levels to define the 2000 beginning stock levels and set the maximum storage capacity at 1.5 times this level.

StoreUnlim: This policy follows the assumptions of the *Store* scenario, with the exception that here, unlimited storage facilities are assumed to be available.

StoreUnlimInt: This policy follows the assumptions of the *StoreUnlim* scenario, with the exception that here, producers are able to sell their crops to storage facilities against a guaranteed intervention prices. Under higher prices, the storage facilities will sell the crops to the market. Intervention prices are the currently applicable prices of EUR 101.31 per tonne of wheat, durum wheat, barley, and maize. Stock clearance for other crops is set at 110% of the base-level price.

TradeR: This policy restricts trade by increasing tariffs gradually as of 2020.

TradeL: This policy causes trade liberalization by completely removing tariffs as of 2020.

Results

The results of the different scenarios are assessed along their impacts in terms of the environment, equality and profitability. For trade scenarios, also bilateral trade flows are compared.

Environmental impacts

Differences in emissions from crop production are calculated. These differences are a result of crop intensification and changes between crops and are reported in the table below. The largest percentage changes in GHG emissions are observed in Central-East and Midwest regions and for NoStore and Store scenarios. Changes under unlimited storage scenarios are smaller, mostly because here large parts of the intensification already occurred before shock, because the increase in production could be stored against a favourable price. In the trade liberalization scenario, production gets enhanced after the shock, driven by the export position of Europe. In the trade reduction scenario, this is the other way around as part of the exports that were initially included get lost.

Table 2: Percentage change in GHG emissions obtained from crop production in the year immediately after a production shock. Cereals are defined as barley, corn, wheat, rice, sorghum and millet.

Reduction of environmental impacts							
Greenhouse gas emissions							
EU Region	Base	NoStore	Store	StoreUnlim	StoreUnlimInt	TradeL	TradeR
Central-East		153	152	3.76	5.2	14.5	-5.1
Mid-West		146.3	146.3	0.24	-2.76	20.9	-8.2
South		-4.62	-5.07	0.67	-1.49	43.2	-13.5

Equality

Variables related to equitable outcomes and conditions that can be derived using GLOBIOM-X are presented in the table below. Equity indicators are computed as the difference between the time-step just after the shock and the time-step of the shock and are computed for the aggregate cereals (rice, wheat, barley, maize and sorghum). Consumption, production, prices and import dependency are all significantly affected by the production shock. In all cases, an increase in production and prices and a decrease in imports is observed. In terms of trade scenarios, the availability, accessibility and stability of cereals all increases, especially related to a trade reduction scenario. This implies that trade liberalization raises the equitability.

Table 3: Changes regarding equitable outcomes and conditions among consumer system outcomes, indicators for EU, measured as the difference between the time-step after and the time of the shock

Equitable outcomes and conditions							
Among consumer system outcomes							
Aggregate indicator	Derived variable of changes in cereals	Base	Store	StoreUnlim	StoreUnlimInt	TradeR	TradeL
Availability	Change in domestic production (1,000 tonnes)	12,216.50	15,226.78	3,716.72	9,104.30	1,250.06	8,612.10
Accessibility	Price change (USD 2,000/tonnes)	8,239	6,998	5,509	-185	3,404	6,208
Utilization	Change in consumption of food (1,000 tonnes)	-16,706	-4,011	981	-507	-201	-101

Utilization	Consumption for feed (1,000 tonnes)	87	878	0	42	12	25
Stability	Cereal import increase (1,000 tonnes)	-9,721	-9,007	-4,333	-51,520	-6,001	1,002

Profitability

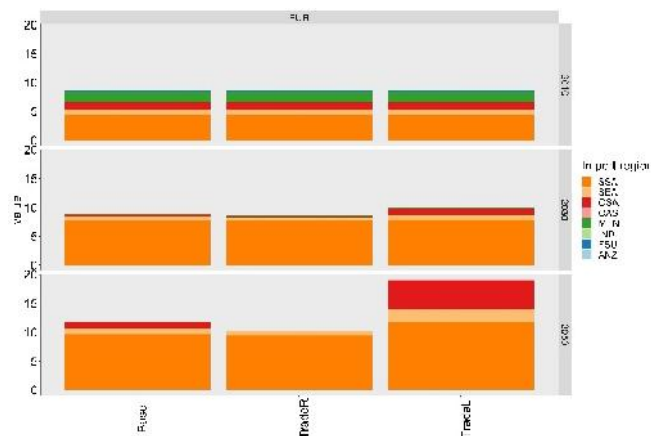
With increased storage possibilities and under added intervention prices the EU agri-food business becomes increasingly competitive under a shock situation. The **openness** variable, defined as the share of trade in total production, increases with storage capacity and intervention prices. The **self-sufficiency** variable, defined as the share of production in total consumption is however largest for the situation without storage and the situation with unlimited storage and intervention prices. For the situation without storage, this is related to the lower level of consumption. The **normalized trade balance** is highest for the *Store* and *StoreUnlim* scenarios, implying that storage benefits the trade balance, but that intervention prices work more trade-distorting. More precisely, compared to a shock without storage, the trade balance increases by 0.08 in the case of limited storage and 0.12 in the case of unlimited storage. With intervention prices, it decreases by 0.09, however. The available stocks in total production are by far largest in the case of *StoreUnlimInt*; however, surprisingly the share of the uptake in consumption is lowest here. This might be due to the model assumption that the uptake of stocked crops takes place against the same price as the storage of those crops. As long as imported products are cheaper than this price, very little consumption of stocked products will happen. As expected, trade restriction scenarios will lead to less openness whereas trade liberalization scenarios lead to more openness.

Table 4: Storage policy induced changes regarding the competitiveness of EU agri-food business, SUSFANS competitiveness indicators calculated in the time-step in which the yield shock occurs

Competitiveness of EU agri-food business								
Performance metric	Derived variable	Formula	Base	Store	StoreUnlim	StoreUnlimInt	TradeR	TradeL
Trade and production	Openness	$\frac{\text{Exports} + \text{Imports}}{\text{Gross production}}$	0.45	0.49	0.5	0.51	0.2	0.61
Trade and production	Self-sufficiency	$\frac{\text{Gross production}}{\text{Gross production} - \text{Exports} + \text{Imports}}$	1.12	1.08	1.06	1.19	1.05	1.31
Trade	Normalized trade balance	$\frac{\text{Country exports}}{\text{World exports}}$	-0.23	-0.15	-0.11	-0.32	-0.2	0.45

Trade and production	Production buffer	$\frac{\text{Exports} - \text{Imports}}{\text{Exports} + \text{Imports}}$	0.05	0.12	0.45	0.32	0.21
Trade and consumption	Consumption buffer	$\frac{\text{Exports} + \text{Imports}}{\text{Gross production}}$	0.05	0.08	0.01	0.05	0.12

If we look more closely at bilateral trade flows between the base scenario and the trade scenarios, it can be observed that a trade reduction scenario leads to a reduction in the trade from Europe. However, this reduction is very low compared to the increase observed under a trade liberalization scenario. Total trade decreases from 23 million tons in the reference scenario to 19.5 million tons in the trade reduction scenario and increases to 31 million tons in the trade liberalization scenario. Especially trade to the region Other South Asia (OSA) is affected by a change in tariffs.



Conclusion

Climate change and extreme weather events lead to short-term variability and shocks to agricultural supply, impacting the entire food system and posing threats to food security. Furthermore, instability in the food system may disturb other systems such as energy and water. Studies into the interdependent demand and supply relationships in these systems require a framework that can take stock of both the climate-induced deviations between expected and observed prices and yields, the impacts on the food commodity market, as well as different adaptation mechanisms that may serve as market stabilization policies, such as storage and different trade-liberalization mechanisms.

This study developed a non-stationary model for market stabilization policy design, called GLOBIOM-X. GLOBIOM-X aims to analyze the impact of climate-induced yield shocks on market stability and how market instability can be contained through the adaptation mechanisms of stockholding and trade liberalization. The model is based on the bio-economic land use model GLOBIOM. GLOBIOM-X runs in annual time steps and can address agricultural land use from the producers' perspective based on expected prices. Stockholding is incorporated in the model by allowing producers to temporarily stock their products and consumers to take-up products from storage facilities.

For the assessment of the effectiveness of trade policies and stockholding options in reducing price spikes and improving food availability, shortfalls in production based on realistic weather events have been quantified. Three types of storage scenarios; baseline-level storage, unlimited storage and storage including intervention prices and a trade reduction and complete trade liberalization scenario

are implemented in order to assess their impact on market stability. Results are assessed in terms of their environmental impacts, equality and profitability. In terms of environmental impacts, a scenario without or with limited storage would lead to large environmental impacts, whereas a scenario with unlimited storage, as well as a trade restriction scenario would mitigate a large part of the otherwise incurred greenhouse gas emissions due to the yield shock. Production increases more than the base in the case of storage; here, after a yield shock occurs, storage facilities are depleted, and producers profit from the expectation of higher prices to re-fill storage facilities. Storage, especially in an unlimited form or with intervention prices are best equipped to reduce the loss in availability, accessibility and utilization of a change in cereals, whereas a trade liberalization scenario mostly works to increase stability in the consumer system. As expected, the competitiveness of the EU agri-food business is mostly positively affected by a trade liberalization scenario. This is increased compared to the base case and compared to the other scenarios for the variables openness, self-sufficiency, normalized trade balance and consumption buffer. An increase of tariffs hampers openness and self-sufficiency and unlimited storage scenarios hamper normalized trade balances and production and consumption buffers.

This paper has helped to give insight to what extent different types of policy measures reduce the negative impacts that yield shocks due to extreme events have on the environment, equitability amongst consumer systems and competitiveness. Both storage and trade liberalization help reduce the increase in greenhouse gas emissions, storage facilities may lead to a more equitable food system on the consumer side, whereas trade liberalization leads to more competitiveness in the EU agri-food business.

Discussion

The analysis in this paper could be further deepened and improved in the following ways. First, the inclusion of risk and uncertainty in producer's decision making. The neoclassical economic framework, where producers have perfect foresight and know the outcome of all their possible production activities before the planting decisions are made does not reflect reality. However, it would also be incorrect to assume that all production shocks come as a complete surprise to a producer. Based on his past experience, a producer might consider the yields of a crop to be more or less volatile and may adjust the cropping calendar, change cropping varieties or crop management. Depending on a producer's level of risk aversion, he/she may adopt certain crop rotation practices as a risk pooling mechanism. To assess the impacts of extreme events on production losses, it is important to properly reflect cultivation practices, and therefore, consider risk and uncertainty in producer's decision making on future land allocation.

Second, by further assessing feedback loops to water, energy and land. Part of the producer's activities involve decision making on water use through irrigation, energy use through inputs and land use through changes in crop allocation and land cover change. Within a modelling framework that assesses medium to long term changes, these decisions can be verified based on historic trends of management change and cropland expansion. However, the magnitude and frequency of production losses that a producer accepts until he/she changes his/her activities needs further research. Furthermore, extreme events do not only impact crop production, but may also lead to feedback loops from water, energy and land based on other sectors. For example, drought spells may lead to a rapid increase in water needs in many sectors. In the agricultural sector, irrigation is often mentioned as a solution for the increased frequency of drought spells under climate change. However, with the increased demand from other sectors, competition for water may rapidly increase, making it potentially impossible for the agricultural sector to expand irrigation or to irrigate areas that were

previously irrigated. To assess the effects of extreme events on crop production, it is important to take these feedback loops into account.

Third, by integrating extreme climate events on the livestock sector in the modelling framework. The livestock sector, an important sector when considering market distortions and food security issues as a result of extreme climate events, is directly impacted by extreme climate events in two ways. First, through the use of crops that may have experienced production losses as an input to the livestock sector via feedstock. Second, through losses in animals due to frost, droughts, heatwaves or an increased occurrence of animal diseases linked to climate extremes. Due to the composition of the livestock herd with followers (i.e. non-producing livestock), the impacts of extreme events on the livestock sector may be better analyzed over the course of several years rather than the annual period of crop production. The impacts of extreme events on the livestock sector and the interactions between the crop and livestock sector therefore need further thought.

Fourth, via a better translation of production fluctuations into price volatility. PE, and CGE models are only to a certain extent able to forecast price fluctuations, because changes in yields and macro-economic parameters that are part of the models explain only a certain share of the total commodity market price. Market fundamentals (production quantities), speculation (e.g. via stock markets) and macro-economic conditions (e.g. via country developments and exchange rates) may all influence commodity prices. Early warning systems of commodity price spikes using an econometric system have been developed and can be used to better inform price expectations of producers' and to calibrate the effect of yield shocks on prices (Cuaresma et al. 2016; Cuaresma et al. 2017a; Cuaresma et al. 2017b).

Fifth, by assessing what magnitudes or frequency of extreme events lead to the elimination of a stable state, a so-called tipping point. Food supply shocks due to crop losses inside and outside Europe may lead to socio-economic tipping points that can be measured both on the producer, as well as on the consumer side. On the producer side, extreme climate events may lead to crop losses of such a magnitude and frequency that farms structurally experience that their costs are larger than their benefits of production. In case this happens, several structural changes in crop production may occur. The extreme droughts may eliminate the possibility of rain-fed agriculture, leading to a shift in crop management from rain fed to irrigated agriculture. It may also be that irrigation is not a possibility due to the available water or not the most profitable option in the specific location. In this case, the crop may disappear from the location altogether and may be replaced by a more profitable crop that is more resistant to the extreme climate events. In case both a shift in cultivation practices and a change of crops may not be a viable option, producers may be forced to leave a certain area, leading to farm exit and land abandonment.

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