Climate change impacts on crop yields in Europe

Why an additional 0.5°C of global warming relative to the present day matters

The link between climate and crop yields is not always direct or linear

In 2022, Europe experienced a summer to remember. Many parts of the continent were hit simultaneously by prolonged and intensive compound heatwaves and droughts.[1] Summer 2022 is the latest addition to the list of high-impact climate extremes that have caused significant losses to the crop re/insurance industry over the last decade in Europe. Historical observations and model-based projections show increasing trends in the geographical extent, persistence, co-occurrence, frequency and intensity of climate extremes in several regions across the continent. But what do changes in the climate system mean for crop yields? Arguably, the link between climate change signals and their impacts on crop yields is not always direct or linear.

Forward-looking views (FLVs) can improve crop risk assessment in a rapidly changing environment

FLVs can help the agriculture sector to better anticipate the unknown future

Crop risk assessment in the context of agri-re/insurance is typically based on historical agroclimatic indicators (yield statistics, weather data, remote-sensing-based retrievals of vegetation properties etc) and realised losses. Although such sources provide insights on the risk landscape for the historical period, they may no longer be representative of a world with rapid and intensifying climate change. Developing FLVs can be a valuable approach to better anticipate the unknown future. In contrast to backward-looking views that tend to lag reality, FLVs also help to improve the assessment of today's situation in a changing environment. In the context of climate change, forward-looking insights are typically based on output from simulations with global Earth System Models. Model-based statements about the projected climate evolution are often based on changes in indicators such as the frequency and intensity of extreme events, the mean state of a climate variable and its variability etc. Despite their high value across different sectors, such insights do not tell us much about impacts on crop yields. Furthermore, they cannot be easily digested by costing models, factored into product development and/or inform decision-making for crop re/insurance.

Translating climate signals into yield outcomes using process-based crop growth models

Crop growth models can translate climate signals into yield outcomes

Process-based crop growth models (CGMs) can be defined as mathematical representations of several biophysical and biogeochemical processes within a crop production system.[2] CGMs are driven by input data related to weather, soils and

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[1] *Copernicus: Summer 2022 Europe's hottest on record (2022).* Available at: https://climate.copernicus.eu/copernicus-summer-2022-europes-hottest-record

[2] Jones, J.W. et al. (2017) "Brief history of agricultural systems modeling", *Agricultural Systems,* 155, pp. 240–254. Available at: https://doi.org/10.1016/j.agsy.2016.05.014

agricultural management practices, with the purpose of mimicking crop growth and development – typically at daily intervals. CGMs are also valuable tools for translating climate signals from global Earth System Models into direct yield impacts, among other things. In this respect, notable efforts are currently ongoing within the Global Gridded Crop Model Intercomparison[3,4] (GGCMI) of the Agricultural Model Intercomparison and Improvement Project[5] (AgMIP). Although CGMs have been well-established tools for decision making within a scientific context for several decades, their application in the agricultural re/insurance sector is an innovative step towards an improved and independent risk assessment.

Generating physically plausible parallel climate realizations with initial condition large ensembles

Initial-condition large ensembles produce a range of physically plausible climate outcomes

The production of initial-condition large ensembles (LEs) is a relatively new research area within the climate modelling community. LEs are generated by running simulations with the same fully coupled Earth System Model many times under the same greenhouse gas emissions scenario, but initiated by a different state (starting point).[6] This method allows the production of parallel and spatially consistent climate unfolding trajectories for historical and future time horizons. As an example, Figure 1 illustrates the evolution of global air temperature anomalies from a 40-member initial-condition LE conducted with version 1 of the Community Earth System Model (CESM1) in the framework of the Large Ensemble Community Project[6,7] (supercomputing resources provided by NSF/CISL/Yellowstone). Each line in Figure 1 corresponds to a unique plausible climate trajectory,

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[3] Elliott, J. et al. (2015) "The Global Gridded Crop Model Intercomparison: data and modeling protocols for Phase 1 (v1.0)", *Geoscientific Model Development*, 8(2), pp. 261–277. Available at: https://doi.org/10.5194/gmd-8-261-2015

[4] Müller, C. et al. (2017) "Global gridded crop model evaluation: benchmarking, skills, deficiencies and implications", *Geoscientific Model Development*, 10(4), pp. 1403-1422. Available at: https://doi.org/10.5194/gmd-10-1403-2017

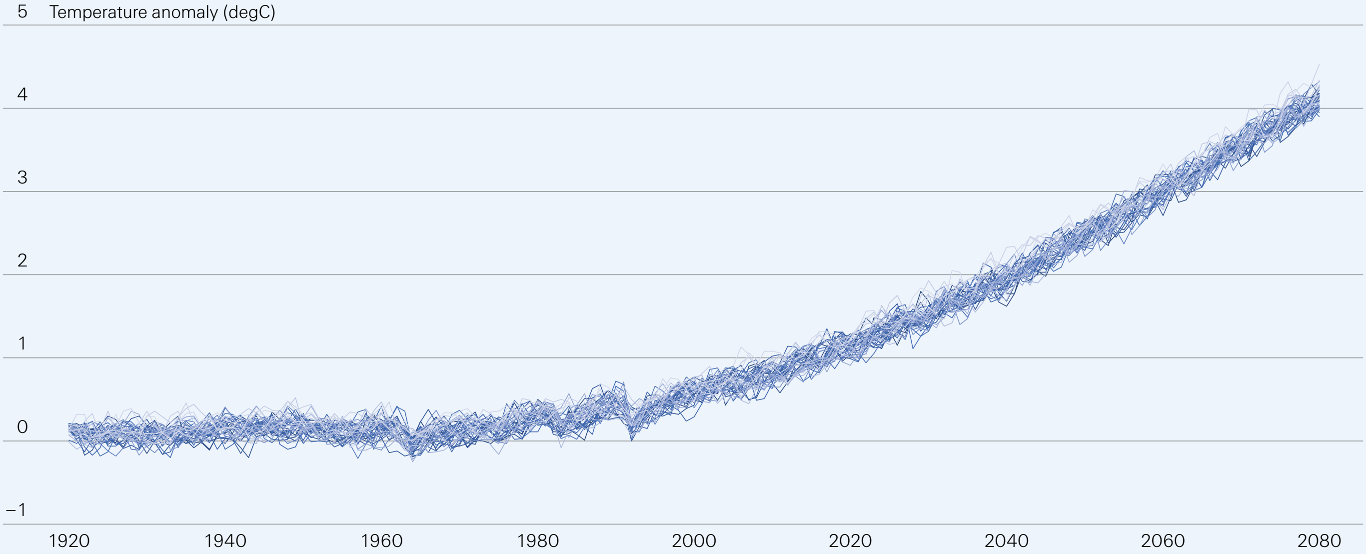
[5] Rosenzweig, C. et al. (2013) "The Agricultural Model Intercomparison and Improvement Project (AgMIP): Protocols and pilot studies", *Agricultural and Forest Meteorology*, 170, pp. 166–182. Available at: https://doi.org/10.1016/j.agrformet.2012.09.011

[6] Kay, J.E. et al. (2015) "The Community Earth System Model (CESM) Large Ensemble Project: A Community Resource for Studying Climate Change in the Presence of Internal Climate Variability", *Bulletin of the American Meteorological Society*, 96(8), pp. 1333-1349. Available at: https://doi.org/10.1175/BAMS-D-13-00255.1

[7] *CESM Large Ensemble Community Project* (no date). Available at: https://www.cesm.ucar.edu/projects/community-projects/LENS/.

Figure 1

Global 2m-air temperature relative to 1850–1900



Annual average global air temperature anomaly for the CESM 40-member LE. Each ensemble member represents a trajectory with a unique sequence of internal climate variability, superimposed upon the same external response. Note that for the historical period, none of the lines correspond to the actual temperature trajectory in the real world, but to a parallel situation that could happen given the climate dynamics.

consistent with the model's physics. The spread across the ensemble is, by design, solely driven by internal climate variability, caused by the chaotic nature of the climate system, and ultimately the response of large-scale atmospheric circulation patterns to the human intervention in the climate system (eg, greenhouse gases and aerosol emissions). LEs have been predominately applied in scientific research, but, despite the promising potential, their application as tools for risk assessment in the private financial sector is currently very limited.

The many possible futures of winter wheat and maize yields in Europe

This report presents an attempt to translate plausible climate scenarios into crop yield outcomes in Europe. The analysis focuses on two major cereal crops, (soft) winter wheat and maize, representative of the winter and summer crop season in Europe, respectively.

Combining insights from CGMs and LEs helps to capture analogues of observed yield losses and detect unseen crop failures

Specifically, daily weather data from the CESM LE was used as an input for two process-based CGMs for wheat and maize. Although a newer version of the dataset is now available, the analysis sticks to the older version of the CESM LE[7] since the product was tested in a variety of applications in the scientific literature.[8] Soil-related data from Soil Grids[9] and in-house information on local agricultural management practices were used as input for the simulations. Each model was run for non-irrigated conditions in a spatially explicit (gridded) mode 40 times, covering a 60-year period (1981–2040) across the whole of Europe, resulting in a total of 2400 simulated years per crop. Combining insights from large ensembles and process-based crop growth modelling results in a view that incorporates both stochastic and mechanistic elements. The approach helps to capture analogues of observed yield losses, as well as to detect unseen but physically plausible crop failures under both historical and future conditions. The analysis focuses on climate change impacts on crop yields; the role of other important risk drivers is not addressed. Moreover, the yield variability in the simulations is driven by the effect of weather perils on crops that include droughts, heatwaves, heavy precipitation, low temperatures, shortfalls in solar radiation and climate-related changes in the length of the growing season. All model runs were performed on an "as-if" basis by following assumptions about farm management practices that are representative of today's world and remain constant across all simulated years. Arguably,

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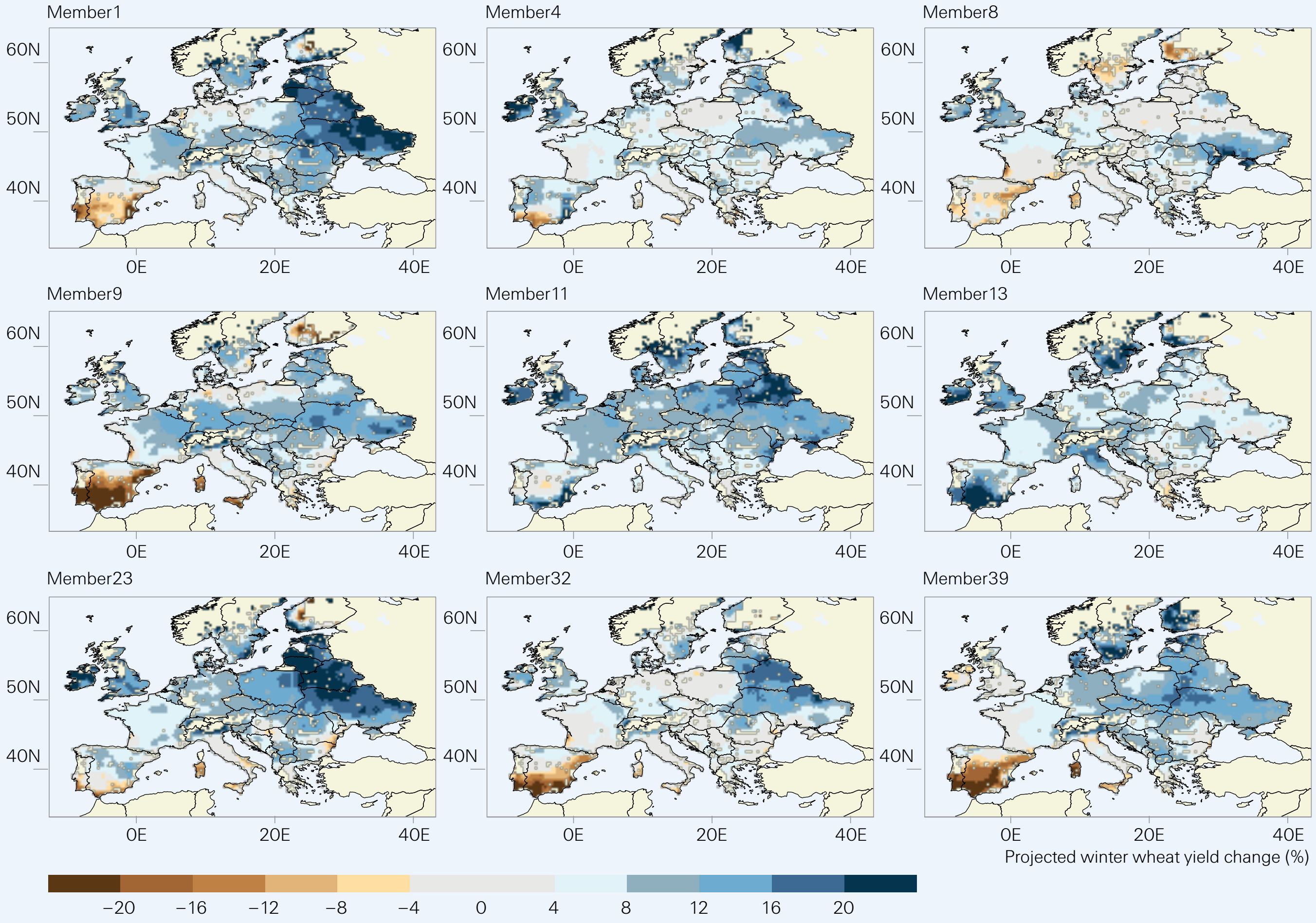
[8] Deser, C. (2020) "Certain Uncertainty: The Role of Internal Climate Variability in Projections of Regional Climate Change and Risk Management", *Earth's Future*, 8(12). Available at: https://doi.org/10.1029/2020ef001854

[9] Poggio, L. et al. (2021) "SoilGrids 2.0: producing soil information for the globe with quantified spatial uncertainty," *SOIL*, 7(1), pp. 217–240. Available at: https://doi.org/10.5194/soil-7-217-2021.

Figure 2



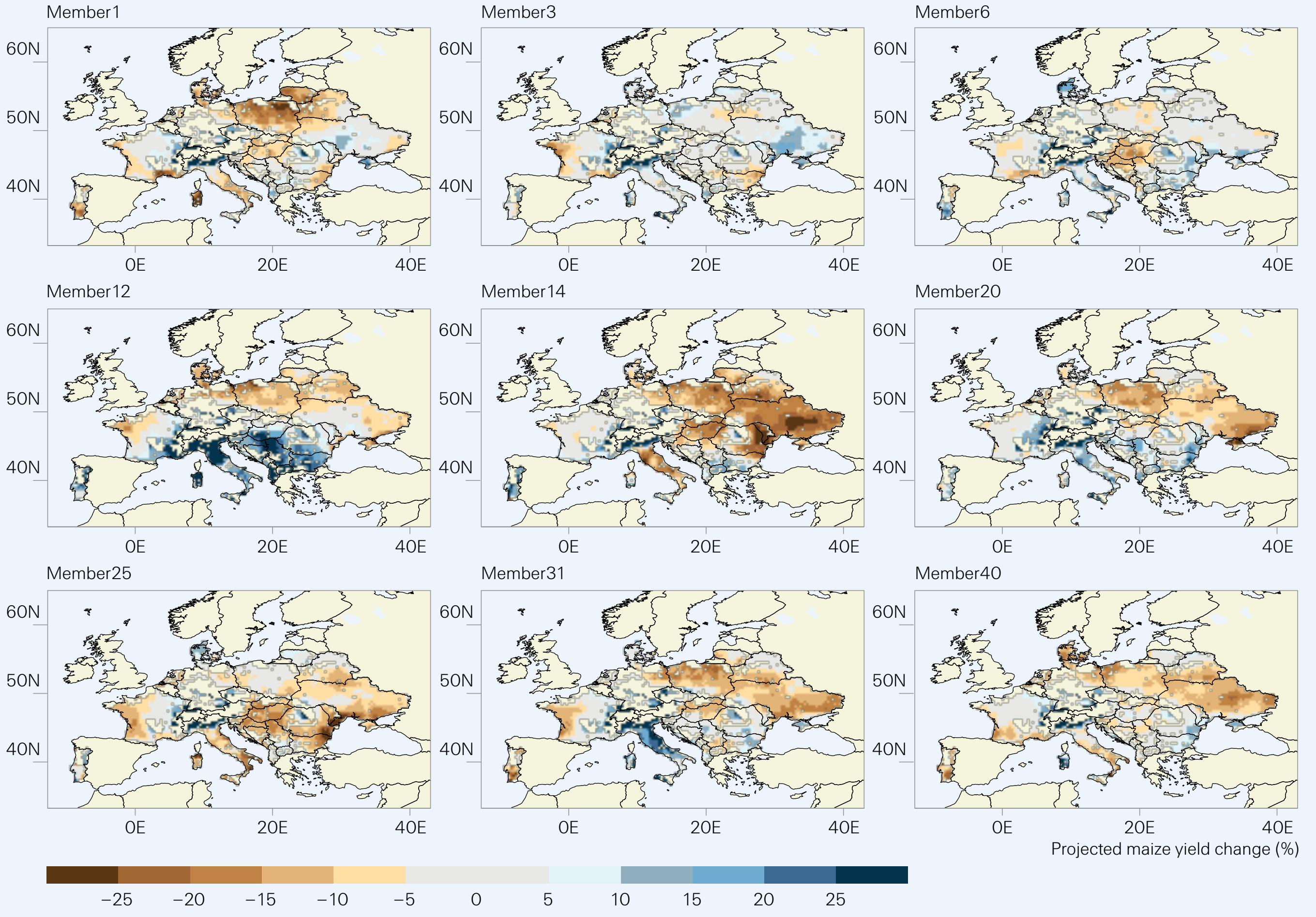
Model-based percentage yield change for winter wheat. For illustration purposes, only a subset of all ensemble members is shown. The changes are calculated as the relative difference between the 2011–2040 and 1981–2010 averages.

our research is highly dependent on the methodological assumptions, tools and input data used. We always adapt our risk view as new scientific insights become available. Thus, the results presented in this report should be treated as indicative.

Assessing risks to the crop re/insurance business with a range of crop yield scenarios

Figures 2 and 3 illustrate the percentage yield change for winter wheat and grain maize in Europe for a future period (2011–2040) compared to historical conditions (1981–2010). The range in the sign and magnitude of the change between the ensemble members is driven by internal climate variations; it is larger locally and more pronounced for maize than winter wheat. For example, although most of the realisations presented in Figure 2 generally show an increasing trend of winter wheat yields, the magnitude might differ substantially due to internally generated climate variations. The simulations for maize demonstrate a larger spread than winter wheat (Figure 3). For instance, in Hungary, although most of the members presented suggest overall negative changes, a positive change or nearly no change at all can still be plausible. It is challenging to state with confidence which outcome will dominate in the real world since all of them are possible to some extent. Furthermore, even low-likelihood events can have a high degree of physical occurrence plausibility and pose significant risks to the crop re/insurance industry. The spread in the model-based yields due to the inherent uncertainty of the climate system is, however, of high value to risk assessment since it allows a range of possible outcomes to be considered.

Figure 3



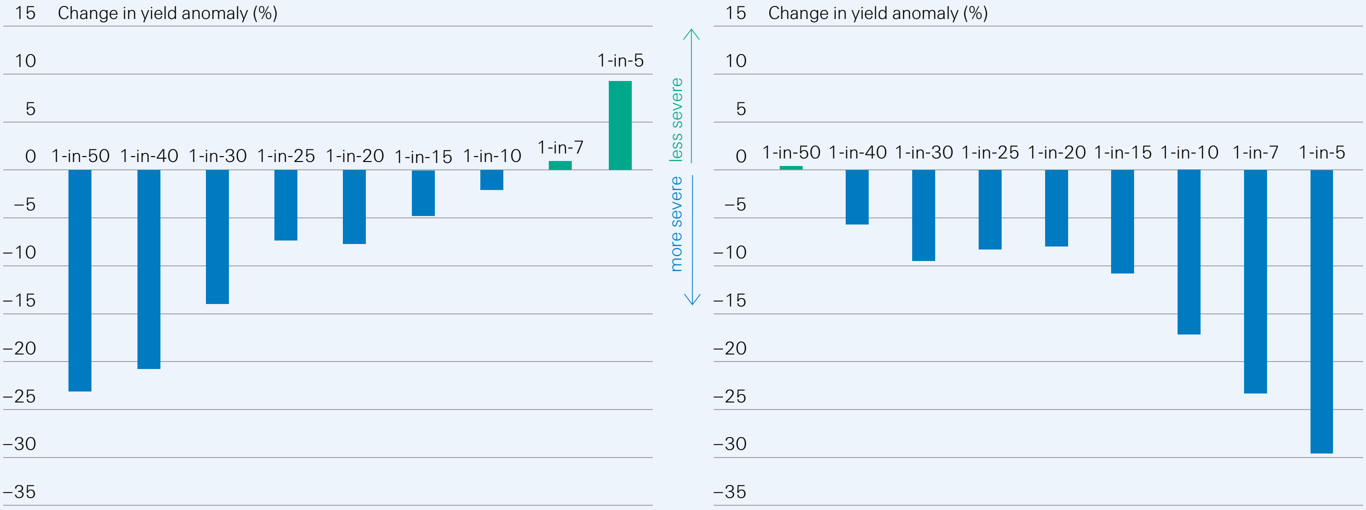
Model-based percentage yield change for maize. For illustration purposes only, a subset of all ensemble members is shown. The changes are calculated as the relative difference between the 2011–2040 and 1981–2010 averages.

Asymmetry in the response of the yield distribution to global warming

Present-day extreme yield losses may occur more frequently in the future

Model-based detrended yield anomalies (expressed as percentage deviations from the long-term average) were aggregated from grid to continental-level using crop-specific weights for the harvested area. Then, two distributions were derived for Europe by pooling yield anomalies across ensemble members and years corresponding to a world that has warmed by either 1.0°C or 1.5°C since pre-industrial times. The percentage difference between the two distributions per event return period is displayed in Figure 4. The results for both crops reveal that the yield distribution shows an asymmetric response to the jump from the 1.0°C to 1.5°C level of global warming. In addition, they suggest that present-day extreme yield losses may occur more frequently in the future. For example, the analysis shows that in the 1.5°C warming scenario, Europe would experience a present-day 1-in-100-year winter wheat yield anomaly around once every thirty years. Furthermore, at this warming level, the frequency of a winter wheat yield anomaly on the scale of the 2018 heatwave is projected to increase more than threefold. In contrast, the results for non-irrigated maize reveal a strong negative impact of climate change predominantly on events with a more frequent occurrence. Yet, climate impacts on severe crop failures are not negligible. For instance, the results indicate that the frequency of low maize yields in Europe, such as observed following the dry and hot summer 2022, increase by around 30% in the 1.5°C warming scenario. It is important to stress here that the aggregated view discussed in this report might not be representative of regional (eg, country-level) climate change impacts on crop yields.

Figure 4



Model-based changes in the severity of events with varying return period for winter wheat (left) and maize (right). The change is expressed as the percentage difference in the magnitude of the yield anomaly between a world that is 1.5°C warmer and one that is 1.0°C warmer. Negative values correspond to increased severity.

The road ahead

It will likely remain possible for weather and climate risks in agriculture to be modelled…

The analysis reveals that even if net-zero CO_2 and the 1.5°C climate target are achieved, substantial impacts on both the severity and frequency of the yield distribution of the two crops in Europe are unavoidable, in the absence of meaningful adaptation in farm management practices. In addition, severe climate change impacts on crop yields may still emerge earlier than expected (before the 1.5°C warming level is reached). The results stress the urgency for stringent reductions in greenhouse gas emissions. Moreover, they imply that in a changing climate, elementary risk management tools – like insurance – are becoming more relevant. In most areas, it will likely remain possible for weather and climate risks in agriculture to be modelled even in a world that is 1.5°C

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warmer, meaning that they are likely to remain insurable, assuming that their nature remains random and unpredictable and all stakeholders involved agree to the possible changes in terms and conditions.

Agri-underwriters, risk modellers and portfolio owners are encouraged to have a sound understanding of the changing environment and factor its possible impacts into risk assessment and decision-making. Furthermore, we identify calls to action for agri-re/insurers, which include:

FLVs can improve the representativeness of costing distributions and pricing adequacy of crop insurance products

What can primary insurers do? When costings agricultural risks, primary insurers can benefit from better assessing the representativeness of reference distributions. Backward-looking yield distributions that are routinely used by the industry for risk assessment may not be representative of the future and can result in under-pricing risks. Insights from forward-looking views can provide quantitative assessments of the possible climate impacts on crops, with the purpose of improving pricing adequacy. Whenever necessary, insurance product structures and capacity limits can be readjusted and deployed cautiously.

Emphasis can be given to return period estimation, portfolio steering and accumulation control

What can reinsurers do? First, reinsurers can assess individual transactions and in some cases even calculate their own original actuarial rates with the purpose of quantifying the pricing adequacy of primary insurance products. Moreover, innovative methods can be applied to better assess the return period of specific catastrophic events and their response to the changing environment. Then, emphasis can be given to portfolio steering and accumulation control – a historically stable portfolio might not continue to be stable in a warmer world, for example. Arguably, spreading risks out geographically doesn't necessarily translate into better diversification. Developing sophisticated optimisation approaches that explicitly account for possible climate impacts can help reinsurers (and global insurers) to better steer towards a globally diversified portfolio. Agri-re/insurers can also steer their portfolios towards more attractive markets where climate change can bring benefits for some crops and/or the rate of change in yield variability is slower than others. Furthermore, teleconnections are key drivers of diversification and changes in their patterns should be continuously monitored and factored into portfolio planning and steering.

Multi-method analyses can help to further explore the plausibility space

What can both primary insurers and reinsurers do? Re/insurers could benefit from advancing risk assessment preferably with multi-method analyses. This report presented an attempt to assess climate impacts on crop yields, but this does not imply that we cannot learn from other approaches. The development of other novel methods (for example, based on data-driven approaches, event-based storylines, multi-model large ensembles etc) that can bring benefits to risk assessment within a crop re/insurance context and help to further explore the plausibility space is welcomed. In addition, exploring different views makes decision-making less likely to fall into single-approach traps. Furthermore, re/insurers can play a role in supporting agricultural adaptation strategies to climate change impacts.

At Swiss Re, we continuously monitor, assess and promote recent advances in new technologies (eg, introduction of more resistant cultivars, enhanced efficiency fertilisers, robotics, automation, precision agriculture etc) and farm management practices (eg, shift to different crop types, urban and vertical farming, regenerative agriculture etc) that have the potential to partially mitigate climate-driven crop yield losses.

We hope that these actions can help the crop re/insurance business proactively manage climate risks in agriculture, improve actual-vs-expected loss ratios and portfolio performance and ultimately strengthen the security and resilience of the food system.

Swiss Re Management Ltd.
Swiss Re
Mythenquai 50/60
P.O. Box
8022 Zurich
Switzerland

Telephone +41 43 285 3095
swissre.com

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