Climate risk management in agriculture

Jacek Kulawik

Abstract

Climate change and climate policy are the two principal sources of climate risk, which pose numerous threats to agriculture and the entire agri-food sector, while simultaneously offering developmental opportunities. Hence, there is an evident need to integrate the management of this risk as a component of a holistic system. In this context, the primary objective of the article is to conduct a comprehensive analysis of the sources and effects of climate risk in agriculture, and to assess the effectiveness of available risk management instruments, with particular emphasis on adaptation, mitigation, and its transfer to the financial market. The objective was achieved by answering four research questions. Both these questions and the objective itself serve merely as means to scientifically substantiate the adopted thesis. The article takes the form of a review-monographic study. The sources from the literature were selected through a combination of the manual technique with a simplified version of the snowballing backward method and two artificial intelligence (AI) assistants: Gemini and SciSpace. The analysis leads to the following conclusions: (1) farmers and agricultural policymakers should endeavour to use the entire range of climate risk management instruments flexibly and intelligently; (2) adaptation to climate change, preferably combined with the strengthening of resilience, offers the greatest potential for coping with climate risk and represents a strategy that does not even require subsidisation or other direct public interventions; (3) the transfer of climate risk from agriculture is possible, but it requires a perspective encompassing the entire insurance and financial market as well as an understanding of their limitations.

Keywords: climate risk in agriculture, agricultural climate risk insurance, climate risk management in agriculture, climate change and agriculture.

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Introduction

The year 2024 turned out to be the hottest in the 175-year history of measuring global atmospheric air temperature[1]. Nowadays, however, increases in temperature are more frequently related to the years 1850–1900, which are treated as the half-century preceding the Industrial Revolution. Within this framework, the global average air temperature in 2024 represents an increase of 1.42–1.65°C. Thus, according to certain research centres, the world has already exceeded the 1.5°C target set for the end of this century in the 2015 Paris Climate Agreement. There is no disagreement, however, that Europe is the continent warming approximately twice as fast as the rest of the world. Average temperatures are rising particularly rapidly in Central and Eastern as well as South-Eastern Europe[2]. It is also undisputed that carbon dioxide, methane and nitrous oxide emissions are at their highest levels for the past 800,000 years. Few people question the fact that this rise also results from human activity, including agricultural activity. In other words, agriculture and the entire food sector contribute to anthropogenic climate change. Agriculture, forestry and other land use sectors (AFOLU) nonetheless possess some potential for absorbing and retaining greenhouse gases. Extrapolations of current trends generally indicate that the average temperature increase by the end of this century will exceed at least 3°C compared to the period 1850–1900, unless globally coordinated actions are undertaken[3]. Should this scenario materialise, global GDP in cumulative terms could decrease by 15% to 34%. However, if humanity were to allocate around 1–2% of its annual GDP to measures counteracting climate change, it would be possible to limit temperature increases by approximately 2°C, which might suffice to stabilise the situation. The cost of inaction – understood as the difference between the consequences of climate change and the expenditure required to mitigate it – is estimated at 11–27% of cumulative GDP.

According to K. Prandecki and W. Wrzaszcz, the increase in average air temperature in Poland will proceed faster than across Europe as a whole, and significantly faster than during the years 1981–2010[4]. Even more alarming is the fact that the

1. M. Guff, *The global temperature may be even higher than we thought*, "New Scientist" 2025, 4. June, access 9.06.2025.
2. Climate Change Service, *European State of the Climate Report 2024 (2025), Copernicus Europe's eyes on Earth*, access 9.06.2025; European Environment Agency, *European Climate Risk Assessment Report 01(2024)*, access 9.06.2025.
3. Boston Consulting Group and University of Cambridge, *The Economic Case for Climate Investment is Clear, but Not Bradly Understood*, 2025.
4. K. Prandecki, W. Wrzaszcz, *Uwarunkowania środowiskowo-klimatyczne rozwoju rolnictwa* [in:] *Środowiskowo-klimatyczne uwarunkowania rozwoju rolnictwa i obszarów wiejskich w Polsce w latach 2004–2030*, red. W. Wrzaszcz, M. Wigier, Warszawa, IERiGŻ PIB, 2024.

actual pace of temperature rise in Poland turns out to be higher than that projected by climate models. The north-eastern provinces, particularly in winter and spring, are especially vulnerable. The negative effects of climate change on Polish agriculture are broadly standard: (1) the emergence of extreme weather events; (2) changes in precipitation patterns and problems with water availability; (3) differentiation in the length of growing seasons; (4) the spread of invasive species and new diseases. However, water scarcity may prove to be the most critical challenge.

Agriculture is a source of anthropogenic climate change due to its contribution to greenhouse gas emissions, but it is even more strongly affected by the adverse consequences of these changes. These consequences concern crop and livestock production, food security, food quality, as well as the standard and quality of life of farmers[5]. Their synthetic expression is the so-called climate risk – encompassing, on the one hand, the growing variability of key weather parameters tending towards extreme values, and on the other, political shocks resulting from adaptation measures, attempts to curb climate change, or sudden policy reversals and inaction. In this context, managing this type of risk is essential. It should be emphasised that Polish literature lacks works that directly address climate risk management in agriculture. This article therefore represents an attempt to fill this research gap. In foreign literature, by contrast, one encounters articles and book chapters devoted to such management, but their authors most frequently focus on adaptation and mitigation strategies or on specific physical risks (e.g. drought), or on isolated instruments such as drought risk management or crop and activity diversification. The present study also incorporates risk transfer, which represents a novelty in the international literature.

Methodological assumptions

In terms of formal classification in Poland (as per the Regulation of the Minister of Science and Higher Education of 22 February 2019), the article resembles a monographic-review study, as it addresses a clearly formulated research problem (managing catastrophic risks in agriculture) and draws upon the most up-to-date literature, while placing it within a historical perspective. A useful point of reference here

5. M.C. Cheng, *Three Essays on the U.S. Agriculture Under Climate Change: A Crop – Livestock Framework*, PhD thesis, College Station, TX, Texas A&M University, 2024, access 1.06.2025; S. Frei, *Effect of Climate Change on Risk Management Practices in Agriculture Switzerland*, "International Journal of Modern Risk Management" 2024, Vol. 2, No. 2; P.R. Shulela, J. Skea et al. (ed.), *Intergovernmental Panel on Climate Change 2023. Climate Change 2022: Mitigation of Climate Change*, Cambridge University Press, Cambridge, UK, New York, access 1.06.2025.

is the convention adopted by the "Journal of Economic Literature" (JEL) – a journal with a very high impact factor (nearly 13) and assigned the maximum value of 200 points in Poland in the discipline of economics and finance. Articles published in JEL are review-monographic studies, with each issue discussed from a historical and evolutionary perspective. Accordingly, JEL's publisher does not object to references to publications dating as far back as the 19th century or earlier.

Throughout the article, a combination of a modified version of the snowballing backward technique and the manual (traditional) method for reviewing the literature was employed. The essence of snowballing backward lies in constructing a so-called seed set of key titles and then working backwards to incorporate further items[6]. The search phrase consisted of the English and German equivalents of the expression climate risk management in agriculture. The modification involved the seed set consisting of fifteen English-language and two German-language publications. The author of the article has been monitoring these publications for nearly thirty years and has a thorough familiarity with the material published in them. Additionally, it was assumed that the articles in question would have an impact factor and a minimum of 70 points in the Polish academic classification. Such an approach can be regarded as defining inclusion and exclusion criteria, commonly used in systematic literature reviews based on digital databases. This combination, supported by a thorough understanding of the research field, is at least as effective as a systematic literature review based on digital databases[7]. As a result, the analysis presented further on is highly up-to-date and addresses the most important issues in this field in a logical manner. Furthermore, two artificial intelligence assistants – Google Gemini and SciSpace – were utilised.

The principal objective of the article is a comprehensive analysis of the sources and consequences of climate risk in agriculture and an assessment of the effectiveness of available instruments for managing it, with particular emphasis on adaptation, mitigation and its transfer to the financial market. This objective is achieved by answering the following research questions:

6. C. Wohlin, *Guidelines for Snowballing in Systematic Literature Studies and Replication in Software Engineering*, Technical Report EBSE-2007–01, School of Computer Science and Mathematics, Keele University, 2007.
7. B. Danglot, O. Vera-Perez, 2. Yu et al., *A snowballing literature study on test amplification*, "Journal of Systems and Software" 2019, Vol. 157; S. Jalali, C. Wohlin, *Systematic Literature Studies: Database Searches vs. Backward Snowballing*, Proceedings International Conference on Evaluation and Assessment in Software Engineering, 2014; Vrije Universiteit Amsterdam, University Library, *Snowball method-research skills-advanced-libGuides*, https://libguides.vu.nl/c.php, access 7.02.2025; C. Wohlin, M. Kalinowski, K. Romero Felizardo et al., *Successful combination of database search on snowballing for identification of primary studies in systematic literature studies*, "Information and Software Technology" 2022, Vol. 147; K. Wnuk, T. Garropalli, *Knowledge Management in Software Testing: A Systematic Snowball Literature Review*, "e-Informatics Software Engineering Journal" 2018, Vol. 12, No. 1.

1. How is climate risk defined and classified?
2. What constitutes the essence of climate risk management?
3. How does adaptation to climate change differ from mitigation?
4. What are the possibilities of transferring climate risk from agriculture to the financial market?

The objective and the answers to these research questions serve solely to scientifically substantiate the following thesis: climate risk management in agriculture constitutes a serious challenge, primarily due to the potential of climate change to generate extreme weather events which, in formal terms, require highly advanced probabilistic and statistical tools for their description. However, for management to be reasonably effective and efficient, integration of available instruments is necessary, supported by responsible public policy – which, paradoxically, itself also constitutes a source of risk.

Climate change

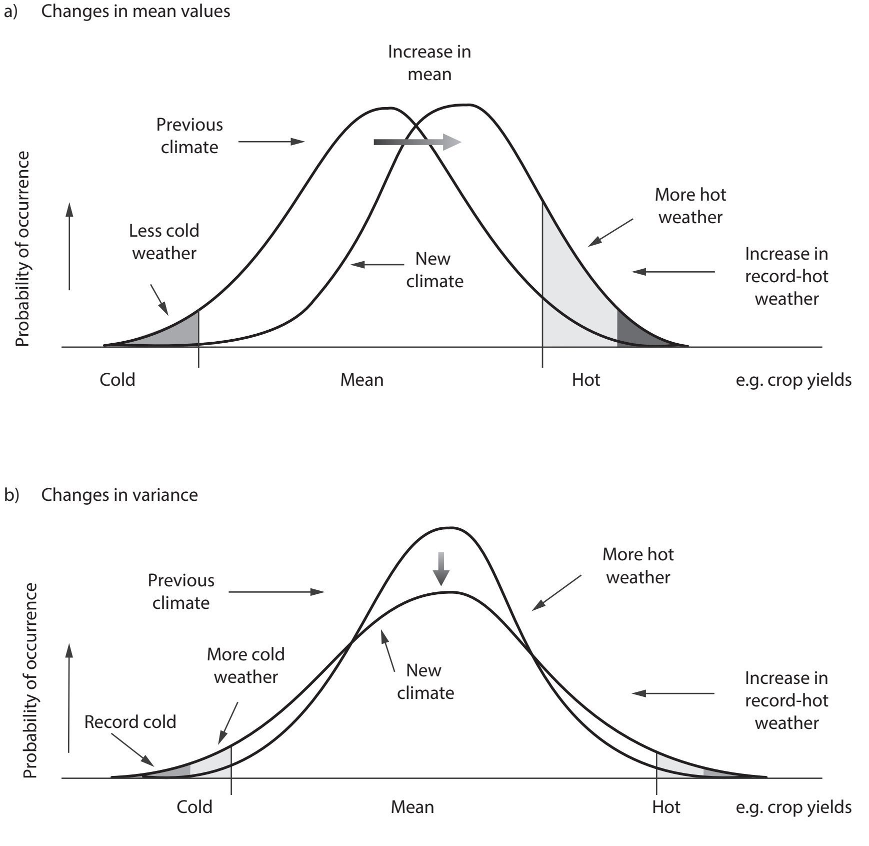
Climate change is often perceived as a kind of "multiplier/trigger/detonator of other risks" – the latter term having been introduced by the United States Department of Defence, i.e. the Pentagon. Among such risks are even those of geopolitical significance[8]. The consequences of climate change also include the destruction of natural and infrastructural systems. In statistical terms, climate change, in its simplest form, means variations in the average values of weather parameters and in the measures describing their variability. In more advanced analyses, however, the remaining moments of the distributions of these parameters are already taken into account, particularly at their extremes (so-called tail distributions)[9]. The sources of climate change may be natural processes or those of anthropogenic origin. It is important to identify them over sufficiently long periods and to bear in mind that climate change affects both the mean values and the variance of weather parameters – as illustrated in Figure 1.

A direct consequence of climate change may be extreme weather events, i.e. relatively rare but highly destructive phenomena that may generate catastrophic and systemic risks, as well as induce their cascading, complex, and chaotic nature. It is always essential, however, to distinguish between climate – defined by the World Meteorological Organization (WMO) as the average course of weather over a period

8. D. Carlin, M. Arshad, K. Baker, *Climate Risks in the Agricultural Sector*, UN environment programme/finance initiative, New York 2023.
9. The World Bank, *Agricultural Risk Management in the Face of Climate Change*, Washington D.C., 2015.

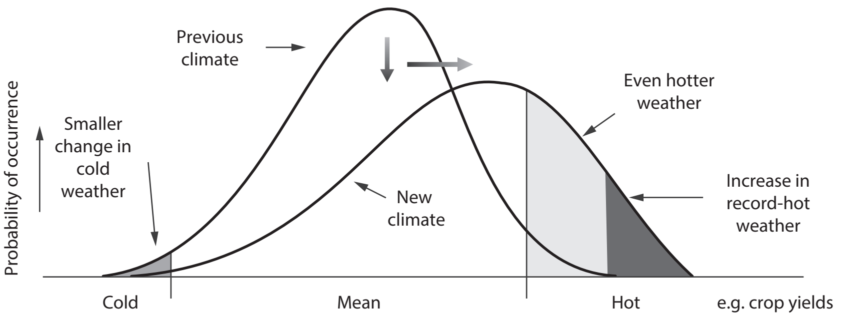
of at least 30 years – and weather, understood as the current state of atmospheric parameters (temperature, humidity, wind, pressure, etc.) in a given location[10]. Consequently, weather risk should be understood as the current frequency/probability of the occurrence of the above atmospheric conditions and their potentially adverse impact[11].

Figure 1. The impact of climate change on the distributions of mean values and variances of weather parameters



10. K. Kożuchowski (ed.), *Meteorologia i Klimatologia*, Warszawa, Polish Scientific Publishers PWN, 2012.
11. G. Dionne, D. Desjardins, *A reexamination of the US insurance markets capacity to pay catastrophe losses*, "Risk Management and Insurance Review" 2022, Vol. 25.

c) Simultaneous increase in mean and variance



Source: Author's own elaboration based on S. Ramasamy, Climate risks: Assessment and management in agriculture, FAO, 2023, access 19.05.2025.

Impact of climate change on agriculture

As indicated earlier, climate change exerts a multifaceted impact on the agricultural sector. In detail, the following phenomena and processes occur on a global scale:

- rising temperatures, which affect the amount and distribution of precipitation, with the potential occurrence of extreme events;
- difficulties for work carried out in open spaces on farms caused by extreme weather events (primarily by heat waves);
- fluctuations in crop yields resulting, among others, from the increase in atmospheric carbon dioxide concentration;
- greater uncertainty regarding the development of productivity in animal husbandry;
- a higher population of pests and spatial spread of diseases;
- shifts in the regional distribution of favourable and unfavourable conditions for agricultural activity;
- a decline in the total factor productivity and the rate of technical progress;
- growing problems with water supply and intensifying competition in this area, along with the possibility of armed conflicts[12].

12. M.C. Cheng, *Three Essays on the U.S. Agriculture Under Climate Change: A Crop – Livestock Framework*, PhD thesis, College Station, TX, Texas A&M University, 2024, access 1.06.2025; S. Frei, *Effect of Climate Change on Risk Management Practices in Agriculture Switzerland*, "International Journal of Modern Risk Management" 2024, Vol. 2, No. 2; G.S. Malhi, M. Kaur, P. Kaushik, *Impact of Climate Change on Agriculture and Its Mitigation Strategies: A Review*, "Sustainability" 2021, Vol. 13, No. 3; A. Ortiz-Bodea, T.R. Ault, C.M. Carrillo et al., *Anthropogenic Climate Change Has Shoved Global Agricultural Productivity Growth*, "Nature Climate Change" 2021, Vol. 11, No. 4.

The essence, measurement and classification of climate risk

Climate risk is a direct consequence of climate change, whereby the former term may be understood as the vulnerability and exposure to extreme weather events themselves as well as to the indirect negative economic, market, and political consequences of this change, and to those triggered by mitigation measures[13].

Advanced methods for measuring climate risk, referred to in the literature as climate risk assessment (CRA), are specific scenario analyses developed under the "what if" convention. Their full cycle should include the following phases:

1. Preparation of heat maps of climate risk, which will help to understand its components and formulate general assumptions regarding their impact on the agricultural sector and particular types of farms.
2. Selection of objects for comparison.
3. Adjustment of the most suitable climate model to specific conditions, which will first make it possible to estimate the frequency/probability of the occurrence of a particular risk and the expected damage/loss arising from it.
4. Incorporation of the results obtained in step three into crop and livestock growth models to estimate expected yields and productivity, as well as revenues and costs.
5. Calculation of the financial effects obtained in phase three and the proposal of a method for their compensation, including the transfer of climate risk to insurers. In the case of professional management of this risk, the farmer should also develop strategies for negotiating more favourable conditions with providers of external capital, i.e. banks, leasing companies, suppliers of production means, etc. (a modified proposal contained in "Strategies to address climate risks and capture opportunities. A guide for agricultural finance institutions"[14]).

Among possible classifications of climate risk, the central place is occupied by its division into transition risks and physical risks. Their specific characterisation in agriculture is presented in Table 1. The challenge lies in how to integrate climate risk with other types of risks within farms and the entire agricultural sector.

13. O.D. Cardona, K.M. van Alst, J. Birkmann et al., *Determinants of risk: exposure and vulnerability*, Cambridge University Press, Cambridge, UK, New York, 2012.
14. Environmental Defense Fund, *Strategies to address climate risks and capture opportunities. A guide for agricultural finance institutions*, Deloitte, 2023, access 15.05.2025.

Table 1. Main types of climate risk

Type of risk	Kind of risk	Effects of materialisation
Transition risk	Increase in carbon tax rate	Higher operating costs in high-emission sectors
	Restrictions in public policies	Limiting the scope of activities affected by a given factor
	Progress in low-emission technologies	Competitive pressure on farmers adopting low-emission technologies
	Changes in market preferences of consumers and recipients	Possible decline in demand for products with a high carbon footprint
	Growing investor activity	Demands for emission reduction from farmers
	Increasing reputational risk	Pressure from investors, consumers, and non-governmental organisations on high-emission producers
Physical risk	Droughts and heat stress	Decrease in production and increase in its costs
	Extreme storms and floods	Reduction in production volume and deterioration of its quality
	Rising sea levels	Loss of biodiversity, so-called river salinisation, decline in income and food security
	Forest fires	Decline in agricultural production, destruction of infrastructure, and difficulties in performing fieldwork in open spaces
	Ocean salinisation	Loss of biodiversity and lower populations of fish and seafood
	Expansion of invasive species	Reduction in agricultural system resilience and threats to health and food security

Source: Author's own elaboration based on D. Carlin, M. Arshad, K. Baker, Climate Risks in the Agricultural Sector, UN environment programme/finance initiative, New York 2023.

Naturally, both types of climate risk are manifestations of climate change. Physical risk is its direct consequence but must be strictly linked to water availability or excess[15]. This risk may additionally be divided into acute and chronic[16]. The former generally includes extreme weather events that directly translate into an increase in the frequency and magnitude of damage/loss. This is therefore closely related to the possibility of its transfer to the insurance market, as these two parameters constitute

15. Ibidem.
16. A. Gupta, A. Owusu, J. Wang, *Assessing and Attributing Climate Change response of U.S. Insurance Firms*, "The Geneva Papers on Risk and Insurance Issues and Practices" 2024, Vol. 49, No. 3.

the basis for calculating insurance rates and subsequent premium amounts. Chronic risk, on the other hand, refers to long-term shifts in the seasonal patterns of precipitation and temperature distributions and their cumulative values.

Transition risk arises when society undertakes adaptation measures to climate change or mitigation of its causes. Such efforts are often succinctly referred to as attempts to transition towards a low-emission economy. This, in turn, generates various political, market and technological risks. Transition and physical risks can be transferred to the insurance and banking market, which implies the emergence of financial risk for these institutions. They must then be integrated and modelled jointly with risks typical of banks and insurers, i.e. market, liquidity, organisational, insurance, credit, or reputational risk. At present, in banks and the insurance industry, management of total exposure to risks is conducted within the framework of Enterprise Risk Management (ERM).

Climate risk management

It is generally accepted in the foreign literature – since Polish authors do not explicitly define climate risk management – that climate risk management (CRM) is understood as an integrated ex-ante and ex-post combination of instruments and strategies from the fields of technology, institutions and policy, which will enable adaptation to climate change and mitigation of its causes[17]. In the case of technology and institutions, this concerns technical and technological progress, weather and climate forecasts integrated with crop and livestock management models, and programmes for strengthening resilience, local communities and social capital. Political interventions, in turn, include actions aimed, on the one hand, at reducing income risk, and on the other, at enhancing adaptive capacity and resilience to change. Their purpose is also to create incentives for systematic responses to the effects of climate change and for the rational use of budgetary support for traditional and index-based insurance, as

17. V. Chandra, Ch. Padhy, S. Mahapatro et al., *Climate risk assessment and management in agriculture: An overview*, "International Journal of Agricultural Extension and Social Development" 2024, Vol. 7, No. 2; S. Frei, *Effect of Climate Change on Risk Management Practices in Agriculture Switzerland*, "International Journal of Modern Risk Management" 2024, Vol. 2, No. 2; N. Grochowina, *Climate Risk Management in Dryland Agriculture: Technological Management and Institutional Options to Adoption*, Springer, 2023, access 5.06.2025, p. 55–71; L. Kouadio, E. Rahn, *Agricultural climate risk management and global food security: Recent progress in South-East Asia* [in:] *Evaluating climate change impacts*, V. Lyubchich et al., New York, Chapman and Hall/CRC, 2020, access 5.06.2015, p. 348–359; E. Sihem, *Management of Climate Risks and Its Effects on Agricultural Productivity: Evaluating the Impacts of Government Policy*, "International Journal of Food and Agricultural Economics" 2019, Vol. 7, No. 3; E. Surmaini, F. Agus, *Climate Risk Management for Sustainable Agriculture in Indonesia: A Review*, "Journal of Pertanian" 2020, Vol. 39, No. 1.

well as for alternative risk transfer. The importance of local knowledge and practices applied for decades by farmers themselves should by no means be underestimated.

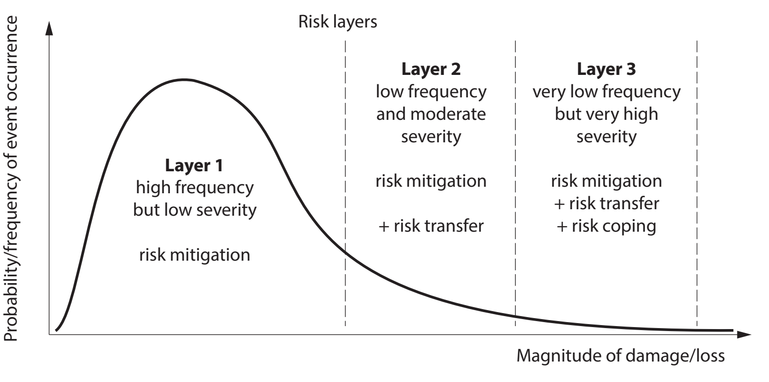
In the most general sense, climate risk management in agriculture should refer to the ISO 31000 standard "Risk management – principles and guidelines". Its current Polish version is contained in PN-I-SO 31000:2018.08. This management is conceived as a process consisting of five phases:

1) defining the context (scope, internal and external objectives, opportunities and threats);
2) risk identification (sources, areas of impact, events, consequences);
3) risk analysis (level, probable effects);
4) risk evaluation (comparison, ranking);
5) risk treatment (plan development, plan implementation).

These phases are linked by communication and consultation, as well as by monitoring (documentation, recording, indicators, reports). It should be added that the above standard is only a general framework and one of several approaches (COSO, Basel III, FERMA, HACCP, IT Risk Management Framework). In agriculture, particularly in small-scale farming, it requires significant simplification.

The World Bank, in its publications, uses two approaches to climate risk management in agriculture – the standard and the three-layer model[18]. In the first case, this management, referred to as a management cycle, consists of five phases: risk assessment, analysis of solutions/tools/instruments, their implementation, risk monitoring, and evaluation. The essence of the three-layer approach is presented in Figure 2.

Figure 2. Three-layer approach to climate risk management in agriculture



Source: The World Bank, Agricultural Risk Management in the Face of Climate Change, Washington D.C., 2015.

18. The World Bank, *Agricultural Risk Management in the Face of Climate Change*, Washington D.C., 2015.

Adaptation to climate change

In general terms, adaptation to climate change is understood as adjustments within natural, social and economic systems aimed at reducing its future negative effects and exploiting the opportunities it creates[19]. In a more specific sense, it concerns the implementation of appropriate operational, agronomic and zootechnical measures and practices, rather than directly influencing climate change itself. This understanding of adaptation encompasses both self-insurance – reducing the scale of future damage – and self-protection, i.e. actions aimed at reducing the probability/frequency of their occurrence. Equally importantly, these measures have a clearly anticipatory aspect of ex-ante management of future risks. Moreover, the fact that adaptation is also intended to facilitate the discounting of potential benefits from climate change means that it also functions as an instrument for managing speculative risks. Thus, adaptation fits into the currently dynamically developing trend in risk management known as balanced chance and risk management[20]. A review of adaptation practices in agriculture is presented in Table 2.

Table 2. Set of available adaptation measures to climate change in agriculture

Area of activity	Adaptation instruments
Crop management	– Change in sowing/planting/harvest dates – Selection of more suitable plant varieties – Adjustment in crop structure – Regionalisation of crops – Agroforestry, silvopastoral systems, etc. – Limiting the expansion of invasive species
Fertilisation	– Change in practices – Precision farming – Use of organic fertilisers – Use of slow-release fertilisers – Increased importance of leguminous crops

19. A.B. McCarl, *Climate change: What do we do about it? Economic issues regarding agricultural adaptation and mitigation*, "American Journal of Agricultural Economics" 2025, Vol. 107, No. 2.
20. W. Gleißner, *Grundlagen des Risikomanagements. Handbuch für ein Management unter Unsicherheit*, 4. Auflage, Vahlen, München 2022; W. Gleißner, *Einführung in das Risikomanagement. Umgang mit Chancen und Gefahren in Unternehmen*, Vahlen, München 2025; T. Reichmann, M. Kißler, U. Baumöl, *Controlling-Konzeption*, 9. Auflage, Vahlen, München 2017.

Area of activity	Adaptation instruments
Water management	– Use of irrigation – Precision irrigation – Changing irrigation timing – Preventing soil salinisation – Rainwater retention – Layered cultivation schemes – Information systems on the relationship between water, fertilisation and weather
Soil and land use	– Change in land use system – Erosion control – Use of deep-rooted plants – Prevention of soil compaction – Organic fertilisation, cover crops, catch crops, and mixtures including legumes and perennials – Selection of plants absorbing carbon dioxide
Animal production	– Animal stock control – Use of feed additives – Feed management and feed reserve management – Improvement of sanitary conditions and veterinary care – Herd management
Permanent grasslands	– Selection of more suitable grass species and varieties – Rationalisation of grazing – Erosion control – Restoration of degraded grasslands – Fertilisation and use of deep-rooted plants
Diversification	– Production and sowing structures, as well as agricultural and non-agricultural income structures; non-agricultural sources of income
Fires	– Implementation of appropriate procedures; – Use of landscape elements that limit the spread of fires; – Development of contingency plans
Risk management	– Combination of various risk management tools; – Forecasting changes in the external environment; – Cooperation and integration
Post-harvest crop activities	– Loss reduction; – Reuse of unused food and raw materials; – Rationalisation of storage and sales channels
Information processes and knowledge transfer	– Improvement of education; – Enhancing the functioning of agricultural advisory and research systems; – Implementation of digital agriculture practices
Public policies	– Supporting technologies and practices that increase resilience to climate change; – Development of good governance; – Infrastructural changes; – Initiating and implementing policies promoting diversification and international food trade development

Source: A.B. McCarl, Climate change: What do we do about it? Economic issues regarding agricultural adaptation and mitigation, "American Journal of Agricultural Economics" 2025, Vol. 107, No. 2; P. Smith, K.V. Calvin, J. Niken et al., Which practices co-deliver food security, climate change mitigation and desertification, "Global Change Biology" 2020, Vol. 26, No. 3.

The application of adaptation also follows from a simple fact: the pace of mitigation is generally slow and subject to further delay due to changes in climate policy. Sometimes, as after the re-election of Donald Trump as President of the USA, such change can be fundamental. Following his administration, which once again withdrew from the 2015 Paris Agreement, many other countries also considered such a decision. Meanwhile, it is much easier to gain public support and funding for adaptation measures. Unfortunately, coordination of the relevant public expenditures for this purpose is often lacking, as "silo-based" governance still prevails in state structures – i.e. the independence of ministries, agencies and similar institutions.

Mitigation of climate change

In agriculture, efforts should also be made to implement technologies and innovations that reduce greenhouse gas emissions. In the most general sense, these may include feed supplements that lower the intensity of methane emissions from livestock, as well as agronomic practices, particularly in the areas of plant fertilisation or field drainage[21]. If, for example, EU agriculture were to widely implement the model of climate-smart agriculture (CSA), by 2030 this sector could emit 6% less greenhouse gases than in 2020[22].

The entire agricultural technology market, often referred to as "agritech", plays a major role in mitigating the negative effects of climate risk. This includes, among others, biotechnologies that reduce the use of various agrochemicals and the intensity and frequency of cultivation treatments. Compared with traditional technologies in field crops, the reduction of greenhouse gas (GHG) emissions here ranges from 7% to 35%[23]. By analogy to all studies focusing on the implementation of modern technologies and innovations in agriculture, it may be assumed that the mitigation strategy is primarily applied by larger farms. Of course, this hypothesis requires solid verification. Also of great interest is the field of production of so-called cultivated meat and plant-based substitutes for traditional meat. Initially, these segments developed very slowly; later, there was a clear acceleration in market dynamics, but now a phase of stability has appeared. We must therefore wait to see whether such meats will actually become substitutes for traditional meat.

21. B. Henderson, S.F. Havlik, P. Valin, *Policy strategies and challenges for climate change mitigation in the agriculture, forestry and other land use (AFOLU), sector*, OECD, Paris 2021.
22. World Economic Forum, *Transforming Food Systems With Farmers: A Pathway for the EU*, 2022, access 7.05.2025.
23. B. Rutkowska, W. Szulc, T. Sosulski et al., *Impact of reduced tillage on CO_2 emission from soil under maize cultivation*, "Soil and Tillage Research" 2016, Vol. 180.

Mitigation is primarily intended to reduce future exposure to the negative effects of climate change by decreasing net greenhouse gas emissions into the atmosphere and/or the heat accumulated within the Earth system. This broader understanding of mitigation, as proposed by A.B. McCarl, also implies the use of geoengineering, namely:

1) increasing the reflectivity coefficient of solar radiation reaching the Earth;
2) physically capturing carbon dioxide, also referred to as its sequestration.

Additional instruments of mitigation include the production of bioenergy and biomaterials, and increasing the albedo coefficient (the surface's ability to reflect light, which reduces its warming).

The main possibilities for mitigating the negative effects of climate change in agriculture are presented in Table 3.

Table 3. Strategies mitigating climate change in agriculture

Strategy	Mechanism of action	CO_2 emission	Methane emission	Nitrous oxide emission
Change in crop structure	Sequestration, emission	X	X	X
Plant fertilisation	Sequestration, emission	X		X
Change in inputs in crops	Emission	X		
Change in cultivation systems	Emission	X		X
Plant cover	Sequestration, emission	X		X
Transformation of grasslands	Sequestration	X		
Irrigation	Emission	X		
Biofuels	Compensation/offset	X	X	
RES	Compensation/offset	X	X	X
Change in animal stocking rates	Emission	X	X	X
Enteric fermentation	Emission	X	X	X
Size of animal herds	Emission		X	X
Change in breeding system	Emission		X	X
Organic fertilisers	Emission		X	X
Rice cultivation area	Emission		X	
Afforestation	Sequestration	X		
Forests	Sequestration	X		X
Technological progress	Emission, sequestration	X	X	
Albedo manipulation	Heat reflection			

Source: A.B. McCarl, Climate change: What do we do about it? Economic issues regarding agricultural adaptation and mitigation, "American Journal of Agricultural Economics" 2025, Vol. 107, No. 2; P. Smith, K.V. Calvin, J. Niken et al., Which practices co-deliver food security, climate change mitigation and desertification, "Global Change Biology" 2020, Vol. 26, No. 3.

Traditional insurance as an instrument of climate risk management

Drought is the main type of physical risk within the broader category of climate risk, contributing most significantly to declines in yields and productivity in agriculture (FAO, 2021). Alongside heatwaves, it also poses the greatest threat to livestock production – either directly through heat stress, which worsens animal welfare and reduces feed intake, thereby lowering individual productivity under otherwise constant conditions, or indirectly by limiting feed resources. However, the potential for mitigating this risk through traditional insurance is limited.

Losses in agriculture caused by climate change were estimated at 26% of total losses globally by the end of the previous decade (FAO, 2019). In developing countries, however, this ratio was as high as 83%. It is estimated that rising temperatures between 1991 and 2017 compelled insurers to pay out approximately USD 28 billion in compensation to farmers[24].

Crop insurance can mitigate the direct financial losses incurred by farmers due to the materialisation of extreme weather events, yet farmers must then face higher insurance premiums, which reduce their profitability and liquidity, thereby constraining their potential for adaptation and mitigation efforts within the entire climate risk management toolkit[25]. Apart from rising premiums, insurers may impose limits on their liability for damage to fixed assets caused by physical disasters in the case of farmers who do not insure their crops – or may even refuse to provide coverage altogether[26]. Farmers' situations may also be further complicated by the fact that most of their work is performed outdoors, where heat significantly reduces productivity. An additional concern is that droughts and heatwaves greatly increase the likelihood of forest fires, as was the case in Australia in 2019–2020. Although farmers there received government compensation, it covered only around 20% of their losses on average[27]. In Poland, a particularly reprehensible practice is the burning of grass by some farmers, which can also trigger forest fires.

When climate risk materialises in the form of extreme weather events, it is often modelled in the literature as catastrophic risk. This approach dates back to the work

24. N.S. Diffenbaugh, F.V. Davenport, M. Burke, *Historical warming has increased US crop insurance losses*, "Environmental Research Letters" 2021, Vol. 16, No. 8.
25. D. Carlin, M. Arshad, K. Baker, *Climate Risks in the Agricultural Sector*, UN environment programme/finance initiative, New York 2023.
26. Agriculture Economic Insights, *How does wildfire affect U.S. Agriculture*, 13.09.2021, ei.ag/2021/09/13/wildfire-smoke-impact-agriculture, access 6.05.2025.
27. Ibidem.

of K. Borch (1962)[28]. The Norwegian economist and actuary constructed his model in the framework of maximising the expected utility of the insurance company. Let us briefly examine the formal aspect of his reasoning. Let L_i denote a random loss or compensation paid by the insurer *i*, Q_i its capital, and $F_i(L_i)$ the cumulative distribution of L_i. The expected utility function can be written as follows:

$$U_i\left(L_i\right)=U\left(Q_i,F_i\left(L_i\right)\right)=\int_0^{\infty}U_i\left(Q_i-L_i\right)dF_i\left(L_i\right).$$

An insurer exhibiting risk aversion may improve its welfare by entering into a collective contract or pooling agreement (L^P) with other companies in the sector, numbering N. Hence:

$$L^P=\left(L_1^P\left(L_1...L_N\right)...L_N^P\left(L_1...L_N\right)\right),$$

where: $L_i^P(L_1...L_N)=L_i^P(\overline{L})$ represents the total payments made by the insurer in accordance with the agreement. The contract itself must satisfy the allocation condition to ensure full coverage of liabilities towards clients.

$$\sum_{i=1}^{N}L_i^P\left(\overline{L}\right)=\sum_{i=1}^{N}L_i\ .$$

The agreement will be Pareto-optimal if there exist non-negative constants $k_1...k_n$, satisfying the following equation:

$$k_iU_i^{'}\left(Q_i-L_i^P\left(\overline{L}\right)\right)=k_1U_1^{'}\left(Q_1-L_1^P\left(L\right)\right)\quad \textit{for everyone}\quad i=1...N,$$

where: $U_i^{'}$ denotes the insurer's marginal utility. It should be noted that this equation is independent of $F_i(L_i)$. It follows that the optimal agreement does not depend on the distribution of losses but on their total magnitude.

In 2002, D.J. Cummins, N. Doherty and A. Lo published an article that extended, generalised, and empirically verified Borch's theorem[29]. The novelty consisted in introducing insurer neutrality towards risk and limiting liability for losses so as to minimise insolvency while maximising compensation payments. In other words, these authors addressed the functioning of the entire insurance market. In 2022, G. Dionne and D. Desjardins, building on the concepts of D.J. Cummins et al., conducted new empirical calculations showing that, with a well-developed reinsurance and alternative

28. K. Borch, *Equilibrium in a reinsurance market*, "Econometrica" 1962, Vol. 30, No. 3.
29. J.D. Cummins, N. Doherty, A. Lo, *Can insurers pay for the „big one"? Measuring the capacity of the insurance market to respond to catastrophic losses*, "Journal of Banking and Finance" 2002, Vol. 26, No. 2–3.

risk transfer market, the United States managed catastrophic risk relatively effectively without relying on state budget intervention[30].

Insurance companies can adopt various strategies to respond to climate risk affecting both themselves and their clients. Broadly speaking, these strategies fall into two categories: traditional and innovative[31]. The traditional approach focuses on risk avoidance – withdrawing from the most hazardous sectors to prevent losses[32]. Mitigation, in turn, involves reducing climate risk through higher rates and premiums, limiting liability for damages, and transferring part of the risk to public authorities[33]. The innovative approach entails adapting to risk and investing in improved methods of analysis and prediction, using increasingly sophisticated modelling techniques[34]. According to A. Gupta et al., US insurers most exposed to climate risk are generally not leaders in adaptation, yet this group still performs well financially due to strong integration between management boards and specialised technical experts. However, this situation may change rapidly. A report by Bain & Company clearly shows that by 2030 only 25–33% of losses caused by natural disasters are likely to be compensated by insurance policies, as insurers face growing challenges in pricing such risks[35].

Climate change presents a challenge for traditional property insurers, as physical risk primarily affects their liabilities, while transition risk mainly impacts their assets – yet both risks can occur simultaneously[36]. It is therefore necessary to develop appropriate tools for modelling these risks and their nonlinear interdependencies, referred to as upper tail dependence (UTD). This involves analysing the joint marginal distributions of two random variables: the frequency of claims and their size. In current research, copulas – multivariate cumulative distributions in which marginal distributions of individual variables fall within the interval [0, 1] – are widely

30. G. Dionne, D. Desjardins, *A reexamination of the US insurance markets capacity to pay catastrophe losses*, "Risk Management and Insurance Review" 2022, Vol. 25.
31. A. Gupta, A. Owusu, J. Wang, *Assessing and Attributing Climate Change response of U.S. Insurance Firms*, "The Geneva Papers on Risk and Insurance Issues and Practices" 2024, Vol. 49, No. 3.
32. A. Thomas, R. Leichenko, *Adaptation through insurance: lessons from the NFIP*, "International Journal of Climate Change Strategies and Management" 2011, Vol. 3, No. 3.
33. Z.A. Elum, J.B. Simonyan, *Analysis of Nigerian insurers' perceptions of climate change*, "South African Journal of Economic and Management Sciences" 2016, Vol. 19, No. 4; S.S. Groth, J. Muntermann, *An intraday market risk management approach based on textual analysis*, "Decision Support Systems" 2011, Vol. 50, No. 4.
34. W.C.H. Keskitalao, G. Vulturis, P. Scholten, *Adaptation to climate change in the insurance sector: examples from the UK, Germany and the Netherlands*, "Natural Hazards" 2014, Vol. 71, No. 1.
35. P. Skwirkowski, *Coraz mniej osób może być stać na zakup polisy*, "Rzeczpospolita" 2025, No. 115.
36. N. Gatzert, O. Özdil, *The impact of dependencies between climate risks on the asset and liability side of non-life insurers*, "European Actuarial Journal" 2024, Vol. 14, No. 1.

applied for this purpose[37]. The approach of N. Gatzert and O. Özdil provides a useful illustration of these issues[38]. Let us begin with the analysis of insurer liabilities.

According to the collective risk model, the amount of claims against an insurer up to time t is a stochastic sum of the form:

$$\tilde{S}_t = \sum_{i=1}^{N_t} X_i \ ,$$

where N_t denotes claim frequency and X_i – size of claim *i*.

Due to the increasing frequency of natural disasters as a consequence of progressing climate change, both parameters will rise, thereby increasing UTD between them. To model the dependence structure between N and X, Gatzert and Özdil replace the total claim amount with annual claims aggregated over 52 weeks. Thus:

$$S_1 = \sum_{w=1}^{52} N_w \cdot X_W \ ,$$

where N_w is the weekly (*w*) frequency of claims. Hence, UTD between N_w and X_w now means that if the number of claims is higher in week *w*, their size is also likely to be higher, and vice versa. This relationship is described by a rotated (180°) Clayton copula C_θ^{CL}:

$$C_\theta^{FS}\left(u_1 u_2\right) = u_1 + u_2 - 1 + C_\theta^{Cl}\left(1-u_1, 1-u_2\right)$$

where u_1, u_2 are counterparts of random variables N_w and X_w after integer transformation of probabilities; *F* = frequency; *S* = severity. The strength of dependence is expressed by Kendall's tau coefficient (ρ_τ), i.e. the correlation between ordinal variables. As ρ_τ increases, one moves towards so-called fat-tailed dependencies — rising probabilities of extreme events occurring at the tails of statistical distributions.

Gatzert and Özdil further introduce the possibility of reinsurance by the primary insurer under a stop-loss contract, which limits liability (usually defined as a certain percentage of collected premiums), premium rate adjustments, and additional contributions.

The core of their asset modelling framework is the equation describing the insurer's asset value for one year, A_1:

$$A_1 = A_0 \cdot \left(1 + r_1\right), A_0 = U_0 + p - \Pi \ ,$$

37. P. Smith, K.V. Calvin, J. Niken et al., *Which practices co-deliver food security, climate change mitigation and desertification*, "Global Change Biology" 2020, Vol. 26, No. 3.
38. N. Gatzert, O. Özdil, *The impact of dependencies between climate risks on the asset and liability side of non-life insurers*, "European Actuarial Journal" 2024, Vol. 14, No. 1.

where A_0 is the initial asset level, r_1 the rate of return, W_0 the initial surplus, p premium income, and Π payments to the reinsurer.

In the final formal part of their analysis, Gatzert and Özdil examine the potential for insurer default:

$$DP = P\left(U_1 < 0\right),$$

where *DP* denotes default probability (*P* = probability), followed by the expected surplus ES:

$$ES = E\left[U_1\right].$$

The robustness of their formal assumptions is verified using Monte Carlo simulations under four scenarios:

1. Orderly transition to a climate-neutral economy – the baseline scenario without additional physical or transition risks.
2. Disorderly transition to such an economy.
3. Hot house world, i.e. a world with unmitigated climate warming.
4. Too little, too late, meaning the delayed implementation of climate neutrality policies.

Within each scenario, sub-scenarios were further simulated, incorporating UTD dependence, reinsurance, and premium increases.

All simulations clearly demonstrated that property insurers must improve modelling of extreme events at the lower tail of distributions of key parameters in risk and asset-liability management. Prudent use of reinsurance can reduce solvency and profitability threats. The same holds for raising premium rates where legally and competitively feasible. Conversely, the relaxation or postponement of climate policies can lead to the accumulation of physical and transition risks that may no longer be offset by reinsurance, alternative risk transfer, or higher premiums.

Physical climate risk materialises in the short term, while transition risk emerges over the medium and long term. Both remain statistically interrelated, yet understanding, modelling, and simulating their behaviour – particularly in the lower tails of distributions describing insurers' operations – is essential. For this purpose, various types of copulas are widely used, as recommended by[39] O. Özdil.

Özdil models physical risk through simple extrapolation combined with the assumption of a constant coefficient of variation, allowing a relatively precise reflection of changes in the frequency and magnitude of weather-related hazards that

39. O. Özdil, *A multi-period model for assessing the reinforcing dependence between climate transition and physical risks of non-life insurers*, "The Journal of Risk Finance" 2025, Vol. 26, No. 1.

affect expected financial claims against insurers. Transition risk, on the other hand, is modelled as a stochastic process oriented toward the goal set by the 2015 Paris Agreement – namely, keeping the global temperature increase by 2050 below 2°C relative to the pre-industrial period (1850–1900). Let us again briefly examine the formal approach applied by Özdil.

The starting point is the equation describing the creation of an insurer's surplus U_n, $n \in \{n_0,\dots,N\}$, expressed in discrete time:

$$U_n = (1+r_n)\cdot(U_{n-1}+\pi_n)-(S_n-S_{n-1}), U_{n_0}=E_0,$$

where E_0 denotes initial equity, π_n premium income, r_n the rate of return on the asset portfolio, and $S_n - S_{n-1}$ the increment in claims during year *n*.

Transition risk reflects the shocks caused by climate public policies oriented towards mitigation and adaptation, which in turn affect insurance risks and technological innovations in the insurance industry, as well as the proportions therein between the so-called brown investments (mainly high-emission sectors) and green investments (low-emission companies and RES). It is fundamentally unrealistic to assume that these shocks and their consequences are short-lived events (e.g. occurring within a single year). At this point Özdil already introduces the aforementioned monotonically increasing stochastic process of the world's transition to a net-zero economy by 2050. He wrote it in the convention of expected value (operator E). When it is completed at the moment of not exceeding a temperature increase of 2°C in 2050, we have:

$$E\left[t_n - t_{n-1} \middle| t_{n-1}\right] = \max\left(\frac{1-t_{n-1}}{(N+1)-n}, 0\right), t_{n_0} = 0,$$

with: *t* denoting time, varying from n_0 to *N*.

Of course, this process has an upper bound equal to 1, when 100% of the global climate target assumed in the Paris Agreement is achieved. Hence:

$$\min(t_{\tilde{n}}, 1) = 1 \Rightarrow t_n = 1, \forall n \in \{\tilde{n},\dots,N\},$$

where: $\tilde{n}$ – the stopping year of the stochastic transition process.

The simulations carried out by Özdil were aimed at tracking changes in two measures relating to the safety (solvency) and efficiency of a non-life insurer. The first was the probability of ruin of the company occurring within a finite time (year), RP(n):

$$RP(n) = \left(\min_{n_0 \le m \le n} \{U_m\} < 0\right).$$

This category shows the probability of a negative surplus occurring at least once in the time period up to year *n*. In other words, we then obtain the information that the assets would not suffice to cover all claims.

The second measure is the expected/anticipated surplus, which may later serve as the basis for determining the company's profitability:

$$ES(n) = E[U_n].$$

In the Monte Carlo simulation, Özdil adopted as the baseline scenario the absence of a transition process towards the goal of a maximum 2°C increase in global temperature by 2050. The alternative scenarios were statistical distributions of the transition: Rayleigh, exponential and Pareto, and their combinations with strengthened statistical dependencies between physical and transition risk established using the rotated Clayton copula. The two main conclusions from the simulations are as follows.

1. A disorderly transition to a low- and net-zero-emission economy poses a serious challenge for non-life insurers. In particular, the probability of ruin/insolvency increases in such circumstances. This finding is modified by the deepening of statistical dependencies between physical and transition risk, the type of statistical distribution, and the proportions between brown and green investments. In general, the cash surplus reacts less to changes in the simulation parameters.
2. Non-life insurers must continuously update their climate and risk management models to reflect more precisely the impact of extreme weather events on the frequency and magnitude of losses. The same applies to supervisors and regulators of the insurance sector.

Indices in the management of climate risk in agriculture

The socio-economic approach to climate risk focuses primarily on the growing vulnerability of yields to weather anomalies and on other channels of negative impact, such as constraints on the execution of current and future agronomic operations, increases in their costs, or deterioration in harvest quality. In traditional insurance, the question arose as to how the increased weather and climate risks would affect future rates and premiums[40]. In the case of index insurance, by contrast, an important challenge is to reflect in their design the necessary flexibility, i.e. their

40. J. Tack, K. Coble, B. Barnett, *Warming temperature will likely induce higher premium rates and governments outlays for the U.S. crop insurance program*, "Agricultural Economics" 2018, Vol. 49.

adjustment to the variability of exposure to risks in the individual development phases of the protected crops[41]. In general, the point is to reduce the basis risk embedded in such contracts[42].

In most countries of the world, crop insurance is dominated by products oriented towards protecting revenues from individual activities. Formally, in developed countries they are based on forecasts of expected yields and on futures prices of individual crops. The basic conditions for satisfactory farmer participation in this market segment, and thus for achieving high penetration measured primarily by the area protected, are low policy costs and significant subsidy rates when contracts are of the all-risks type. In return, it is indeed possible to achieve substantial reductions in adverse selection and in ad hoc disaster aid directed to agriculture, which is susceptible to all distortions caused by political processes and procedures, although, on the other hand, the budgetary costs of such a strategy for creating a social and financial safety net are high. It is therefore not surprising that alternative solutions are constantly being sought. An interesting proposal is that presented by E.J. Belasco, J. Cooper and V.H. Smith[43].

These authors refer to and develop a concept already presented in 2008 by D.N. Paulsen and B.A. Babcock. It assumed that farmers would be granted free access to federally subsidised group income protection insurance (the Group Risk Income Protection, GRIP) based on county yields. As is known, this is essentially a type of index contract. The concept assumed that the intermediation of insurance companies would be completely eliminated, which would be the primary source of cost savings for taxpayers. Of course, new costs would appear in exchange, e.g. for marketing, reporting, issuing payment orders to farmers, monitoring and education. To a large extent, however, these processes can be automated, in which case the net cost saving would be indisputable. E.J. Belasco, J. Cooper and V.H. Smith go further still – they propose that their solution should take the form of a permanent ex-ante disaster assistance programme. In this way, farmers would know in advance what assistance they could count on if catastrophic risk materialised and what the conditions for receiving it would be. Equally important is that this support would reach them automatically when the mechanisms activating the index (the so-called triggers) operate, and almost in real time, or at least just before new cropping cycles. It is worth noting that such a system would free agricultural policy from building out ad hoc

41. S. Conradt, R. Finger, M. Spörri, *Flexible weather index-based insurance design*, "Climate Risk Management" 2015, Vol. 10.
42. T. Dalhaus, O. Musshoff, R. Finger, *Phenology information contributes to reduce temporal basis risk in agricultural weather index insurance*, "Scientific Reports" 2018, Vol. 8, No. 46.
43. J.E. Belasco, J. Cooper, H.V. Smith, *The Development of a weather-based crop disaster program*, "American Journal of Agricultural Economics" 2020, Vol. 107, No. 1.

and ex-post support, e.g. based on the very popular preferential disaster loans in Poland and on the restoration of production, as well as on RDP grants.

Another source of inspiration for the above-mentioned authors were three livestock disaster assistance programmes implemented in the USA in 2008, namely the Livestock Forage Program (LFP), the Livestock Indemnity Program (LIP), and the Emergency Assistance for Livestock, Honeybees and Farm-Raised Fish (ELAP). All of them are based on measurements of weather parameters, which are generally available under the Drought Monitor Index. The programmes are administered by the federal Farm Service Agency (FSA) without any participation of insurance intermediaries, which radically reduces the cost of the system and delays in payments to affected farmers.

Halcrow (1949), it has been known that the fundamental drawback of all index contracts is the presence of basis/residual risk, which farmers must handle themselves. This risk can most simply be defined as the difference between systemic and idiosyncratic risk. The point of reference in each case is standard yield insurance based on the yields of individual farms, where there is no danger that losses will exceed the sum insured. In a more advanced approach, we may say that in traditional contracts it should not occur that a farmer's downside risk (incurring losses) exceeds the said sum. In index contracts, by contrast, one must reckon with two types of error: type I – there is a probability of no compensation despite a loss; type II – there is a probability of receiving compensation even though no losses occurred on the farm at all. For completeness, it should be added that we must also consider the economic basis/residual risk in each case. This is a situation in which, at the level of the entire farm, a certain risk remains that the farmer will have to finance personally, even when holding a package of policies and having implemented a refined system for managing overall exposure to various risks. In technical-insurance terms, the consequence of traditional basis risk is lower coverage, which is tantamount to higher deductibles or franchises for farmers.

The research procedure applied by E.J. Belasco, J. Cooper and V.H. Smith is fairly extensive. Smith is fairly extensive. In the first phase, publicly available weather data are used to construct weather indices. These indices then served to construct forecasts of county-level yields for maize for grain, soyabeans, winter wheat, and cotton. Subsequently, by means of regression and simulation, the effect of weather and county yields on farm yields was determined. The essence of the above phases is outlined synthetically below.

The weather index employed by E.J. Belasco, J. Cooper and V.H. Smith is of a composite type, as it was constructed on the basis of so-called degree days and precipitation in the period from 1 April to the end of September for counties in the states forming the five main production centres of the aforementioned crops. After calculating average annual temperatures and precipitation for 1950–2014, the deviations obtained could be regarded as typical values. In turn, county yields were compiled as trend-adjusted values using linear regression to eliminate their increases due to ongoing technological progress. For several reasons, however, both of these weather parameters cannot be used as linear predictors of yields. First, various interactions occur between them. Second, for the occurrence and severity of drought, the temporal distribution of precipitation matters. Third, the relationships between different types of weather and yields may take varied forms. They are particularly complex in cases of drought and other extreme weather events. For insurance, the primary concern is negative deviations of yields from mean values (downside risk).

E.J. Belasco, J. Cooper and V.H. Smith addressed the problem of the relationship between weather and yields by referring to the model used by T. Yu and B.A. Babcock in their 2010 article, in which they also operated with a weather index. Accordingly, the standard deviation for temperature was first calculated as $STDGDD_{it} = \max\left(0, GDD_{it}/std(GDD_i)\right)$. The same was then done for precipitation $STDPRCP_{it} = \min\left(0, PRCP_{it}/std(PRCP_i)\right)$, where: STD – the standard deviation of yields in county i; $STDGDD_{it}$ – standardised degree days for county i and year t; $PRCP_{it}$ – total precipitation for county i and year t. Hence, the following multiplicative weather index is obtained:

$$IP_{it} = STDGDD_{it}{}^{*}\left(-STDPRCP_{it}\right).$$

This index takes positive values when temperatures are higher than normal ($GDD_{it} > 0$) and precipitation is lower than normal ($PRCP_{it} < 0$). In addition to the multiplicative index, the following additive form can also be constructed:

$$IS_{it} = STDGDD_{it} - STDPRCP_{it}.$$

Both indices were calculated for counties, agricultural districts (DIP) and states (SIP).

Given that weather affects yields differently in the individual developmental phases of plants, both indices were additionally calculated with the lower subscript G = AM = April–May; JJ – June–July; AS – August–September; GS – April–September. We may now write the regression model in which the dependent variable Y_{it} denotes the standard deviations of trend-adjusted yields in county i in period t:

$$\begin{aligned} Y_{it} &= \beta_0 + \beta_1 IS\_G_{it} + \beta_2 IS\_G_{it}^2 \\ &+ \beta_3 IP\_G_{it} + \beta_4 IP\_G_{it}^2 + \beta_7 DIP_{dt} \\ &+ \beta_8 DIP_{dt}^2 + \beta_9 SIP_{st} + \beta_{10} SIP_{st}^2 + e_{it}. \end{aligned}$$

The empirical data covered the years 1980–2015. After completing all the calculations, it turned out that the adjusted coefficients of determination are generally low. This certainly stems to a large extent from the fact that the relationships between yields and their determinants are predominantly nonlinear. The parameter estimates exhibited considerable differences at the state level. The analysis of the weather indices themselves showed that precipitation and temperatures in late spring and early summer were decisive for yield levels. When assessing systemic risk, it is essential to use larger territorial units, because local differences in the consequences of its occurrence may offset each other, which may slightly reduce the net effect of drought.

To determine the trigger levels for compensation payments, E.J. Belasco, J. Cooper and V.H. Smith carried out a simulation at the level of representative farms, using the proposal by J. Cooper and B. Delberg (2014). The method has three advantages: (1) it reflects the relationships between yields and prices, which is fundamental for revenue insurance; (2) it preserves spatial correlations between territorial levels of yield differentiation; (3) it allows the determination of correlations between county yields and individual farm yields. Compensation is due when the expected county-level yield falls below the guaranteed county-level yield. The expected yield, in turn, follows from the above-presented regression equations for state-level yields, in which the key independent variables are the various forms of weather indices. Two coverage levels were selected for the proposed programme, i.e. 70% and 85%. The point of reference for the same cover levels were the revenue insurance schemes already operating in the USA. In total, 10,000 iterations of the simulation model were performed. The baseline scenario was the absence of any insurance. Let us add that the programme proposed by E.J. Belasco, J. Cooper and V.H. Smith is an ex-ante disaster assistance scheme and would be available to farmers free of charge.

Table 4 presents the simulation results for 70% coverage for maize for grain and winter wheat only, as these two crops are relevant to Polish conditions. Since the ex-ante programme is aimed at protection against systemic risk rather than that specific to individual farms, the average subsidies and per-hectare revenues are lower in it than in traditional insurance, yet at the same time higher than in the baseline scenario, i.e. with no insurance at all. Unfortunately, the index programme consequently delivers a smaller reduction in risk as measured by the coefficient of variation. As regards basis risk, the type I error proves a decidedly greater problem than the type II error.

Simulation for a protection level of 85% – which is not surprising – resulted in an increase in the amount of subsidies and per-hectare revenues across all scenarios analysed. The coefficients of variation also declined. Very interestingly, however, both errors within basis risk evolved: the first decreased, with the exception of maize for grain, while the second rose sharply compared with 70% coverage and, in the case of maize, was even slightly higher than the first error.

Table 4. Results of the simulation of traditional revenue insurance against the background of the ex-ante disaster assistance programme and the absence of insurance (baseline scenario)

Crop	Subsidy per acre (USD)	Average revenue per acre (USD)	Coefficient of revenue variation per acre	Basis risk	
				Loss but no compensation (Type I, %)	No loss but compensation received (Type II, %)
Maize					
No insurance	–	720	0.30	–	–
Traditional insurance	21.83	742	0.22	–	–
Disaster relief	10.14	730	0.28	10.41	5.58
Winter wheat					
No insurance	–	275	0.52		
Traditional insurance	16.10	291	0.38		
Disaster relief	7.80	293	0.45	9.96	2.84

Source: Author's own elaboration based on: J.E. Belasco, J. Cooper, H.V. Smith, The Development of a weather-based crop disaster program, "American Journal of Agricultural Economics" 2020, Vol. 107, No. 1.

The final part of the simulation by E.J. Belasco, J. Cooper and V.H. Smith is particularly interesting, as it focused primarily on the budgetary costs of traditional revenue insurance and of the proposed index programme. Once again, let us confine ourselves here to comparing maize for grain with winter wheat. As we can see, the index programme for both coverage levels delivers substantial budgetary savings, albeit overall greater for the lower coverage. These savings stem from the programme insuring only systemic risk and from the reduction in administrative costs, which follows from a simple fact – there is no longer any need to involve insurance intermediaries. This is, however, paid for by a decline in protection against negative deviations of yields from mean values (downside risk). In a broader perspective, basis risk and the weaker effectiveness of the index programme in reducing downside risk may cause farmers participating in this programme to obtain bank credit on less favourable terms. This shows that it is very important to apply approaches in which insurance and financial issues are modelled simultaneously[44].

44. D.N. DeLay, B. Brewer, M.A. Featherstone, *The impact of crop insurance on farm financial outcomes*, "Applied Economic Perspective and Policy" 2023, Vol. 45, No. 1.

Table 5. Budgetary costs of traditional revenue insurance against the background of the index-based disaster assistance programme

Specification	Maize for grain	Winter wheat
Average subsidy per acre for 70% coverage		
a. traditional insurance	21.83	16.10
b. free index programme	10.14	7.80
c. reduction (%) = (a – b)/a	53.55	51.55
cost of traditional insurance	2.97	1.14
cost of index programme	1.06	0.42
cost savings	1.92	0.72
change in downside risk protection	-43	-55
Average subsidy per acre for 85% coverage		
a. traditional insurance	26.65	16.58
b. free index programme	17.41	10.33
c. reduction (%) = (a – b)/a	34.67	37.70
cost of traditional insurance	3.14	1.02
cost of index programme	1.82	0.56
cost savings	1.33	0.46
change in downside risk protection	-46	-44

Source: Author's own elaboration based on J.E. Belasco, J. Cooper, H.V. Smith, The Development of a weather-based crop disaster program, "American Journal of Agricultural Economics" 2020, Vol. 107, No. 1.

Summary

Climate change is a source of physical climate risk. It can negatively affect agriculture through multiple channels, particularly when the variability of climate and weather parameters results in the occurrence of extreme events. In statistical terms, these generate distributions of those parameters that are described using so-called fat-tail tools. The risk measured in this way is pure in nature. At the same time, climate change may also create conditions more favourable to conducting agricultural activity. These positive deviations fall within the category of speculative risk. Both types of risk should therefore be managed, combining them with other key threats in agriculture – catastrophic and systemic – and with actions aimed at strengthening the resilience of farms and of the entire agricultural sector. The basic management instrument here is adaptation.

The second source of climate risk is climate policy and the energy policy closely linked to it – which is not addressed in this article – i.e. transition risk. Its source lies in shocks caused both by overly restrictive climate policy and by policy that is poorly designed, imprecisely targeted and not updated in time or even withdrawn altogether, as well as in the absence or postponement of such policy, including under the pressure of lobbyists and populists. Households and enterprises respond in different ways to policy signals, which constitutes a secondary source of transition risk. The basic instrument for managing this climate risk is the mitigation of greenhouse gas emissions. Its effectiveness is directly determined by decisions and actions at the global level, since climate change itself is global in nature. With the re-election of D. Trump as President of the United States and the protests by EU farmers concerning the Green Deal, the chances of implementing such policy have decreased very radically.

Physical climate risk can be attempted to be transferred out of agriculture to traditional non-life insurers. This is not easy, however, due to its aforementioned fat-tailed characteristics and the often limited risk-bearing capacity of the insurance sector, even when supported by co-insurance, reinsurance and retrocession, as well as by alternative risk transfer instruments. Index insurance may indeed be a remedy in the future, but it is by no means simpler in terms of design, nor does it automatically generate significant and lasting (non-subsidised) demand on the part of farmers. Another solution consists of index products with a built-in ad-hoce and ex-ante disaster assistance component. An example of such a solution, which is still being considered in the USA, has been presented.

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