Adaptation and mitigation in climate risk management in agriculture

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Abstract

Climate risk management employs two categories of instruments: adaptation and mitigation measures. This exact framework also applies to the agricultural sector. Hence, the primary objective of this paper is to broaden our understanding of adaptation and mitigation, alongside public policies aimed at managing physical and transition climate risks within agriculture. This objective was met by addressing four research questions and substantiating the proposed research hypothesis. The paper takes the form of a monographic review study. The relevant literature was selected through a combination of manual searching, a modified backward snowballing technique, and the use of two artificial intelligence (AI) systems: Gemini and SciSpace. The analysis yields the following conclusions: (1) adaptation and mitigation should be implemented in an integrated manner, given the complementary and substitutable relationship between them; (2) mitigation generally poses a greater challenge than adaptation, as its application and effectiveness rely heavily on transnational, or sometimes even global, cooperation and coordination. In the case of agriculture, its potential is primarily concentrated on crop fertilisation and the scale of livestock production; (3) governments ought to support farmers' adaptation and mitigation efforts, ideally through indirect means, whilst ensuring that their motivation for pro-climate behaviour is neither undermined nor distorted.

Keywords: agricultural climate change adaptation, agricultural greenhouse gas emission mitigation, agricultural climate risk, agricultural climate risk management.

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Introduction

Preliminary estimates indicate that global greenhouse gas emissions in 2025 reached a record 60.63 billion tonnes of carbon dioxide equivalent. This represents an increase of approximately 5% compared to 2024[1]. In the European Union (EU), this increase stood at 0.4%. Unfortunately, for Poland, data is only available up to the end of August of the previous year. The emissions in question amounted to 6.1 million tonnes, yet crucially, they were as much as 16.4% lower year-on-year[2]. The primary driver behind such a spectacular decline is the increased generation of electricity in renewable energy installations. Conversely, robust research is emerging which demonstrates that previous empirical studies have likely underestimated the negative impacts of climate change on global and local economic growth, potentially by almost an entire order of magnitude. A prime example of this is the paper by A. Bilal and D.R. Känzig[3]. These two researchers demonstrate that a long-term global temperature increase of 1°C could reduce global GDP by as much as 20%.

There are mounting indications that the world as a whole will no longer achieve the 2015 Paris Agreement target of limiting global temperature rise to no more than 1.5–2°C above pre-industrial levels[4]. Meanwhile, reports emerging from the fuel and energy sector remain ambiguous. On the one hand, substantial investments continue to be made in fossil fuels, yet on the other, there is no evident decline in the expansion of renewable energy sources[5]. Aside from the administration of President D. Trump, a leading contemporary climate denier, signs of scaled-back ambitions in energy and climate policy are also discernible within the EU[6]. Importantly, this trend also applies to mainstream political parties. Somewhat traditionally, EU farmers generally remain reluctant to maintain the current trajectory towards climate change adaptation and the

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[1] Climate Trace Emissions Date (Feb/March), 19.02.2026.

[2] KOBIZE, *Krajowy raport inwentaryzacyjny 2025*, 19.02.2026.

[3] A. Bilal, D.R. Känzig, *The Macroeconomic Impact of Climate Change: Global vs. Local Temperature*, “The Quarterly Journal of Economics” 2026, Vol. 141, No. 2.

[4] A. Bełdowicz, *Szczyt klimatyczny COP 30 już za moment. Co się może wydarzyć?*, “Rzeczpospolita”, nr 229, 3.10.2025; A. Bełdowicz, *Potrzeba redukcji emisji, by chronić kluczowy dla Europy prąd atlantycki*, “Rzeczpospolita”, nr 205, 4.09.2025; A. Hołdys, *Ciepłe przejęcie*, “Polityka”, nr 35, 27.08.2025–2.09.2025; M. Sommer, *Nowojorski szczyt klimatycznej smuty*, “Newsweek”, nr 35, nr 25, 8–31.08. 2025; The aforementioned sources contain numerous references to reports by internationally recognised publishers and research centres dealing with climate issues.

[5] M. Janik, *OZE rozwijają się wbrew nieprzychylnemu klimatowi*, “Rzeczpospolita”, nr 211, 11.09.2025; M. Sommer, *Ropa naftowa jednak wciąż ma przyszłość*, “Dziennik Gazeta Prawna”, nr 189, 30.09.2025. Here, too, the authors refer to statistics from reputable institutions and researchers.

[6] A. Wołownia, *Deregulacja możliwa z każdym*, “Dziennik Gazeta Prawna”, nr 194, 7.10.2025; P. Tychmanowicz, *ESG wspiera właściwą ocenę ryzyka*, “Rzeczpospolita”, nr 233, 7.10.2025.

mitigation of its causes. In this context, Poland stands out negatively against the EU backdrop; we remain the only member state that has yet to draft an updated national energy and climate plan[7]. However, it is encouraging that both domestic industry and the non-governmental sector are demanding such a plan. Unfortunately, similar proactive behaviour is lacking among agricultural producers, even though climate change affects them to an ever-increasing extent.

Climate change is the source of two distinct risks that can negatively impact societies and economies. The first is physical risk, which may stem directly from such change, or indirectly if it initially triggers environmental degradation. This risk can precipitate so-called fast-onset hazards. The second – transition risk – is rooted in state policy, as well as its shifts, delays, and omissions[8]. The primary response to both types of threats should be climate change adaptation.

As noted in the first section of this paper, physical climate risk can be further subdivided into acute risk (short-term adverse weather events) and chronic risk, which manifests gradually. Transition risk, conversely, refers to the indirect negative impacts of climate change brought about by market conditions, regulatory frameworks, and novel technologies. The crux of the issue lies in the complex interactions between these pure risk types[9]. For instance, a sharp increase in physical risks may necessitate drastic economic shifts, including the implementation of new, more stringent regulations. Consequently, transition risk also increases. If, on the other hand, greenhouse gas reduction policies are liberalised, physical risk will likely escalate in the future. The same chain of dependency may occur if the energy transition and associated decarbonisation processes are hindered.

Climate change adaptation can be undertaken autonomously, or reactively, when farmers attempt to adjust to the already unfolding consequences of this change. A more demanding, yet highly preferable approach is planned, or proactive, adaptation. This entails requisite knowledge, access to information, resources, and motivation. In both scenarios, however, agricultural producers must be convinced that, on balance, they will derive a net benefit from their investments. Mitigation, meanwhile, can be either direct or indirect. In the former, the aim is to reduce greenhouse gas emissions at their source. Indirect mitigation demands greater effort, competencies, and resources, as achieving a reduction effect requires managing biochemical processes, though this can be accomplished alongside other initiatives. These two climate risk management

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[7] A. Hołownia , *Brakuje sektorowego planu*, “Dziennik Gazeta Prawna”, nr 196, 9.10.2025.

[8] M. Pisu, H. Costa, M.F. D’Arcangelo et al., *Accelerating Climate Adaptation: A Framework for Assessing and Addressing Adaptation Needs and Priorities*, OECD, Paris 2024.

[9] P. Seusing, C. Leichsening, S. Marx, *Klimatrisiken. Herausforderungen im Risikomanagement von Automobilzulieferung*, “Zeitschrift für Risikomanagemant” 2025, No. 1.

strategies interact in multifaceted ways. By integrating them, however, synergies can be harnessed and their respective drawbacks mitigated. Altogether, this presents a formidable challenge for farmers, policymakers, and modellers alike.

Governments must remain an integral component of the adaptation and mitigation management system. This is due to the presence of externalities, information asymmetries, various implementation barriers, and occasionally the need for substantial capital expenditure. Furthermore, governments share the responsibility for the processes of knowledge accumulation and its subsequent transfer. Public authorities have at their disposal a broad array of economic, regulatory, and other instruments that allow them to actively shape the scope and pace of both adaptation and mitigation. While indirect interventions should be prioritised, the effective functioning and co-financing of pro-ecological investments are equally crucial. A distinct challenge for governments, however, lies in pursuing policies that do not diminish farmers' own incentives to engage in adaptation and mitigation.

Methodological framework

This paper meets the criteria of a monographic review study as stipulated in the Polish Regulation of the Minister of Science and Higher Education of 22 February 2019 on the evaluation of the quality of scientific activity. Therefore, the paper explicitly identifies its scientific problem, namely the role of adaptation and mitigation in agricultural climate risk management. It draws upon the most contemporary literature available, whilst framing it within a historical perspective. In doing so, it takes its cue from three leading agricultural economics journals: "Agricultural Economics" (IF-4), "American Journal of Agricultural Economics" (IF-4.7), and "Journal of Agricultural Economics" (IF-4.2). These journals feature similar articles where specific issues are presented from a historical and evolutionary standpoint, referencing 19th-century authors or even earlier periods when justified.

The subject literature was selected using a blend of a modified backward snowballing concept, manual search techniques, and two artificial intelligence assistants (Gemini and SciSpace). The modification to the snowballing method entailed restricting the search to peer-reviewed articles with a high impact factor, which scored at least 70 points in the Polish academic classification system. Polish, English, and German publications were analysed. Preference was given to texts published within the current decade. In the subjective assessment of the author – who has been engaged in the field of financial and risk management in agriculture and the broader national economy for roughly 30 years – the presented analysis boasts a satisfactory level of currency and addresses the issues within this domain logically.

The fundamental objective of the paper is to deepen knowledge concerning adaptation and mitigation, as well as public policies geared towards managing physical climate risk and transition risk in agriculture. The means to attain this objective involves answering the following research questions.

1. What is the essence of adaptation, what types are identified, and what actions does it encompass?
2. What is the role of mitigation in climate risk management?
3. How should governments support the adaptation and mitigation efforts of agricultural producers?
4. How are adaptation and mitigation modelled in contemporary practice?

The objective and the answers to the posed questions serve, in turn, as a foundation to scientifically validate the following hypothesis: farmers have historically always adapted to climate and weather changes, whilst also possessing certain mitigation capabilities, particularly concerning crop fertilisation and livestock production. Today, however, they must be supported by public policies that deploy the full spectrum of available instruments, without simultaneously diluting or skewing the pro-climate motivation of agricultural producers.

Adaptation-oriented action strategies and policies

Several definitions of climate change adaptation exist within the literature. A brief overview of these is provided below. A. Ignaciuk, following the 2007 report by the Intergovernmental Panel on Climate Change (IPCC), defines the aforementioned adaptation as adjustments in human behaviour – both individual and organised – directed towards expected stimuli and their consequences arising from climate and weather changes, whether positive or negative[10]. It is evident that the author frames this climate and weather threat within the convention of speculative risk. Equally important, however, is that one of the objectives of adaptation is to enhance agricultural resilience. K. Coburn views adaptation as a process of adjusting to the current or anticipated climate and its consequences, with the aim of curbing negative impacts or exploiting emergent opportunities[11]. A. Wreford, A. Ignaciuk, and G. Graère adopt a broadly similar stance, though they stipulate that adaptation must be analysed in

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[10] A. Ignaciuk, *Adapting Agriculture to Climate Change. A role for public politics*, OECD, Paris 2015.

[11] C. Coburn, *Climate Change Adaptation Policies to Foster Resilience in Agriculture*, OECD, Paris 2023.

conjunction with mitigation[12]. Coburn observes, however, that while the majority of individuals, businesses, and governments generally concur on the necessity of implementing adaptation, a significant shortfall (the so-called adaptation deficit) is actually observed in this area. This subsequently depletes social welfare and typically exerts further pressure on public finances when it becomes necessary to provide assistance to individuals, businesses, and entire sectors afflicted by extreme weather events. M. Pisu et al. proffer a definition of adaptation that is inherently very similar to that of A. Ignaciuk, referencing the latest IPCC report published in 2022[13]. Other definitions of adaptation can be found, yet in reality, they introduce nothing novel compared to the perspectives outlined above[14].

Unfortunately, adaptation is not always well-executed; it may be implemented partially, incompletely, or not at all. Such occurrences are collectively termed "maladaptation" in the literature, a concept found in successive IPCC reports. This results in an increased physical risk of climate change and heightened vulnerability to its negative ramifications. Moreover, maladaptation tends to generate external costs, for instance, when farmers overexploit groundwater resources to irrigate their fields – often supported by budget subsidies – or transition towards monoculture systems[15]. The primary source of maladaptation is the uncertainty associated with predicting the trajectory and intensity of climate change, and incorporating relevant information into the decision-making processes of agricultural producers.

Fundamentally, two main types of adaptation are distinguished. The first is autonomous (reactive) adaptation, wherein farmers adjust their practices in response to perceived characteristics of the shifting climate and weather parameters[16]. Activities undertaken within this framework align with good agricultural practices and the pursuit of sustainable management. Examples include shifting the timing of agrotechnical operations, diversifying crops, production, and income streams, as well as integrated pest management. The second type is planned (proactive) adaptation, which is preceded by analysis and the formulation of a specific sequence of actions designed to mitigate the negative impacts of future climate change[17]. Although other

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[12] A. Wreford, A. Ignaciuk, G. Graère, *Overcoming barriers to the adaptation of climate-friendly practices in agriculture*, OECD, Paris 2017.

[13] M. Pisu, H. Costa, M.F. D'Arcangelo et al., op. cit.

[14] F. Gomez-Trajos, *Dynamic welfare implications of market-based climate policy under demand uncertainty*, "Journal of Economic Behavior and Organization" 2025, Vol. 238.

[15] R. Badiani, K.K. Jessoe, S. Plant, *Development and the Environment: The Implications of Agricultural Electricity Subsidies in India*, "The Journal of Environment and Development" 2012, Vol. 21.

[16] R. Mendelshon, *Agriculture and Economic Adaptation*, OECD, Paris 2012.

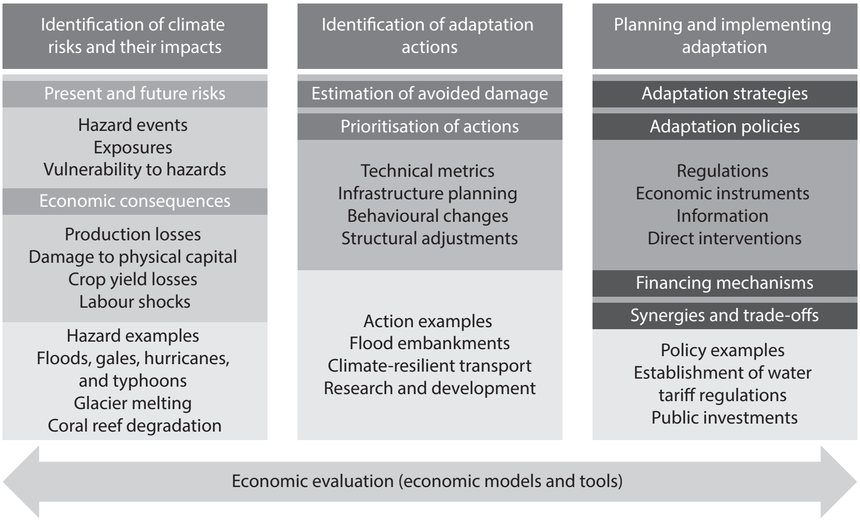
[17] A. Ignaciuk, D. Mason-D'Croz, *Modelling Adaptation to Climate Change in Agriculture*, OECD, Paris 2014.

typologies of adaptation exist in the literature, closer inspection reveals that these fundamentally refer to the instruments of adaptation[18].

The type of adaptation, its strategies and instruments, along with specific actions, are determined by a multitude of factors[19]. Essentially, however, these always revolve around:

- expectations concerning future socio-economic development;
- the fiscal and macroeconomic repercussions of damage caused by climate and weather risks;
- uncertainty regarding the impact of climate change across all conceivable and applied levels and divisions;
- the inherent inertia within socio-economic and technological systems, which impedes the speed of adjustment;
- behavioural aspects of the actions of individuals, organisations, and governments;
- the degree of flexibility in adaptation strategies, plans, and programmes, alongside available alternatives; the real challenge, however, is how to integrate strategies and their components with these determinants. The framework proposed in Figure 1 may be of assistance here.

Figure 1. A multiphase approach to climate change adaptation strategies



Source: Author's own elaboration based on: M. Pisu, H. Costa, M.F. D'Arcangelo et al., Accelerating and Addressing Adaptation Needs and Priorities, OECD, Paris 2024.

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[18] IPCC, *Climate change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel of Climate Change*, Masson-Delmotte 2021.

[19] M. Pisu, H. Costa, M.F. D'Arcangelo et al., op. cit.; S. Hallegate, *Strategies to Adapt to an Uncertain Climate Change*, "Global Environmental Change" 2009, Vol. 19, No. 2.

Adaptation strategies are executed through specific actions or activities. Various classifications of the latter can be found in practice. A. Ignaciuk operates with the following set:

- research and development,
- capacity building and enhancement,
- risk management,
- infrastructure,
- financing mechanisms[20].

C. Coburn, conversely, outlines as many as ten actions:

1) planning and support, encompassing planning in the strict sense, online decision support, land use planning, and early warning systems;
2) water resource-oriented programmes, covering infrastructure development, water management, alongside irrigation and drainage technologies;
3) in crop production: technologies, breeding and selection of climate-resilient crop varieties, soil management, fertilisation, and crop protection;
4) research and/or its funding;
5) agri-environmental programmes, organic farming, payments for conservation services, land reclamation, and the protection of agrobiodiversity;
6) in livestock production: selection and breeding, herd management, and permanent grassland management;
7) building partnerships paired with collaborative planning;
8) agricultural advisory services and targeted assistance, training and education, as well as the dissemination of information and knowledge;
9) cross-cutting approaches, including, inter alia, agroecology and climate-smart agriculture;
10) insurance mechanisms and products[21].

M. Pisu et al., on the other hand, proposed a four-element typology of adaptation actions/activities, which is presented in Table 1.

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[20] A. Ignaciuk, *Adapting Agriculture to Climate Change. A role for public politics*, OECD, Paris 2015.

[21] C. Coburn, op. cit.

Table 1. Adaptation actions/activities according to M. Pisu et al.

Action type	Description	Subtype	Examples
Technical	Tangible investments aimed at reducing exposure and vulnerability to climate hazards	Engineering and technological options drawing upon nature-based solutions	Flood embankments and irrigation systems
Infrastructure planning	Regulatory instruments aimed at reducing exposure and vulnerability to climate hazards		Structural adjustments and climate-resilient systems
Behavioural and organisational	Shifts in practices and strategies aimed at reducing exposure and vulnerability to climate hazards		Alterations to working hours and diets, alongside seasonal migrations
Structural and economic adjustments	Systemic changes aimed at reducing exposure and vulnerability to climate hazards		Solutions stemming from research and development, Reallocation of activities and population

Source: Author's own elaboration based on: M. Pisu, H. Costa, M.F. D'Arcangelo et al., Accelerating Climate Adaptation: A Framework for Assessing and Addressing Adaptation Needs and Priorities, OECD, Paris 2024.

In the present day, adaptation measures at the level of individual farms must be planned and implemented in a highly disaggregated manner, whilst simultaneously integrating the contributions of diverse scientific disciplines. The impacts of climate risk materialisation on the agricultural sector can be analysed through the lenses of climate modelling, agricultural/agronomic sciences, and socio-economic frameworks. The first approach focuses on the probability of atypical weather events occurring, their impact on crop yields, alongside potential adaptations and loss avoidance[22]. These probabilities are generally estimated across large temporal and spatial scales. This naturally introduces forecasting uncertainty regarding the frequency of local weather anomalies. Furthermore, modellers rarely address how these anomalies affect specific developmental stages of plants. While agronomic sciences attempt to establish causal relationships between particular weather parameters and crop yields, as well as plant growth and development in specific stages, they only occasionally investigate the frequency of atypical weather, or the costs and effectiveness of instruments and

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[22] R. Heltberg, R.B. Siegel, S.L. Jorgensen, *Addressing human vulnerability to climate change: toward a "non-regrets" approach*, "Global Environmental Change" 2009, Vol. 19, No. 11.

strategies for managing its consequences[23]. Conversely, the socio-economic approach highlights the relationships between hazards, yields, and agricultural income, yet it simultaneously neglects other pathways that describe the determinants of increased vulnerability to the adverse effects of abnormal weather[24].

A highly intriguing attempt to integrate the three aforementioned concepts for studying the impacts of weather anomalies on farms was proposed by H. Shah, P. Hellegerst, and Ch. Siderius. This international research team employs the concept of critical moments (CMs), which was introduced into academic discourse by A. Groot, S. Werners, and B. Regmi[25]. They defined these as the temporal alignment of hazards with their impacts on crop production and agricultural incomes. In contrast, H. Shah et al. highlighted periods throughout the year when hazards threaten the stability and structure of farming families' livelihoods. They subsequently categorised these risks into direct, compound, and delayed, linking them to crop growth and developmental stages, as well as coping strategies.

The first type refers to isolated weather anomalies. Due to their extremely brief duration of impact, devising and implementing remedial measures is exceptionally difficult. Consequently, one must accept a certain loss in expected yield. Compound hazards consist of a combination of at least two anomalies. This amplifies their adverse effects due to a specific synergistic effect. The later such an overlap occurs, the harder it is to prevent yield damage. Delayed impacts generate so-called ripple effects. Inherently, this involves a specific yield reduction in the initial period, alongside delays in executing optimal agrotechnical operations during the subsequent period. Such a mechanism is also referred to as the cascading accumulation of risk over time. This danger escalates particularly in countries where at least two harvests are gathered annually. Unfortunately, this must also be viewed as a realistic threat in Poland. A detailed overview of the aforementioned impacts is presented in Table 2.

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[23] S.L. Zandalinas, R. Mittler, D. Balfagón et al., *Plant adaptations to the combination of drought and high temperatures*, "Physiologia Plantarum" 2018, Vol. 162.

[24] V. Diogo, P. Reidsma, B. Schaap et al., *Assessing local and regional economic impact of climate extremes and feasibility of adoption measures in Dutch arable farming systems*, "Agricultural Systems" 2017, Vol. 157.

[25] A. Groot, S. Werners, B. Regmi, *Critical climate-stress moments and their assessment in the Hindu Kush Himalaya: Conceptualization and assessment methods*, Nepal, Katmandu 2017, accessed 20.05.2025.

Table 2. Overview of the three types of critical moments of climate change impact on agriculture

Critical moment	Hazard/risk	Timing, plant developmental stage, and impact channels	Possible countermeasures against hazards/risks
Direct impact	Drought/excess water	Sowing: feasibility, cost, limited cultivation window, loss of seeds and emergence vigour	Adjusting sowing/planting dates
	Low temperatures	Emergence: die-off	Adjusting sowing/planting dates
	Low temperatures and/or extreme temperatures	Emergence: root damage Vegetation: stunting and diseases	Advancing sowing/planting dates No recommendations
	Wind, rain	From vegetation to maturity: lodging, increased labour intensity and costs, quality deterioration	Adjusting sowing/planting dates and plant density
	High temperatures	Reproduction: losses in yield and quality	Varietal selection
	Heat stress and extreme temperatures	Maturation: lodging, losses in yield and quality, including reproductive material	Irrigation during flowering, varietal selection, and cultivation techniques
	Torrential rain	Vegetation: flooding of plants	Drainage and varietal selection
	Drought	Vegetation: poor seed set Reproduction: poor seed development and shattering	Drainage, varietal selection, and practices conserving soil water resources Improved water management, increasing the share of leguminous crops
	Atypical rain and hail	Maturity/harvest: anaerobic plant rotting, pre-harvest sprouting, increased costs and labour intensity, soil compaction	Drainage, earlier sowing/planting
Compound impact	High temperatures during initial developmental stages	Various stages: stem shortening and leaf loss Sowing and germination: delayed sowing, poor growth, weight loss, and exposure to subsequent stressors	Advancing the harvest Adjusting sowing/planting dates, seed cooling, irrigation
	Atypical rain	Sowing/planting: exposure to subsequent stressors	Adjusting sowing/planting dates
	Moisture and frost	Germination: delayed sowing, poor plant condition	Early sowing combined with irrigation

Continued on the next page.

Table 2. Overview of the three types of critical moments of climate change impact on agriculture (cont.)

Critical moment	Hazard/risk	Timing, plant developmental stage, and impact channels	Possible countermeasures against hazards/risks
	Humidity and high nocturnal temperatures	Reproduction: sterile reproductive material	Adjusting sowing/planting dates and plant hormone applications
	Low rainfall and frost	Reproduction and seed formation: sterile reproductive material, poor seed grain filling, disrupted photosynthesis	Varietal selection, alongside cultivation and crop protection techniques
	Moisture and thermal stress		
	High humidity and hail		
	Extreme humidity combined with frost/heat/wind	Reproduction: low pollen quality	No recommendations
		Reproduction: lodging	No recommendations
	High temperature and humidity due to torrential rain	Reproduction: sterile ears	Adjusting sowing/planting dates, varietal selection, and hormone application
		Reproduction and maturation: yield losses and fungal diseases	Crop protection
	Wind and rain	Various stages: diseases, lodging and quality deterioration	Advancing harvests and crop protection
	Various stressors across different stages	Various stages: decline in profitability and investment efficiency	No specific recommendations
	Atypical rain and storms	Harvest and seed formation: lodging, heat stress, feasibility of cultivation practices	Adjusting sowing/planting dates, insurance
	Atypical rain, storms, and high temperatures	Early stages: impact on cultivated area and labour intensity	No definitive recommendations
		Seed formation and harvest: tuber rot, heat stress	Irrigation, advancing the harvest
Delayed impacts	Torrential rain	Harvest: its feasibility and subsequent operations, increased costs	Earlier sowing/planting, drainage, weed control
	Atypical rain	Sowing and harvesting: difficulties in executing agrotechnical operations	Adjusting sowing/planting dates, insurance

Source: Author's own elaboration based on: H. Shah, P. Hellegerst, Ch. Siderius, Climate risk to agriculture: A synthesis to define different types of critical moments, "Climate Risk Management" 2021, Vol. 34.

The latest trend in designing and implementing agricultural adaptations involves combining crop and climate models with artificial intelligence in the form of machine learning. This enables highly accurate predictions and assessments of physical climate risk using minimal data, which is also significant for our private farming sector, where systematic accounting is rarely practiced. The positive outcomes of such integration become even more pronounced when appropriate incentives are created to foster breakthrough innovations, which would be more broadly financed through various public-private partnership models[26].

Above all, adaptations with greater implementation flexibility should be prioritised, particularly over shorter periods that necessitate the development of specialised operational frameworks. Accordingly, an additional three types are most frequently proposed, as outlined in Table 3. It is highly desirable to combine these with traditional components of resilience, namely absorbing short-term weather shocks, adjusting to them over the medium term, and transforming the given system over the long term.

Table 3. Non-regret, low-regret and win-win adaptation

Adaptation type	Description	Examples
Non-regret	Cost-effective in the short term across a broad spectrum of future climate changes Lack of significant trade-offs with other objectives	Reducing pipeline and installation leaks, utilising drought-resistant crop varieties
Low-regret	Low costs relative to benefits and few adverse effects across diverse climate change scenarios	Avoiding construction in flood-prone areas
Win-win	Aligned with a broad set of social, economic, and environmental objectives, as well as with mitigation	Greening landscapes and construction, alongside adjusting working hours

Source: Author's own elaboration based on: Climate Change Adaptation Policies to Foster Resilience in Agriculture. Analysis and Stocktake Based on UNFCCC Reporting Documents, OECD Food, Agriculture and Fisheries, OECD, Paris 2023; M. Pisu, H. Costa, M.F. D'Arcangelo et al., Accelerating Climate Adaptation: A Framework for Assessing and Addressing Adaptation Needs and Priorities, OECD, Paris 2024.

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[26] S. Alimagham, P.V. an Loon, J. Villegos-Ramirez, *Integrating crop models and machine learning for projecting climate change impacts on crop in data-limited environments*, "Agricultural Systems" 2025, Vol. 228, p. 104367; X. Gu, J. Zhu, *Climate physical risks and technological innovation in the grain industry chain: an empirical analysis based on machine learning of patent text in China*, "Agricultural Systems" 2026, Vol. 231, p. 104507.

Responsible public authorities should endeavour to influence all four types of adaptation. They have the following options at their disposal:

1) influencing natural adaptations;
2) supporting private adaptations through financial instruments, educating and assisting the most vulnerable individuals, as well as initiating and implementing appropriate strategies;
3) identifying potentially beneficial adaptations;
4) fostering a supportive institutional and market environment;
5) stimulating free international trade geared towards establishing new competitive advantages;
6) executing the aforementioned public infrastructural projects[27].

Government interventions in adaptation are indispensable for several reasons. Firstly, the intensity and unpredictability of extreme weather events are escalating. Secondly, the consequences of climate change are already highly visible and tangible, simultaneously affecting social, natural, and economic systems. Thirdly, certain shifts in climatic and weather parameters are progressing slowly, yet their long-term effects could prove dramatic; hence, they should not be underestimated. Fourthly, the adverse repercussions of climate change disproportionately affect poorer communities, the elderly, and otherwise disadvantaged individuals, thereby exacerbating pre-existing disparities in income, wealth, and societal advancement, as well as those related to their broader well-being[28].

To support adaptive measures effectively and efficiently, public authorities must have appropriate instruments at their disposal.

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[27] M. Chambwera, G. Heal, S. Dubeux, *Economics of Adaptation* [in:] *Climate Change. Impacts, Adaptation, and Vulnerability*, Part A., Cambridge University Press, Cambridge UK 2014, accessed 3.06.2025; A. Ignaciuk, D. Mason-D'Croz, *Modelling Adaptation to Climate Change in Agriculture*, OECD, Paris 2014.

[28] OECD, *Climate Change Adaptation Policies to Foster Resilience in Agriculture. Analysis and Stock-take Based on UNFCCC Reporting Documents*, OECD Food, Agriculture and Fisheries, Paris 2023.

Table 4. Policy instruments to influence adaptation

Instrument type	Problems the instrument aims to alleviate	Probable fiscal effects
Economic (taxes, subsidies)	Financial and behavioural in the case of subsidies. Externalities, behavioural effects, and moral hazard in the case of taxes	Taxes serve as a source of fiscal revenue, whereas subsidies generate expenditure. Fiscal costs are derived from the relationship between taxes and subsidies
Regulatory	Moral hazard, information imperfection, and coordination failure	Relatively low fiscal costs
Information provision (risk and hazard maps, early warning systems, educational processes)	Asymmetric and imperfect information, uncertainty, and ambiguities arising from incomplete information	Relatively low fiscal costs
Direct provision of public goods (flood embankments, irrigation and drainage, infrastructure)	Supporting the creation of positive externalities, strengthening resilience, and alleviating financial constraints	High fiscal costs

Source: Author's own elaboration based on: Climate Change Adaptation Policies to Foster Resilience in Agriculture. Analysis and Stocktake Based on UNFCCC Reporting Documents, OECD Food, Agriculture and Fisheries, OECD, Paris 2023.

Mitigation: essence, typologies, frameworks, and policy instruments

As established in the preceding sections of this article, adaptation focuses on reducing the adverse effects of climate change or capitalising on the opportunities it creates through adaptive measures across natural, social, and economic systems. Mitigation, on the other hand, aims to curtail greenhouse gas emissions or enhance carbon dioxide absorption capacities[29]. Consequently, the primary outcome should be a reduction in the negative repercussions of climate change. While mitigation efforts yield benefits for all entities exposed to climate-induced hazards, they are only truly effective when pursued collaboratively at national, regional, and global levels. Thus, we are dealing with

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[29] R. Martini, *Towards a taxonomy of agri-environmental regulations: A literature review*, OECD, Paris 2023; R.O. Ogunpaimo, C. Rafiat Buckley, S. Hynes et al., *Integrated assessment of farm-level mitigation measures for gaseous emissions*, "Agricultural Systems" 2025, Vol. 223, p. 104188; L. Shen, W. Liu, H. Si, *What affects farmers' intention and behavior to mitigate the impact of climate change? Evidence from Hebei Province, China*, "Journal of Rural Studies" 2025, Vol. 114, p. 103525.

processes that generate public goods. In contrast, adaptation is predominantly local in nature and results in private benefits. Crucially, these benefits can be realised relatively quickly, leading them to be perceived as direct and tangible. This implies that farmers will implement adaptation strategies when the costs incurred remain lower than the ensuing benefits. Adaptation and mitigation are inherently interconnected; however, substitutive relationships may also emerge between them. In other words, the widespread deployment of adaptive measures diminishes the pressure to enforce rigorous and costly mitigation. Conversely, a palpable reduction in greenhouse gas emissions lessens the necessity for adaptive interventions[30]. Finally, it is worth noting that adaptation can occasionally yield public goods as well. This is most easily achieved when it involves water management, the benefits of which are reaped by society and the economy as a whole[31].

From the above, it is evident that adaptation measures must be designed and implemented in alignment with mitigation efforts. Accordingly, the proliferation of renewable energy sources should drive down greenhouse gas emissions, which, in turn, ought to enhance energy security and, over the longer term, at least stabilise energy prices. Hence, it is not without reason that the European Union has been striving for many years to implement various energy and climate packages. Therefore, we require the integration of adaptation and mitigation to exploit the associated potential synergies and positive feedback loops (reinforcement mechanisms), while remaining constantly mindful of the inherent trade-offs. This poses a highly significant challenge for modelling appropriate strategies and conducting effective policies. The issue becomes further complicated as we are confronted with dynamic nexuses: adaptation-mitigation-resilience, and food-climate-water-energy. An additional challenge is the growing need to navigate a broader conceptual framework than that of traditional agriculture, thereby incorporating supply chains, networks, and food sectors into the analysis, alongside forestry and fisheries in the context of mitigation. This demonstrates that only sovereign states –and potentially their alliances – possess the necessary integrating and coordinating capabilities, along with the requisite human, material, and fiscal resources[32].

Fundamentally, two types of mitigation are distinguished from a policy perspective:

1. Direct mitigation, which primarily serves to reduce greenhouse gas emissions or promote their sequestration.

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[30] A. Ignaciuk, *Adapting Agriculture to Climate Change. A role for public politics*, OECD, Paris 2015; M. Pisu, H. Costa, M.F. D'Arcangelo et al., *Accelerating Climate Adaptation: A Framework for Assessing and Addressing Adaptation Needs and Priorities*, OECD, Paris 2024.

[31] 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.

[32] C. Chhun, D. Sehder, C.A. Prentice et al., *Environmental domain tagging in the OECD PINE database*, OECD, Paris 2024.

2. Indirect mitigation, which is additionally oriented towards securing co-benefits. These could include, for example, improving the state of the natural environment and water quality, or making a given location available for recreational and tourism purposes, including agritourism[33]. Naturally, the first type of mitigation policy is generally easier to design, implement, monitor, and evaluate than the second. This occurs because direct mitigation targets the immediate source of emissions, such as the combustion of fossil fuels. Conversely, indirect mitigation focuses on the consequences of emissions themselves, or on overarching and antecedent causes. Broadly speaking, this involves restoring and conserving natural greenhouse gas sinks (such as forests and wetlands), protecting biodiversity, and developing renewable energy sources.

Various policy instruments are utilised in both of the aforementioned types of mitigation. A concise overview of these is provided in Table 5.

Table 5. Instruments utilised in direct and indirect mitigation

Instrument category	Instrument type	Examples
Economic	Subsidies Taxes Emissions trading system	Payments to producers, carbon offsetting, tax reliefs Carbon tax on CO_2 emissions EU ETS and tradable certificates
Regulatory	Performance standards Technological standards, framework regulations	Maximum emission level standards Bans and mandates for phase-outs Market regulations and zoning
Other	Public investment and consumption Informational Voluntary agreements	Research and development, infrastructure, procurement. Labelling/marking, education, training

Source: Author's own elaboration based on: OECD, The IFCMA's climate policy database: A proposal for a policy instruments typology and data structure, OECD, Paris 2024.

As previously indicated, in mitigation analyses and models, agriculture is primarily grouped with forestry and other activities, such as fisheries, to form the land-use sector (Agriculture, Forestry and Other Land Use, AFOLU). The mechanisms for reducing greenhouse gas emissions within such an aggregate are referred to as "mode of mitigation", which translates to "modes". Generally, two types are distinguished: mode of mitigation per GHG type, and mode of mitigation per land management. The former signifies the reduction of specific greenhouse gases,

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[33] A. Ignaciuk, *Measuring Policy Progress on Climate Change Mitigation in the Agriculture Forestry and Other Land Use (AFOLU) Sectors*, OECD Technical Paper, OECD, Paris 2024.

whereas the latter pertains to the potential for lowering their emissions by leveraging the more complex biochemical interactions of various land-use management systems[34]. Let us characterise them in a concise manner.

Within the AFOLU sector, particularly in agriculture, the primary sources of methane emissions are predominantly the enteric fermentation of ruminants and the application of natural fertilisers. Opportunities to reduce CH_4 emissions lie in altering the microbiological composition within the digestive tracts of ruminants, as well as improving the management and application of natural fertilisers (limiting the volatilisation of particulate matter). It should be noted at once that methane can be recovered in biogas plants to generate electricity and heat, and even converted into so-called biomethane, which can subsequently be injected into the main gas grid. These fertilisers also constitute a source of nitrous oxide (N_2O) emissions. For the sake of analytical completeness, it is worth mentioning that nitrous oxide is used in medicine, the food industry, the automotive sector, and even in the aerospace industry. However, this gas can be released from soils in large quantities, primarily through the chemical transformation of synthetic nitrogen fertilisers, but also from harvest residues and the excrement of grazing livestock. There are numerous proven and continually refined agrotechnical methods and technologies available here that allow for a noticeable reduction in this type of emission. Finally, carbon dioxide must be mentioned; within the AFOLU sector, this stems chiefly from the use of energy carriers, primarily fossil fuels and their derivatives. The mitigation of these emissions is the domain of rationalising and modernising energy management. Again, as a point of order, one must add that CO_2, aside from being the most quantitatively significant greenhouse gas, is widely utilised in industry. It is also essential for the proper functioning of plant photosynthesis. Ongoing efforts are continually being made to increase the capacities for its absorption by plants (so-called CO_2 fertilisation). The remaining greenhouse gases have a disproportionately greater impact on generating the greenhouse effect than carbon dioxide. Finally, it should be noted that the cited examples of the beneficial utilisation of greenhouse gases clearly suggest that mitigation must be continuously analysed in close correlation with the circular economy.

The second mode of mitigation, which involves land management, encompasses carbon sequestration, the improvement of such management itself, the restoration of degraded land and ecosystems, and the provision of specific services by the latter. Broadly speaking, sequestration consists in capturing CO_2 from point emission sources and transporting it to underground geological formations or natural reservoirs such as soils and forests, thereby slowing down its release process. Improving the use of

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[34] Ibidem.

major land areas is geared towards reducing the emissions of all primary greenhouse gases. Specifically, this involves various agri-environmental schemes as well as climate-smart agriculture (CSA), regenerative, organic, and ecological farming. Afforestation and reforestation also fall into this category, although they are sometimes included in a third group (land and ecosystem conservation). This final group further comprises the restoration of peatlands, wetlands, natural grasslands, and floodplains to their original state. A close relationship can be observed here between these activities, water management, and disaster risk management.

As a kind of partial summary of what has been written so far on mitigation, one might attempt to formulate certain policy recommendations. Firstly, land occupied by the AFOLU sector must be viewed as suitable for strictly agricultural activities, afforestation, ecosystem protection and restoration, as well as carbon sequestration. Secondly, focus should be placed on the emissions of all greenhouse gases, generalising them in the form of CO_2 equivalents. Thirdly, apart from counting the populations of various livestock species, there is also a need for standard measures that aggregate them into a single collective item (various constructs, such as livestock units).

A rational response of economic entities and other organisations or institutions to climate change should be the implementation of climate risk management systems and/or subsystems, the overarching objective of which ought to be strengthening their resilience, and occasionally also their economic value. Larger entities should integrate these into their overall risk management framework and other ongoing processes, while also deploying early warning systems for both the threats and opportunities arising from climate change. Within such subsystems, it is necessary to, inter alia, continuously monitor any potential requirements for acquiring insurance coverage against physical climate risks.

At present, at least within the EU, integrating risk management and opportunity identification with the sustainability strategies of economic entities, particularly those operating on a larger scale, is becoming an ever greater challenge. This also translates into their decisions regarding the location of their operations in regions less exposed to the current and future adverse effects of climate change. Furthermore, it follows that both types of climate risk will increasingly impact the competitive standing of regions, and even entire countries. Naturally, estimating long-term climate risks is by no means an easy task. Various types of extrapolations can be employed here, but stochastic simulations (including Monte Carlo methods) and scenario analyses generally prove to be more effective. The use of climate models, however, constitutes a separate issue. It is rather difficult to even imagine economic entities constructing them independently, which is abundantly clear in the case of agricultural holdings. At this juncture, a scope of action emerges for public policies, which could support the development of such models and ensure their free provision to interested parties. In agriculture today, the results of climate modelling are becoming quite indispensable for the design of index-based insurance.

The aforementioned sustainability within the EU is in itself a source of risk, entailing both financial and non-financial implications, yet it also generates new developmental opportunities. Outside of agriculture, their management is regulated in the EU by means of relevant directives under the ESG (Environmental, Social and Governance) framework. Non-agricultural entities will progressively become subject to obligations regarding the reporting of their impact on the natural environment, society, and corporate governance. Although these obligations have been relaxed and postponed due to criticism of the European Green Deal, they will nonetheless indirectly affect commercial farms operating within supply chains. Accordingly, buyers of agricultural products may require farmers to evidence, for instance, their carbon footprint, and thus their level of greenhouse gas emissions. The connection to climate risk here is self-evident. Furthermore, agriculture is also subject to distinct sustainability regimes under specific provisions of the Common Agricultural Policy (CAP). The conditionality of receiving certain subsidies is directly and indirectly linked to compliance with sustainable development and climate regulations, which thereby become a source of specific types of risk.

When sustainability-related risks are analysed more closely, it is striking that physical and transition risks are utilised in this context as well. Their essence is virtually identical to that of climate risk. The interactions between them are also highly similar. Accordingly, an increase in physical risk should generally prompt actions aimed at its reduction, which most frequently leads to a higher transition risk. The latter may also increase in situations where an importer of agri-food products – for instance, in response to a severe drought – scales up their foreign purchases. This, however, entails the lengthening of supply chains, and consequently, a rise in greenhouse gas emissions. Naturally, the risk of dependency on foreign suppliers also emerges in such cases. Reputational risk may similarly increase under such circumstances. Consequently, managing sustainability risks requires a precise representation of their quantitative and qualitative aspects. In line with this, the following methods are most commonly employed for their identification: economic value added, discounted cash flows, brainstorming and its variants, deterministic scenario analyses, and system dynamics[35].

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[35] A. Creutzmann, W. Gleiβner, *ESG-Dashboard als Basis für Business Judgment-Entscheidungen*, "ESG – Zeitschrift für nachhaltige Unternehmensführung" 2023, Jg. 2, H. 2; W. Gleiβner, S. Ihlau, *Implikationen des Nachhaltigkeitsmanagements nach CSRD und des Risikomanagementsystems nach StaRUG für die wertorientierte Unternehmenssteuerung*, "Betriebs-Berater" 2024, Jg. 12, H. 8; P. Stein, *Management von Nachhaltigkeitsrisiken. Einsatz ausgewählter quantitativer und qualitativer Methoden für die Praxis*, "Zeitschrift für Risikomanagement" 2025, No. 4.

Modelling of adaptation and mitigation

This issue has been analysed in a highly comprehensive and up-to-date manner by M. Pisu et al[36]. Let us present their primary findings. As a preliminary point, the research group unequivocally states that modelling adaptation and mitigation poses a major challenge due to their local nature, the intrinsic uncertainty of climate change, and the multiplicity of objectives sought to be achieved through them. The first group of models they discuss are integrated assessment models (IAMs). These are designed to examine the interactions between economic activities and biophysical processes in the context of climate change, typically on a global scale. They are utilised to model both adaptations and mitigations dynamically, over long time horizons. The main difficulty here lies in the precision of reflecting local and regional specifics, as well as economic impact channels.

The second type of models discussed by M. Pisu et al. is computable general equilibrium (CGE). These are grounded in economic flows, which are best captured within national accounts. They facilitate the modelling of intersectoral relations and can be adapted to specific requirements with relative flexibility. However, their weakness stems from the failure to account for market frictions and uncertainty. Depicting the transition process towards a new equilibrium can also prove challenging. The structures and capabilities offered by CGE models are worth elucidating through the article by T. Calvacanti, Z. Hens, and C. Santos[37].

These authors analyse three industries engaged in the production of so-called dirty energy: oil, natural gas, and coal, alongside renewable energy sources (the "green" industry). Traditional industries emit carbon dioxide, in contrast to Renewable Energy Sources (RES). Oil, gas, and coal can be mutually substituted within the intermediate goods sector, which collectively includes agriculture, forestry, and fisheries. In order to curb CO_2 emissions, a carbon tax for energy producers was introduced, triggering a reallocation of resources throughout the national economy and supporting RES. The entire resource reallocation mechanism, together with its macroeconomic and distributional effects, depends on how carbon tax revenues are utilised – whether they are allocated to fund wasteful expenditure, subsidise RES, finance other useful spending, or provide rebates to households – as well as on intersectoral input-output flows, the elasticity of their substitution coefficients,

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[36] M. Pisu, H. Costa, M.F. D'Arcangelo et al., op. cit.

[37] T. Calvacanti, Z. Hensa, C. Santos, *Climate Change Mitigation Policies: Aggregate and Distributional Effects*, "The Economic Journal" 2025, Vol. 668.

and the variance in labour force quality. From a formal standpoint, the model comprised: households, incorporating the professional qualification characteristics and choices of their members; the production sphere (an intermediate goods subsector and a final goods subsector); equilibrium conditions; and the rules for calculating the carbon tax (based on CO_2 emissions). The model was calibrated using real-world data from the USA, China, and Brazil.

Following the appropriate simulations, it emerged that achieving the Paris Agreement targets by 2030 in the USA would entail a loss of between 0.4% and 0.8% in the annual GDP growth rate. In the case of Brazil, the mitigation cost measured in this way ranged from 0.3% to 0.4%, whereas in China, it would be as high as 1.7% to 3.8%. These figures demonstrate why reaching a global climate agreement is so exceedingly difficult. On the other hand, the introduction of a carbon tax would lead to a pronounced wage divergence within the national economy. Wages would increase in the RES industry and other intermediate and final goods sectors, while certain individuals employed in the "dirty energy" sector could experience a drastic loss of earnings. It is worth adding that similar conclusions have been reached by other researchers as well[38]. The situation, however, looked different in the EU, where a specific CO_2 emission mitigation instrument is applied in the form of emissions trading (EU ETS) – which bears similarity to a carbon tax. According to G.E. Metcalf and J.H. Stock, there is a lack of robust evidence pointing to its negative impact on the economy[39]. Returning once more to the simulation by T. Calvacanti, Z. Hens, and C. Santos, it is noteworthy that following the introduction of a carbon tax in the USA, the value added generated in agriculture, forestry, and fisheries could decrease by up to 5.7% if the resulting revenues were squandered. Conversely, in one of the scenarios, i.e. their beneficial allocation (the Cobb-Douglas function), it could increase by 1%. Incidentally, it should be noted that Poland, to a large extent, utilises the revenues from the EU ETS system inefficiently. According to the Supreme Audit Office (NIK), the state budget received approximately PLN 94 billion from this source between 2013 and 2023, yet only 1.3% of this amount was allocated to purposes related to the reduction of greenhouse gas emissions[40].

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38. S. Black, J. Chateau, F. Jarmote, *Getting on track to net zero: Accelerating a global just transition in this decade*, "Staff Climate Notes" 2021, Vol. 2022(010); C. Böhringer, S. Peterson, T.F. Rutherford, *Climate policies after Paris: Pledge, trade and recycle: Insights from the 36th energy modelling forum study (EMF36)*, "Energy Economics" 2022, Vol. 103.
39. G.E. Metcalf, J.H. Stock, *The macroeconomic impact of Europe's carbon taxes*, "American Economic Journal: Macroeconomics" 2023, Vol. 15, No. 3.
40. NIK, *NIK o gospodarowaniu środkami pochodzącymi ze sprzedaży uprawnień do emisji gazów cieplarnianych*, 30 October 2024, nik,gov.pl, accessed 15.10.2025.

The third group of models analysed by M. Pisu et al. are Input-Output (I-O) models. These serve to investigate the propagation of shocks associated with climate and weather changes across the entire national economy. Generally, they require fewer computational resources than CGE models, but they fail to capture dynamics, as they operate on constant coefficients. Hence, their utility is largely confined to short-term analyses, particularly regarding marginal impacts.

Dynamic stochastic general equilibrium (DSGE) models are intended to overcome the weaknesses of CGE and I-O models. They depict the dynamism of economic processes and the transition paths to new equilibria reasonably well, but perform somewhat poorer in describing intersectoral and international linkages. However, studies devoted to adaptation and mitigation utilising these models only began to emerge in the current decade.

The final class of models reviewed by M. Pisu et al. are agent-based models (ABMs). Within these frameworks, the agents can include households, firms, and governments. Their behaviours and mutual interactions form the basis for constructing these models and identifying the macroeconomic consequences of both planned and already implemented adaptation and mitigation measures. Overall, ABMs are rather complex constructs that require vast amounts of detailed data and, in terms of expertise, highly skilled modellers, as they are difficult to parameterise, calibrate, estimate, and validate.

Adaptations and mitigations can also be analysed using solely econometric tools – which, in turn, may create issues regarding the external validation of the obtained results – and can be combined, for instance, with climate models. An interesting area of econometric application involves causal impact analyses and impact evaluations. Ideally, the researcher should possess adequate panel datasets. By applying the appropriate estimators in such cases, one can derive the various effects of pro-climate public interventions. Since causal and impact analyses primarily allow for the estimation of the gross effects of an intervention, it is justifiable to supplement them with cost-benefit analyses, cost-effectiveness analyses, and multi-criteria analyses[41].

The Organisation for Economic Co-operation and Development (OECD) boasts highly extensive experience in modelling the impact of adaptation and mitigation in agriculture. In this context, let us briefly examine two studies dedicated to this subject. J. Antón et al. constructed a microeconomic simulation model intended for the comparative analysis of the impact of no climate change, marginal change, and a high probability of extreme weather events – both in the absence of adaptation and

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[41] Source: Author's own elaboration based on: OECD, *The IFCMA's climate policy database: A proposal for a policy instruments typology and data structure*, OECD, Paris 2024.

under conditions of diversification and structural adaptation – taking into account the possibility of utilising individual crop insurance, insurance based on average regional yields, weather indices, and disaster relief[42]. The model was grounded in expected utility theory. Its calibration, meanwhile, was conducted for farms representative of agriculture in Australia, Spain, and Canada. Furthermore, two agricultural policy objectives were adopted: (1) the reduction of overall farm income risk; (2) the provision of minimum compensation for an extreme drop in income. The effectiveness and efficiency of achieving these two objectives were subsequently analysed using a standard probabilistic approach in the Bayesian sense, as well as minimax and satisficing criteria.

The second OECD study, broadly outlined below, is a paper authored by A. Ignaciuk and D. Mason-D'Croz[43]. The basis of the modelling is the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT), developed and continuously refined at the International Food Policy Research Institute (IFPRI). It integrates a partial equilibrium model with a hydrological model. The former is used to simulate policy and trade, while the latter serves to simulate water systems and water stress. Furthermore, IMPACT is integrated with two biophysical climate models to enable the construction of climate scenarios. In total, A. Ignaciuk and D. Mason-D'Croz operated with four climate scenarios and one baseline alternative scenario of this type. In terms of adaptation, on the other hand, there were two strategies: (1) investing in the research and development sphere; (2) changing irrigation technologies (flood irrigation, sprinklers, drip irrigation).

Adaptation and mitigation are the two fundamental strategies for coping with advancing climate change, which affects the productivity and efficiency of agriculture, the incomes generated in this sector, and its risk exposure, with Sub-Saharan African countries being in the most precarious position. Henceforth, however, we shall focus solely on methods of adaptation. There is quite a considerable number of them. This array, as we recall, encompasses: the introduction of new crop varieties, especially drought-resistant ones; the alteration of agrotechnical timings; irrigation as well as soil and water conservation; and insurance[44]. If appropriately combined, it is possible to formulate so-called "climate-smart" strategies, which are characterised by: (1) a sustainable increase

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42. J. Antón, S. Kimura, J. Lankowski et al., *A comparative study of risk management in agriculture under climate change*, OECD, Paris 2012.
43. A. Ignaciuk, D. Mason-D'Croz, *Modelling Adaptation to Climate Change in Agriculture*, OECD, Paris 2014.
44. S. Di Falco, J.P. Chaves, *On crop biodiversity, risk exposure, and food security in the highlands of Ethiopia*, "American Journal of Agricultural Economics" 2009, Vol. 91; M. Kassie, H. Teklevold, H. Marenya et al., *Production risk and food security under alternative technology choices in Malawi: Application of a Multinomial Endogenous Switching Regression*, "Journal of Agricultural Economic" 2014, Vol. 66.

in agricultural productivity and incomes through the joint optimisation of the system (climate change adaptation – soil conservation – water conservation); (2) the bolstering of resilience to climate change itself; (3) the reduction of greenhouse gas emissions[45]. It is, however, crucially important that "climate-smart" agriculture becomes an integral component of agricultural, rural, and food policies. Only then will there be an opportunity to boost yields, limit their volatility (and thus also the risk), and maintain food security. It is also worth noting that the mere enhancement of biodiversity can directly lead to a reduction in production risk in agriculture and minimise the environmental damage caused by this sector[46].

With regard to agricultural risk exposure, the question of whether individual climate change adaptation measures within a "climate-smart" strategy are complementary or substitutional to one another remains poorly understood. The root of this lies primarily in researchers focusing on single crops rather than the overall cropping patterns of farms[47]. Consequently, estimations of risk shifts, and therefore the hedging potential of adaptation ventures, are either overstated or understated. This stems from the fact that certain cropping patterns lead to risk reduction based on the philosophy of diversification, whereas in other instances, the interactions between crops may be negative in nature – since an increase in the yields of some agricultural products occurs at the expense of declining yields in others[48]. Undoubtedly, the research conducted by G. Issahaku and A. Abdulai provides a deeper insight into the aforementioned dependencies[49]. Let us examine them more closely, as a highly interesting and advanced methodological approach was employed in their work. Conversely, less attention will be devoted to a detailed reporting of the obtained results, which pertain to agriculture in Ghana.

Switching regression occupies a central place in the methodology of G. Issahaku and A. Abdulai. This is a method of describing the dependence of one or multiple statistical variables on other observable statistical variables by means of several mathematical functions, the form of which remains linked to the conditions under which

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[45] T.T. Deressa, R.M. Hassan, C. Ringler et al., *Determinants of farmers' choice of adaptation methods to climate change in the Nile Basin of Ethiopia*, "Global Environmental Change" 2009, Vol. 19.

[46] S. Di Falco, J.P. Chaves, *On crop biodiversity, risk exposure, and food security in the highlands of Ethiopia*, "American Journal of Agricultural Economics" 2009, Vol. 91.

[47] S. Di Falco, M. Veronesi, *How can African agriculture adapt to climate change?: a counterfactual analysis from Ethiopia*, "Land Economics" 2013, Vol. 89, No. 4; M. Kassie, H. Teklevold, H. Marenya et al., *Production risk and food security under alternative technology choices in Malawi: Application of a Multinomial Endogenous Switching Regression*, "Journal of Agricultural Economic" 2014, Vol. 66.

[48] J.M. Antle, *Testing the stochastic structure of production: A flexible moment based approach*, "Journal of Business and Economic Statistics" 1983, Vol. 1.

[49] G. Issahaku, A. Abdulai, *Adoption of climate-smart practices and its impact on farm performance and risk exposure among smallholder farmers in Ghana,* "Australian Journal of Agricultural and Resource Economics" 2020, Vol. 64.

these variables manifest. In practice, linear functions that differ in their parameter values are most commonly utilised. The foundations of this method were laid out in 1972 by E.R. Quandt[50]. The starting point for his considerations were the two regression equations below:

$$Y_t = x_{1t}\,\beta_1 + \varepsilon_{1t} - \textit{regime 1},$$

$$Y_t = x_{2t}\,\beta_2 + \varepsilon_{2t} - \textit{regime 2},$$

where: $t = 1, \ldots, T$; $x_{1t,}\, x_{2t}$ – vectors of exogenous variables.

The observed dependent variable Y_t in each period is generated by regime (conditions) 1 or 2, but never by both simultaneously. The probability of it being regime 1 remains constant.

G. Issahaku and A. Abdulai relied on a far more advanced switching regression model applied to study the impact of climate change adaptation measures, drawing primarily on the previously cited works by S. Di Falco alongside J.P. Chaves and M. Veronesi, as well as M. Kassie et al. Let us assume that the farmer's objective is to select adaptation activities that will maximise their benefits on the *i*-th plot, which we shall denote as the latent variable V_{ij}^*. Unfortunately, the latter cannot be directly observed. It can, however, be expressed as a function of the observable characteristics of the farmer, the farm, and the village, i.e. by means of *Xi* alongside unobservable factors ε_{ij}:

$$V_{ij}^* = X_{ij}\,\beta_j + \theta_j\,\bar{X}_{ij} + \varepsilon_{ij}.$$

Let us now denote by Vi an indicator that reflects the farmer's observed choices regarding adaptation measures:

$$V_i = \begin{cases} 1 & \text{if and only if} \quad V_{i1}^* > \max\limits_{k \neq 1}(V_{ik}^*) \quad \text{or} \quad \varepsilon_{ij} < 0 \\ M & \text{if and only if} \quad V_{iM}^* > \max\limits_{k \neq j}(V_{ij}^*) \quad \text{or} \quad \varepsilon_{iM} < 0 \end{cases}$$

where: $\max\limits_{k \neq j}(V_{ik}^* - V_{ij}^*) < 0$.

We can see that the farmer will choose activity *j* on plot *i* that maximises their expected benefits V_{ij}^*, provided they are higher than under any other alternative $k \neq j$, i.e. if $\varepsilon_{ij} = \max\limits_{k \neq j}(V_{ik}^* - V_{ij}^*) < 0, \forall j, k \in M$.

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[50] R. Quandt, *A New Approach to Estimating Switching Regressions*, "Journal of American Statistical Association" 1972, Vol. 67.

G. Issahaku and A. Abdulai determined that the farmer would choose from the following options: (1) making changes solely within the cropping pattern; (2) implementing soil and water conservation measures exclusively; (3) combining the two aforementioned undertakings; (4) applying no adaptation measures whatsoever. The latter constitutes the reference scenario. Assuming that the model error ε_{ij} follows an independent and identically distributed Gumbel distribution, the probability of the farmer opting for variant *j* can be determined using the multinomial logit (MNL) model formulated by D. McFadden in 1973:

$$P_{ij} = P(\varepsilon_{ij} < 0 \mid X_i) = \frac{\exp(X_{ij}\beta_j + \bar{X}_{ij}\delta_j)}{\sum_{k\neq 1}^{M} \exp(X_{ij}\beta_k + \bar{X}_{ij}\delta_k)},$$

where: $\bar{X}_{ij}$ – a vector of means characterising the plots; δ_j – parameters to be estimated, which was accomplished via the maximum likelihood method.

In the subsequent phase, the impact of the selected variants on total farm revenues and the skewness of their distribution, serving as a measure of risk, was investigated. For this purpose, a multinomial endogenous switching regression (MESR) model, developed by F. Bourguignon, M. Fournier, and M. Gurgand in 2007, was employed.

Let *j=1* denote the reference variant, namely the absence of any climate change adaptation measures. In turn, let *j=2* represent solely shifts in the cropping pattern, *j=3* denote soil and water conservation, and *j=4* reflect the combination of variants 2 and 3. In the convention of switching regression, these are customarily referred to as regimes. Each choice outcome is described by the corresponding equations:

$$\begin{cases} \text{regime 1:} & y_{i1} = Z_{i1}\alpha_1 + \bar{Z}_{i1}\theta_j + u_{i1} & \text{if} & V_i = 1 \\ & \vdots & \vdots & \vdots \\ \text{regime M:} & y_{ij} = Z_{ij}\alpha_j + \bar{Z}_{ij}\theta_j + u_{ij} & \text{if} & V_i = J, \end{cases}$$

where: y_{ij} – the dependent variable (farm revenues and the skewness of their distribution); Z_i – a vector of farm and farming family characteristics; u – the model error with an expected value of zero and variance $Var(u_{ij} \mid X_i, Z_i) = \sigma_j^2$; α_j – a vector of parameters to be estimated; $\bar{Z}_i$ – mean plot characteristics; θ_j – parameters to be estimated.

To ensure that the α_j estimates are unbiased and consistent, it is still necessary to correct for sample selection bias. To this end, it was assumed that the errors ε_{ij} and u_{ij} would be linearly correlated for each *j*. Consequently, the expected value of uv_{ij} will be equal to $E[u_1 \mid \varepsilon_1, ..\varepsilon_i] = \sigma \sum_{j=1...M} p_j \varepsilon_j$, where p_j is the correlation between u_{ij} and ε_{ij}, and δ is the standard deviation of ω_{ij}. We must therefore modify the formula presented above:

$$\begin{cases} \text{regime 1:} & y_{i1} = Z_{i1}\alpha_1 + \sigma_1\hat{\lambda}_{i1} + \bar{Z}_{i1}\theta_j + \omega_{i1}, & \text{if} & \mathrm{V}_{\mathrm{i}} = 1 \\ & \vdots & \vdots & \vdots \\ \text{regime M:} & y_{i1} = Z_{ij}\alpha_j + \sigma_j\hat{\lambda}_{ij} + \bar{Z}_i\theta_M + \omega_{ij}, & \text{if} & \mathrm{V}_{\mathrm{i}} = \mathrm{J}, \end{cases}$$

where: $\lambda_{ij} = \sum_{k \neq j}^{M} p_j \left[\frac{\hat{P}_{ik} \ln(\hat{P}_{ik})}{1 - \hat{P}_{ik}} + \ln \hat{P}_{ij} \right]$ is the inverse Mills ratio; p_j – the correlation between ε_{ij} and u_{ij}; the random error ω_{ij} with a mean equal to zero; $\hat{P}_{ik}$ – the probability that adaptation *j* was applied on plot *i*.

In the final part of their modelling, G. Issahaku and A. Abdulai focused on assessing the expected benefits from the implementation of climate change adaptation measures for the farmers who undertook them. These benefits will amount to:

$$E(y_{i2} | V_i = 2) = \mathbf{Z}_{\mathbf{i2}} \boldsymbol{\alpha}_2 + \sigma_2 \hat{\lambda}_{ij} + \bar{Z}_i \theta_2$$

$$E(y_{iJ} | V_i = J) = \mathbf{Z}_{\mathbf{ij}} \alpha_j + \sigma_j \hat{\lambda}_{ij} + \bar{\mathbf{Z}}_i \theta_j.$$

The reference point, however, is the counterfactual scenario, i.e. assuming that such farmers did not apply these adaptations:

$$E(y_{i1} | V_i = 2) = \mathbf{Z}_{\mathbf{i2}} \alpha_1 + \sigma_j \hat{\lambda}_{ij} + \bar{\mathbf{Z}}_i \theta_j$$

$$E(y_{i1} | V_i = j) = \mathbf{Z}_{\mathbf{ij}} \alpha_1 + \sigma_j \hat{\lambda}_{ij} + \bar{\mathbf{Z}}_i \theta_j.$$

By subtracting the values obtained from the counterfactual scenario formula from the values derived from the benefits formula, we obtain the average treatment effect on the treated (ATT):

$$ATT = E(y_{2i} | V_i = 2) - E(y_{i1} | V_i = 2) = Z_{i2}(\alpha_2 - \alpha_1) + \bar{\mathbf{Z}}_{i2}(\boldsymbol{\theta}_2 - \boldsymbol{\theta}_1) + \hat{\lambda}_{ij}(\sigma_2 - \sigma_1),$$

where: $\hat{\lambda}_{ij}$ (.) along with the Mundlak device ($\bar{\mathbf{Z}}_{i2}$) serves as a correction for sample selection bias and potential endogeneity, which would stem from the omission of certain explanatory variables.

G. Issahaku and A. Abdulai empirically verified their models based on data derived from a survey of 476 farms located across 25 local communities in Ghana, conducted at the turn of 2015 and 2016. In total, 1,001 cultivated plots were examined, predominantly featuring maize and cowpea. A straightforward presentation of the revenue distributions revealed that, in the absence of climate change adaptation measures, skewness was negative and variance was at its highest.

Regarding the determinants for implementing "climate-smart" practices, this involves a broad set of variables. In particular, erosion risk and the level of land drainage positively influenced their adoption. Age, on the other hand, exhibited a negative and statistically significant correlation. In other words, older individuals were, on average, less interested in the climate. Conversely, household size and the number of livestock owned, as well as the use of herbicides, exerted a different impact. Farmers' engagement in non-agricultural activities had an opposing effect. If the adaptations took the form of a package of measures, it logically follows that their introduction should be positively correlated with access to agricultural extension services. It must be acknowledged as a self-evident fact that an identical correlation emerged for the variables "intensity of rainfall variability", "drought risk", and "farmers' membership of producer associations".

Among the revenue determinants, herbicides exerted a positive influence when farmers implemented solely soil and water conservation measures or the entire package of analysed adaptation initiatives. Herbicides should therefore be regarded as a complement to these. Intuitively, rainfall anomalies had a particularly negative impact on the revenues of farms that had not implemented any adaptations whatsoever. Finally, these revenues were positively correlated with plot fertility and off-farm income.

The final part of G. Issahaku and A. Abdulai's empirical analysis involved estimating the ATT for revenues and their skewness (downside risk exposure). The corresponding values for the entire studied population are compiled in Table 6.

Table 6. Mean ATT values for the logarithm (log) of revenues and the skewness of their distributions (a measure of risk exposure) across three climate change adaptation variants

Specification	Adaptation decision		ATT
	farmer implements	farmer does not implement	
Log of crop revenues			
- solely shifting the cropping pattern	5.848	5.192	0.656***
- soil and water conservation	5.978	5.356	0.622**
- comprehensive package	1.149	5.565	1.149***
Log of revenue skewness			
- solely shifting the cropping pattern	1.280	0.970	0.310***
- soil and water conservation	-0.150	-0.231	0.081***
- comprehensive package	0.734	0.523	0.211***

***, ** Significance at the 1% and 5% levels.

Source: Compiled on the basis of: G. Issahaku, A. Abdulai, Adoption of climate-smart practices and its impact on farm performance and risk exposure among smallholder farmers in Ghana, "Australian Journal of Agricultural and Resource Economics" 2020, Vol. 64.

It is evident that in the case of revenues, the optimal strategy entails the joint implementation of all the considered climate change adaptations. The situation is more distinctly varied regarding revenue skewness. Here, admittedly, both strategies frequently increase it, thereby reducing production risk. However, combining changes in the cropping pattern with soil and water conservation yields a lesser hedging effect than mere shifts in the cultivated area. This in no way alters the self-evident conclusion that farmers possess an array of options within agrotechnology to mitigate production risk, without having to wait for subsidised crop insurance to be offered to them. Public authorities should not hinder this, but on the contrary – they ought to encourage farmers to maximally utilise internal tools for self-protection and self-insurance.

Conclusion

Climate change adaptation is easier for farmers to understand and accept, as they exercise direct influence over it; furthermore, a surplus of benefits over incurred costs can be realised more swiftly. It is also less exposed to political risk. However, it is dominated by private economic adaptations, which are largely reactive due to the profound uncertainty and ambiguity regarding the pace and scale of climate change, as well as the proportion of its negative and positive impacts on agriculture. Measures falling within the scope of planned, proactive adaptation and public-private partnerships are also highly necessary. It must also be borne in mind that many adaptation actions are predominantly local in nature. Adaptation by no means resolves all the problems associated with climate change, nor is there a universal framework for its application. Its unit costs increase in tandem with the intensity of the impact, whilst the effects are uncertain and frequently deferred in time. There is also the risk of the emergence of so-called maladaptation. Furthermore, in the EU, following agricultural protests directed against the European Green Deal, a shift in course can be observed within the CAP towards favouring remuneration for pro-climate practices in the form of various subsidies, even though this entails substantial budgetary costs – be they direct, indirect, or transactional. This concomitantly diminishes farmers' motivation for self-insurance and self-protection.

Mitigation is inherently more oriented towards managing climate transition risk. On the one hand, its fundamental premise in agriculture rests on the frequently cited fact that this sector is a driver of climate change, as it contributes to rising greenhouse gas emissions stemming from the transformations of natural and synthetic fertilisers and generated in the digestive tracts of ruminants, particularly methane and nitrous oxide. On the other hand, agriculture mitigates the adverse effects of these very emissions, since carbon dioxide is captured by plants during photosynthesis and converted into organic carbon, which remains in the soil for a certain period. These circumstances mean that agriculture is sometimes perceived as a relatively inexpensive bridge towards transitioning to a low-carbon economy. This would be the case if the sector were integrated into the emissions trading system, yet this remains the exception rather than the rule. In reality, the co-benefits of implementing mitigation in agriculture are also frequently overstated. A crucial issue, however, is how to construct the entire system of agricultural governance and subsidisation so that farmers apply fertilisers rationally and manage livestock production professionally, as both direct and indirect mitigation should be concentrated in these areas. Conversely, agricultural policy makers should view mitigation in agriculture as a component of initiatives within larger aggregates, such as AFOLU and food chains, networks, and sectors. Finally, we should all understand that significant, large-scale mitigation cannot be implemented without effective international cooperation and coordination, along with the financial support of poor countries by wealthy ones (including China), which are primarily responsible for the current level of greenhouse gas emissions. At present, these arguably constitute the greatest challenges. We must also constantly bear in mind that mitigation is equally not a universal panacea. Poorly designed and implemented, it can even increase greenhouse gas emissions; it is susceptible to carbon leakage and additionally generates transactional and budgetary costs as well as behavioural distortions.

Public authorities ought to participate in designing policies oriented towards the implementation of adaptation and mitigation on farms, both directly and indirectly, by applying unique and continuously updated combinations of the entire available toolkit on each occasion, supported by various models, and grounded in the solid microeconomic foundations of farmers' decision-making processes regarding the overarching management of their total exposure to diverse risks. The multitude of assumptions and simplifications adopted in modelling, the uncertainty and ambiguity concerning the further trajectory of climate change, and the diverse interests of political actors constitute the primary reasons for the difficulties in constructing an optimal policy regarding adaptation and mitigation. Its implementation is a separate issue, as almost globally there is an observable reluctance to undertake more ambitious pro-climate policies, particularly in the area of mitigation. This is because the latter frequently demands substantial costs and sacrifices, whilst its effects are deferred in time, uncertain, and their distribution remains unknown. In this context, pragmatic pro-climate policies in agriculture nowadays are those that focus primarily on creating incentives and regulations tailored to farmers' preferences and the budgetary capabilities of states, supplying them with information and weather alerts, and offering training and educational programmes. Regarding direct interventions, governments should support the sphere of research and development, which in Poland is becoming increasingly underfunded, and invest in and/or co-finance infrastructure projects through various forms of public-private partnerships. Naturally, major infrastructural undertakings should nonetheless be coordinated at intersectoral and interregional levels.

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