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RESEARCH

National climate change impact assessments underestimate the potential of autonomous adaptation

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Abstract
Central Europe is projected to lose up to 25% of its crop productivity by 2050 because of climate change, posing significant challenges to agricultural systems and food security. Effective adaptation strategies must consider not only domestic impacts but also global climate effects, including international trade dynamics. We performed a multilevel analysis of climate change impacts on agriculture, using the Czech Republic, a landlocked, crop production-based economy with an open market, as a case study. We integrated the global biosphere management model (GLOBIOM) with the gridded global crop model EPIC-IIASA. Climate impacts were projected with five global circulation models under three climate scenarios, with and without CO_2 fertilization, and applied in national, EU-regional, and global productivity change scenarios. The results show that national-only assessments underestimate both risks and opportunities: production is projected to decline by up to 9% when global interactions are excluded but to increase by up to 8% when trade and market effects are included. Autonomous adaptation mechanisms, such as cropland reallocation, shifts in management intensity, and trade adjustments, buffer biophysical yield losses and improve economic outcomes. Neglecting global interactions in national climate change assessments increases the risk of maladaptation and policy inefficiencies. The incorporation of international market linkages enhances the ability to design robust adaptation strategies, enabling countries such as the Czech Republic to maximize resilience while minimizing environmental and socioeconomic trade-offs.

Keywords Climate change · Adaptation · Agricultural trade · Czech Republic · Integrated assessment · Food security

Introduction

Climate change is expected to pose substantial agricultural challenges in Central Europe, with potential crop productivity declining by up to 25% by mid-century (Pörtner et al. 2022). Maize yields can decrease by as much as 25%, whereas wheat losses may reach 15%, depending on the extent of CO_2 fertilization between 2040 and 2069 (Eitzinger et al. 2013; Webber et al. 2018). Robust adaptation strategies must be developed to address these anticipated agricultural losses. A key question is whether focusing solely on the direct, national impacts of climate change provides a sufficient foundation for planning and decision-making (Ercin et al. 2021). While national climate change assessments are crucial for designing adaptation strategies, the global nature and interconnectedness of climate change effects and agricultural markets may significantly influence national resilience and adaptation efforts (Ercin et al. 2019). Ignoring the effects of climate change on global agricultural production and international trade when national adaptation strategies

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are developed increases the likelihood of maladaptation; as such, assessments risk underestimating or overestimating the impacts of national climate change (Pörtner et al. 2022).

Key players in the global agricultural market have relied on national and global agricultural models to assess impacts and develop adaptation plans, such as those for the USA (e.g., Baker et al. 2018), Brazil (e.g., Zilli et al. 2020), and the European Union (EU) (e.g., Blanco et al. 2017). Moreover, 18 countries have started incorporating global frameworks to better understand and address challenges in the agricultural sector and associated linkages to climate mitigation and adaptation, for example, via the Food, Agriculture, Biodiversity, Land-Use, and Energy (FABLE) (FABLE 2019). However, in the case of the Czech Republic, climate change impact assessments are based predominantly on country- or region-scale modeling approaches. Although the Czech Republic does not play a dominant role in the global agricultural market, its agricultural sector remains an essential component of the national economy and rural livelihoods (Prochazka et al. 2023). Furthermore, changes in crop suitability and agricultural area expansion may position it as a more significant regional player within the EU as a consistent food supplier (Papadimitriou et al. 2019).

Czech agriculture is a cereal-based sector, where wheat production represented 62% of cereal production in 2024, followed by barley with 22% and maize with 9% (CZSO 2025). The Czech Republic's agricultural trade is strongly oriented toward the European Union, with approximately four-fifths of all exports directed to EU Member States and only a minor share reaching markets outside the EU (Zábojníková and Kamenický 2024). Germany remains its key trading partner. Although cereals account for more than half of domestic agricultural output, the Czech Republic overall is a net importer of agricultural products (Zábojníková and Kamenický 2024). The impacts of climate change on Czech agriculture have been extensively studied via biophysical models focused on single commodities such as maize (Pavlik et al. 2019), barley, and wheat (Trnka et al. 2004a; Trnka et al. 2004b; Thaler et al. 2012; Eitzinger et al. 2013), as well as livestock (Potopová et al. 2023) and provisioning ecosystem services (Lorencová et al. 2013). Some studies have also modeled multiple key crops (Hlavinka et al. 2015; Pohanková et al. 2022, 2024) or analyzed agroclimatic indicators (Eitzinger et al. 2013) at specific sites. Papadimitriou et al. (2019) incorporated transnational market interactions into assessments of the Czech Republic, and a European-scale model was used to simulate variations in imports and exports on the basis of shared socioeconomic pathways (O'Neill et al. 2014). Potopová et al. (2023) used climate projections to determine the future water consumption of livestock in the country, and more recently, (Poláková et al. 2025) integrated the feedback loop from local to global by integrating the national yield response into a general equilibrium model. Despite their contributions, these studies share common limitations. First, they fail to capture climate change impacts outside their spatial domains, restricting their ability to assess the Czech Republic's relative competitiveness within the EU. Second, they omit or aggregate agricultural market dynamics beyond Europe, such as international trade, leading to a biased understanding of the country's autonomous adaptation potential.

Building on the approaches of Baker et al. (2018) and Papadimitriou et al. (2019), this study develops a comprehensive, multilevel framework to assess the Czech agricultural sector's autonomous adaptation to climate change. We hypothesize that global climate change impacts and international market dynamics play critical roles in shaping the effectiveness of national adaptation strategies. We evaluate the Czech agricultural sector's autonomous adaptation potential by integrating national, regional, and global drivers through two globally consistent modeling tools: a partial equilibrium model of agriculture and forestry and a gridded global crop model. This framework enables us to quantify how national climate impacts interact with global productivity changes and market responses. This study aims (1) to assess the direct impacts of climate change on Czech agriculture; (2) to evaluate the limitations of adaptation assessments that rely solely on national-scale climate impact studies; and (3) to assess the autonomous adaptation potential of the Czech agricultural sector when both national and global drivers are considered together. By explicitly representing interactions between the Czech Republic and international markets, this approach provides a more comprehensive understanding of the conditions under which autonomous adaptation may emerge.

Methods

Models

We apply the global biosphere management model (GLOBIOM) (Havlík et al. 2014), a partial equilibrium model that represents the global agriculture, forestry, and bioenergy sectors. GLOBIOM has been widely applied to assess climate change impacts and mitigation pathways at the global (Nelson et al. 2014; Hasegawa et al. 2018; Fujimori et al. 2019) and EU levels, including the recent impact assessment of the European Commission's Fit-for-55 package (EC 2021). Unlike models that aggregate countries into broader regional blocks, GLOBIOM explicitly represents market relationships among EU Member States, making it particularly suitable for national-scale analyses (Frank et al. 2015). It is also included among the IPCC's Integrated Assessment Models (IAMs), where it complements the MESSAGE model by representing the land-based mitigation sector (Krey et al. 2020) and climate impacts (Awais et al. 2024). Beyond food production, GLOBIOM incorporates land competition with forestry as well as demand for feed and bioenergy (Havlík et al. 2011, 2014), enabling analysis of cross-sectoral trade-offs and co-benefits. Its detailed representation of agricultural commodities, including wheat, barley, and maize, provides a robust basis for evaluating cereal-based agricultural systems such as those in the Czech Republic. Additional information about the global and European versions of GLOBIOM was reported by Havlík et al. (2014) and Frank et al. (2015), respectively.

GLOBIOM represents the supply, demand, and commodity markets for the agricultural sector. Commodity markets and international trade are represented for 57 economic regions, one for each EU member state and the UK, and 29 additional regions outside the EU. Within each region, a representative consumer optimizes consumption on the basis of preferences and commodity prices, while producers maximize margins, and GLOBIOM is used to solve for the market equilibrium scheme that achieves overall welfare maximization. The supply side of the model follows a bottom-up approach using detailed spatial data for land cover, land use, management systems, and biophysical and technical costs. The EU28 is represented at the NUTS2 level, ensuring fine-scale detail. Crop, livestock, and forest production activities are considered via biophysical modeling frameworks. The crop model EPIC is used to compute crop productivity, fertilizer requirements, and irrigation management practices. The European crop sector is modeled via crop rotations for 18 key crops, derived from EUROSTAT statistics at the NUTS2 level, with the CropRota model (Schönhart et al. 2011). The livestock sector and its production system parameters are modeled with the RUMINANT model (Herrero et al. 2013). Primary forest productivity and harvesting costs are estimated via the global forest model (G4M) (Kindermann et al. 2008). Six dynamically modeled land use types (cropland, grassland, short-rotation tree plantations, managed forests, natural forests, and other natural land) can be converted on the basis of the demand and profitability of land-based activities. Within Europe, no deforestation for agricultural expansion is assumed because of restrictive land use legislation (Bauer et al. 2024).

Autonomous adaptation

Climate change adaptation refers to "the process of adjustment to actual or expected climate and its effects" (Pörtner et al. 2022). The adjustment can be explicitly planned or occur spontaneously, triggered by farmer or market changes as a response to climate change—referred to as autonomous adaptation (Pörtner et al. 2022; Maskell et al. 2025). In GLOBIOM, autonomous adaptation to climate-induced changes in crop yields can be explored through adjustments in production, consumption, and trade patterns. Supply-side adaptation occurs through land reallocation by expanding cropland into other land cover types, altering crop shares at the national level, or shifting between low-input and high-input management systems (Leclère et al. 2014). Consumers adapt by modifying both the quantity and structure of food consumption on the basis of price signals (Mosnier et al. 2014). International trade serves as another crucial adaptation mechanism. Climate-induced changes in productivity may shift comparative advantages across regions, enabling trade to redistribute surplus production from favorable regions to deficit regions (Janssens et al. 2020). In GLOBIOM, economic regions adjust trade quantities and trading partnerships to buffer productivity shocks and maintain market balance.

Climate change impacts

To represent the effects of climate change on crop productivity, the global gridded crop model EPIC-IIASA (Balkovič et al. 2013) was run in conjunction with five distinct global circulation models (GCMs) from the Coupled Model Intercomparison Project Phase 6 (CMIP6) (O'Neill et al. 2016; Jägermeyr et al. 2021). We selected the three climate scenarios from the latest protocol of the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP) ISIMIP3b (Eyring et al. 2016). They consisted of a combination of the Shared Socioeconomic Pathways (SSPs) and Representative Concentration Pathways (RCPs), SSP1–2.6, SSP3–7.0, and SSP5–8.5 (Gidden et al. 2019), simulated with climate data driven by five general circulation models (GCMs): GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0, and UKESM1-0-LL. Supplementary Table 1 provides further details about each model. SSP1–2.6 describes a pathway with a mitigation effort to keep the level of warming below 2 °C by 2100, which is consistent with the Paris Agreement; SSP3–7.0 represents an unmitigated pathway, whereas SSP5–8.5 represents the highest emission pathway (O'Neill et al. 2016).

EPIC-IIASA estimated the productivity of four key crops (maize, rice, soy, and wheat). Productivity for 17 additional crops (including barley, silage maize, cotton, and sugar beet) was computed on the basis of their C3/C4 photosynthesis pathways, following the approach of Janssens et al. (2020) (Supplementary Table 2). The projected climate impacts were then incorporated into GLOBIOM as productivity changes compared to those in the year 2000. The EPIC-IIASA projections were available at a 0.5×0.5 degree resolution and upscaled to 2×2 degree cells, matching the resolution of GLOBIOM's land units, using a weighted average based on the respective crop areas in the year 2000.

Livestock impacts were modeled indirectly through changes in feed production rather than explicit productivity impacts.

Scenario design

We implemented three climate impact scenarios to assess the limitations of adaptation assessments that rely solely on national-scale climate impact studies. In the national scenarios, productivity changes were applied only to Czech production systems, keeping yields elsewhere consistent with socioeconomic assumptions. In the regional scenarios, changes extended to the EU27, including the UK. Both scenarios accounted for endogenous changes in global productivity and market interactions. In the global scenario, productivity impacts were applied across all the regions modeled (Table 1). This scenario design isolates the effects of country- and region-scale assessments from global-scale impacts, enabling comparisons of climate-induced productivity changes. All the scenarios included the same autonomous adaptation options, although economically optimal adaptations differed on the basis of whether national, regional, or global effects were modeled.

To assess the direct effects of climate change on agriculture, we deliberately decoupled the SSP and RCP dimensions. Unlike biophysical impact models such as EPIC-IIASA, economic models such as GLOBIOM capture major socioeconomic drivers—including population growth, GDP, technological change, and food demand—which allow us to isolate the influence of different radiative forcing trajectories while keeping socioeconomic conditions constant across all scenarios (Rogelj et al. 2018). Although the SSP–RCP pairing in CMIP6 enables models such as EPIC-IIASA to generate integrated biophysical and socioeconomic narratives, economic models offer greater flexibility to separate and independently analyze the contributions of each dimension, especially not additional mitigation from the land-based sector associated with the SSP trajectories. For this reason, all climate impact scenarios in GLOBIOM are evaluated under SSP2 socioeconomic conditions (O'Neill et al. 2014); in this way, we also understand in isolation the autonomous response of the agricultural sector.

Following this logic and to ensure consistency and robustness, we use the notation *SSP–RCP* for the direct outputs from EPIC-IIASA and *RCP* alone for the direct outputs from GLOBIOM. A comparison of the results across these scenarios reveals important differences in national crop production patterns and in the autonomous adaptation responses expressed through market indicators.

Results

Our results focus on projected relative changes to the no-climate change scenario for different agricultural indicators in the Czech Republic, the EU28, and globally by 2050.

The biophysical effects of climate change on yields (see Fig. 1a) vary from −27% to 6% across crops, scenarios, and climate models. Compared with the maize yield, the wheat yield declines less severely in these scenarios, ranging from −5% (RCP 8.5) to 6% (RCP 7.0), whereas the maize yield declines by −22% (RCP 8.5) to 5% (RCP 2.6). Overall, the effects of climate change on crop yields in the Czech Republic follow a pattern similar to that observed for wheat (− 5% to + 10%), reflecting the dominance of C3 crops in Czech agricultural production. Wheat (C3) and maize (C4) both show the greatest yield declines under the high-emission scenario RCP8.5 without the CO_2 fertilization effect. The wheat and maize yields decrease from −12% to 2% and from −27% to 3%, respectively, when CO_2 fertilization effects are not considered. UKESM1-0-LL consistently projects the most negative impacts, whereas GFDL-ESM4 shows the most positive impacts across crops and climate scenarios. The large variation among GCMs can be attributed to differences in their CO_2 concentration pathways in the CMIP6 experiment and their climate sensitivity. By the end of the century, UKESM1-0-LL registers the greatest temperature increase, whereas GFDL-ESM4 is the lowest across all climate scenarios (Jägermeyr et al. 2021).

Table 1 Climate impact scenarios assessed in this study, showing the regional extent, rationale, CMIP6 climate scenarios, and general circulation models (GCMs) used to evaluate the effects of biophysical climate change on crop productivity

Climate impact scenario	Regional extent	Rationale	Climate scenarios	GCMs
National	Czech Republic	Climate impacts are applied to crop productivity in the Czech Republic. The rest of the world retains SSP2 productivity levels	SSP1–2.6 w/o CO_2 SSP1–2.6 w/CO_2 SSP3–7.0 w/o CO_2 SSP3–7.0 w/CO_2 SSP5–8.5 w/o CO_2 SSP5–8.5 w/CO_2	GFDL-ESM4 IPSL-CM6A-LR MPI-ESM1-2-HR MRI-ESM2-0 UKESM1-0-LL
Regional	EU27 + UK	Climate impacts are applied to crop productivity in the EU27 and the UK. The rest of the world retains SSP2 productivity levels		
Global	World	Climate impacts are applied to global crop productivity		

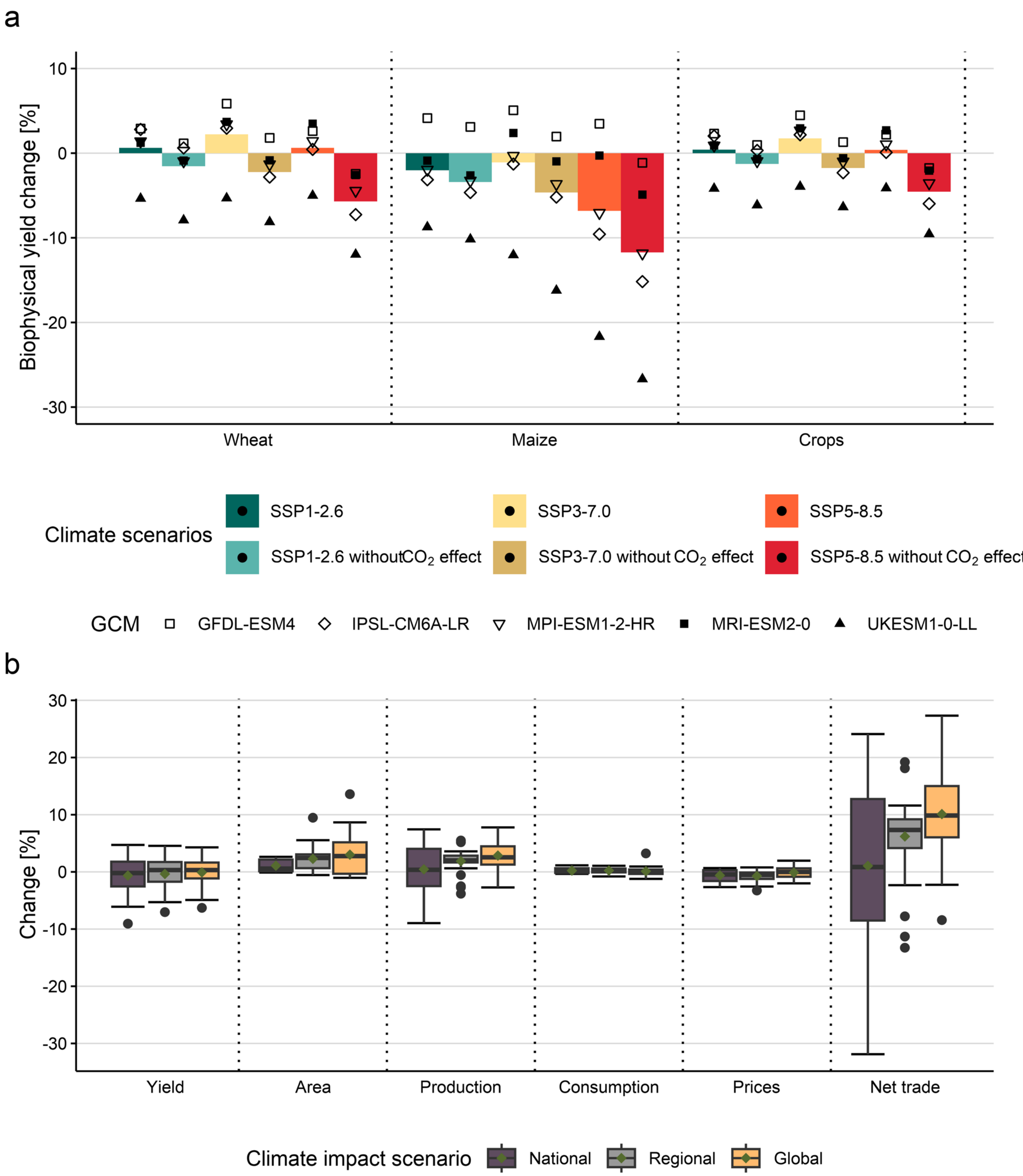

Fig. 1 Effects of climate change on crop yields and agricultural indicators in 2050 in the Czech Republic under climate and impact scenarios. **a** Biophysical yield changes relative to a no-climate change baseline (%) simulated by EPIC-IIASA for wheat, maize, and aggregated crops under SSP1-2.6, SSP3-7.0, and SSP5-8.5, each with and without CO_2 fertilization. The bars show the multimodel means (GCM ensemble average), and the symbols denote individual general circulation models (GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0, and UKESM1-0-LL). **b** Changes (%) in sectoral indicators, yield, area, production, consumption, prices, and net trade under national, regional (EU), and global climate impact contexts. Boxplots indicate interquartile ranges, whiskers show ranges excluding outliers, black lines denote medians, and filled dots mark means. The results aggregate 30 climate scenarios ($n = 30$)

Economic response to the effects of climate change in the Czech Republic

An overview of how the biophysical effects of climate change on yields propagate across agricultural indicators under different climate impact scenarios is shown in Fig. 1b. GLOBIOM transfers the initial effect on yields to the response of agricultural indicators via supply and demand adjustments to agricultural production in the country. Markets, production, and consumption patterns adjust to the assumed yield and trade conditions, with the goal of maximizing total economic surplus by 2050 globally, including in the Czech Republic. Producers respond to climate change primarily through agricultural area expansion, which averages 3%, rather than intensified management practices (−0.08%) (see Fig. 1b, global climate impact scenario and the olive-green point). The area changes remain within ± 5% across all scenario dimensions, reaching 14% under the most extreme scenario (RCP 8.5 without CO_2 fertilization effects). In contrast, yield changes are small, are centered mostly at approximately 0%, and show limited variability across scenarios. The combined area increase and stable yield result in a mean production increase of 3%, with changes within ± 10%. Consumption in the Czech Republic is stable across most scenarios, and only a small change (3%) is expected under RCP 8.5 without CO_2 fertilization effects. Net trade (calculated as exports minus imports) displays the greatest variation in all the indicators, with changes ranging from −8% to 27%, depending on the scenario. On average, net trade increases by 10%, indicating a net export surplus in response to climate change effects.

To investigate the drivers of heterogeneity in the selected indicators induced by climate change, an in-depth analysis with GLOBIOM is needed. The univariate regression lines of the selected indicators plotted against the biophysical effect on yields are shown in Fig. 2. The slope coefficient reflects the local response and can be understood as the ability of a variable to change, interpreted as adaptive capacity. A value of 1 can be interpreted as a percentage change in the impact of climate change on yields in response to an equivalent percentage change in a given indicator. The intercept coefficient can be interpreted as a local change driven by indirect climate change effects and price effects transmitted by international markets. An intercept value other than 0 suggests that local changes arise from effects in other regions transmitted via price effects through international trade (Nelson et al.

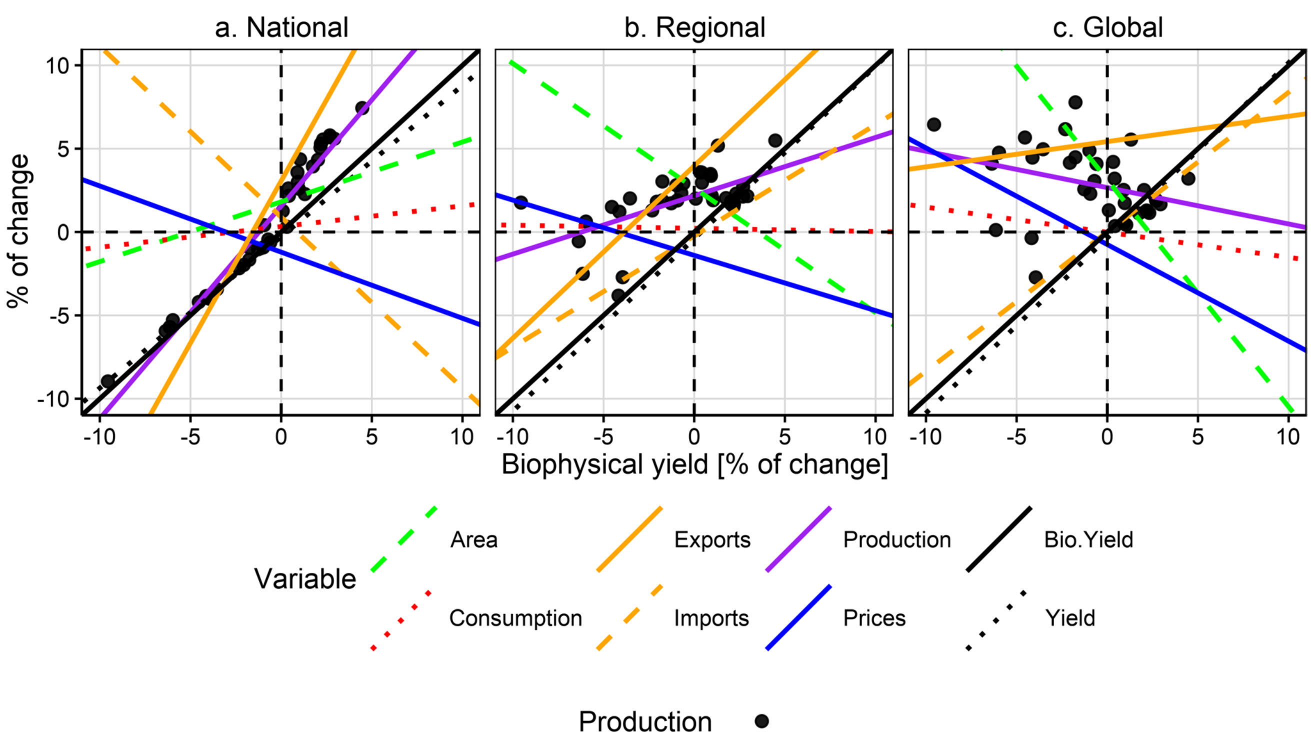

Fig. 2 Economic responses to biophysical yield changes in the Czech Republic under three climate impact scenarios(**a** national, **b** regional, and **c** global) for 2050. Each panel shows the percentage change in economic variables plotted against biophysical yield changes (%). The black dots represent changes in production, whereas the colored lines indicate univariate regressions for selected variables: area (green), consumption (red), exports (orange), imports (dashed orange), production (purple), prices (blue), biophysical yield (black), and yield (dotted black)

2014). The slope and intercept coefficients for each climate impact scenario are also reported in Supplementary Table 3.

The yield in the Czech Republic appears unresponsive in terms of productivity management. With a slope close to 1 and an intercept close to 0, there is no additional compensation through management for climate change impacts on yield (see Fig. 2c). The yield shows a slight local effect on crop reallocation between C3 and C4 crops because of differential climate change impacts (Supplementary Table 5). The area change shows a negative relationship between biophysical productivity and area, indicating a strong response in the Czech Republic. The area of specific crops is expected to decrease as the productivity of the crops increases. Climate change has led to a decrease in the cultivated areas of most impacted crops, and losses in production have been offset by imports from more favorable areas in the EU28. The same inverse relationship and market reallocation trend are shown by the production regression line but are less responsive than the area changes are, with a smaller slope and intercept. The increase in production for crops is positively impacted by climate change, and for negatively impacted crops, production decreases and imports increase. Exports and imports are positively related to changes in biophysical yield. Exports are more responsive than are imports, with the highest intercept value indicating that the increase in exports is driven by the reallocation of production shares in the EU28 and is less dependent on national yield and area responses. The consumption response is relatively small, and it displays a negative relationship with climate change impacts.

Hence, the response to climate change in the Czech Republic occurs predominantly on the supply side through management intensity, cultivated land reallocation, and trade adaptation.

Comparing domestic, regional, and global climate impact scenarios

The responses of agricultural indicators across different climate scenarios are shown in Fig. 1b. The purple bars correspond to the climate impacts only in the Czech Republic, the gray bars correspond to the climate impacts in the EU28, and the yellow bars correspond to the climate impacts globally. The means and standard deviations for each climate impact scenario are presented in Supplementary Fig. 1. When shifting from national to regional and global climate change impact scenarios, the variability and response of agricultural indicators differ.

The yield is not strongly affected by shifting climate impacts. On average, the yield decreases by 0.6% in the national scenario to 0.08% in the global scenario. However, the national scenario shows greater variability (SD 3.2). In contrast, the area progressively increases from 1 to 3%, with the greatest variability associated with the global impact scenario (SD 3.2). Changes in production occur in response to area expansion, with the greatest effect occurring in the global impact scenario. Hence, the overall effect on production is positive in the regional and global impact scenarios. The greatest variability occurs when impacts are isolated to the Czech Republic. In this case, production is projected to decrease to 9% in the most severe scenario without CO_2 fertilization effects, in contrast to a 4% decrease when CO_2 is considered. When climate change impacts are considered globally, the negative response in production is less pronounced, with production increasing between 0.1% and 8% in most climate scenarios. On the demand side, consumption remains unresponsive to differences in climate impact scenarios. Net trade varies greatly across national and global assessments. No effect in response to climate change is observed in the national impact scenario (1%, SD 14), whereas net trade increases progressively in the regional (6%, SD 6.5) and global (10%, SD 7.2) scenarios.

The relationship between the yield response to biophysical changes due to climate effects remains the same across the three impact scenarios (Fig. 2a, b, and c, dotted black line). However, the area response varies greatly among impact scenarios. While in the regional and global climate impact scenarios, area displays an inverse relationship with variations in the biophysical yield, in the national scenario, area has a positive relationship with changes in biophysical yield, indicating a less responsive relationship and a reduced effect of international price transmission. Moreover, national and regional climate impact scenarios are positively related to production, with a limited response and a generally stable trend in the Czech Republic. Consumption remains unresponsive to climate change in all the scenarios, whereas import changes display a negative relationship in the national impact scenario, with a decrease in imports as national productivity increases because of climate change. Although supply-side autonomous adaptation mechanisms remain the most responsive to climate change impacts across all impact scenarios, the behavior of production differs when climate change impacts are applied globally.

The level of agreement in the direction of changes (positive or negative) across national, regional, and global climate impacts for selected agricultural and food system indicators under various climate scenarios is shown in Fig. 3. The level of agreement refers to the consistency in the sign of changes, and the values represent the percentage change in the global climate impact scenario. Strong agreement (blue) is observed for variables such as crop self-sufficiency, livestock self-sufficiency, and crop yields, particularly in scenarios that include CO_2 effects, reflecting consistent increases in crop-related indicators due to CO_2 fertilization. In contrast, indicators such as grassland area, food consumption from livestock, and feed consumption

Indicator	RCP 2.6 w CO_2	RCP 2.6 no CO_2	RCP 7.0 w CO_2	RCP 7.0 no CO_2	RCP 8.5 w CO_2	RCP 8.5 no CO_2	RCP 8.5 x GCM MRI-ESM2-0	RCP 8.5 x GCM GFDL-ESM4	RCP 8.5 x GCM MPI-ESM1-2-HR	RCP 8.5 x GCM IPSL-CM6A-LR	RCP 8.5 x GCM UKESM1-0 LL
Biophysical crop yield	0.42%	-1.27%	1.75%	-1.76%	0.40%	-4.54%	1.04%	-4.13%	2.70%	2.19%	0.08%
Crop yield	0.43%	-1.98%	1.69%	-2.46%	-0.17%	-5.05%	1.03%	-4.63%	2.52%	2.04%	-0.22%
Crop production	0.36%	2.57%	1.12%	4.48%	3.20%	5.67%	0.43%	4.47%	1.88%	1.23%	1.30%
Livestock production	-0.04%	-2.18%	-0.06%	-2.21%	-1.30%	-2.13%	-0.56%	-2.16%	-2.61%	-0.17%	-3.32%
Cropland	-0.07%	4.64%	-0.57%	7.11%	3.38%	11.29%	-0.59%	9.54%	-0.63%	-0.79%	1.53%
Grassland	0.00%	-2.15%	0.02%	-2.15%	-2.04%	-2.15%	0.07%	-2.15%	-2.05%	0.03%	-2.13%
Food consumption from crops	0.00%	-0.07%	-0.33%	-0.06%	-0.05%	-0.18%	0.00%	-0.12%	-0.30%	-0.31%	-0.41%
Food consumption from livestock	-0.00%	-0.26%	-0.00%	-0.30%	-0.00%	-0.39%	0.00%	-0.39%	0.00%	0.00%	0.00%
Feed consumption	-0.10%	-0.59%	-0.12%	-0.63%	0.03%	-0.54%	-0.68%	-0.50%	-1.05%	-0.26%	-1.67%
Crop exports	2.41%	5.75%	3.75%	6.65%	4.75%	8.45%	0.97%	5.86%	6.78%	4.21%	4.01%
Livestock exports	-0.21%	-9.25%	-0.19%	-9.19%	-5.49%	-8.82%	-2.39%	-8.90%	-11.06%	-0.69%	-14.02%
Crop imports	3.02%	1.64%	2.88%	-3.96%	-2.84%	-5.34%	-1.79%	-5.95%	4.32%	2.41%	-0.97%
Livestock imports	-0.10%	-1.80%	0.13%	-1.67%	0.10%	-2.28%	0.01%	-2.14%	0.16%	0.05%	0.23%
Crop prices	0.24%	0.62%	0.06%	0.90%	0.30%	0.95%	0.13%	1.11%	-0.35%	-0.12%	0.18%
Livestock prices	-0.34%	0.14%	-0.27%	1.48%	-4.16%	3.18%	-0.42%	2.02%	-3.83%	-3.24%	-1.93%
Crop self-sufficiency	0.34%	1.11%	0.77%	1.96%	1.36%	2.66%	0.61%	1.98%	1.53%	0.96%	1.40%
Livestock self-suffiency	-0.04%	-1.93%	-0.06%	-1.93%	-1.30%	-1.76%	-0.56%	-1.80%	-2.61%	-0.17%	-3.32%

Not Agreement; National and global agreement; National, regional and global agreement; Regional and global agreement; National and regional agreent

Fig. 3 Agreement in the direction of percentage changes (positive or negative) in selected agricultural and food system indicators in different climate scenarios. The values represent the percentage changes in global climate impact scenarios in reference to the value in the no-climate change baseline, and the colors indicate the level of agreement in the sign of change across national, regional, and global scales. Red represents no agreement, orange indicates regional and global agreement, green represents national and regional agreement, yellow represents national and global agreement, and blue represents agreement across all three scales. Indicators are assessed under the RCP2.6, RCP7.0, and RCP8.5 scenarios, with and without CO_2 fertilization effects

frequently display no agreement (red), indicating high variability in responses across scales, especially in the national impact scenario. The trade variables exhibit mixed levels of agreement: crop exports often align regionally and globally (orange) under high-emission scenarios such as RCP 8.5, whereas livestock exports and imports show considerable disagreement. Land use changes exhibit relatively consistent agreement for croplands (often blue or orange) but limited agreement for grasslands, highlighting regional variability. Notably, high-emission scenarios (RCP8.5) tend to be characterized by greater uncertainty, with frequent divergence among the national, regional, and global impact scenarios, especially for trade and consumption patterns. Livestock-related indicators remain highly uncertain across impact scenarios because of the variable response of cropland expansion. As cropland expansion is driven by the effects of climate change in the rest of the world, which is transmitted through price effects in the Czech Republic, land use shifts from grassland to cropland occur (see Supplementary Table 7); therefore, the production of beef and milk is consistent among the scenarios in which climate change impacts are considered globally. Overall, the results demonstrate that while some indicators exhibit consistent trends across scales, others, particularly those related to trade and consumption, remain highly uncertain and dependent on the scale at which climate change impacts are considered.

Impact of autonomous adaptation on production and trade

The effects of climate change on yield reduced Czech agricultural production from −526 to 342 kilotons (first column of Fig. 4). The equivalent reduction in production as the level of warming increased across the RCP is robust (black error bars in Fig. 4), but there is considerable uncertainty across the GCM scenarios (red error bars in Fig. 4). Without the CO_2 fertilization effect, the decline is as high as 1210 kilotons (black dots in Fig. 4). The individual effects on the production of autonomous responses, such as shifts in management systems (MGMT), the overall effects of yields due to climate change and management system productivity (TOT YLD), and area expansion (TOT AREA) (middle columns of Fig. 4), were based on the findings of Leclère et al. (2014). We estimate that shifts in management systems play a marginal role in production (second column of Fig. 4). Production is expected to decline from −4 to −74 kilotons (see Fig. 4c) and −71 kilotons without the effect of CO_2. These results are robust among the RCP and GCM scenarios. However, the effect of area expansion is considerably greater than that of shifts in management systems.

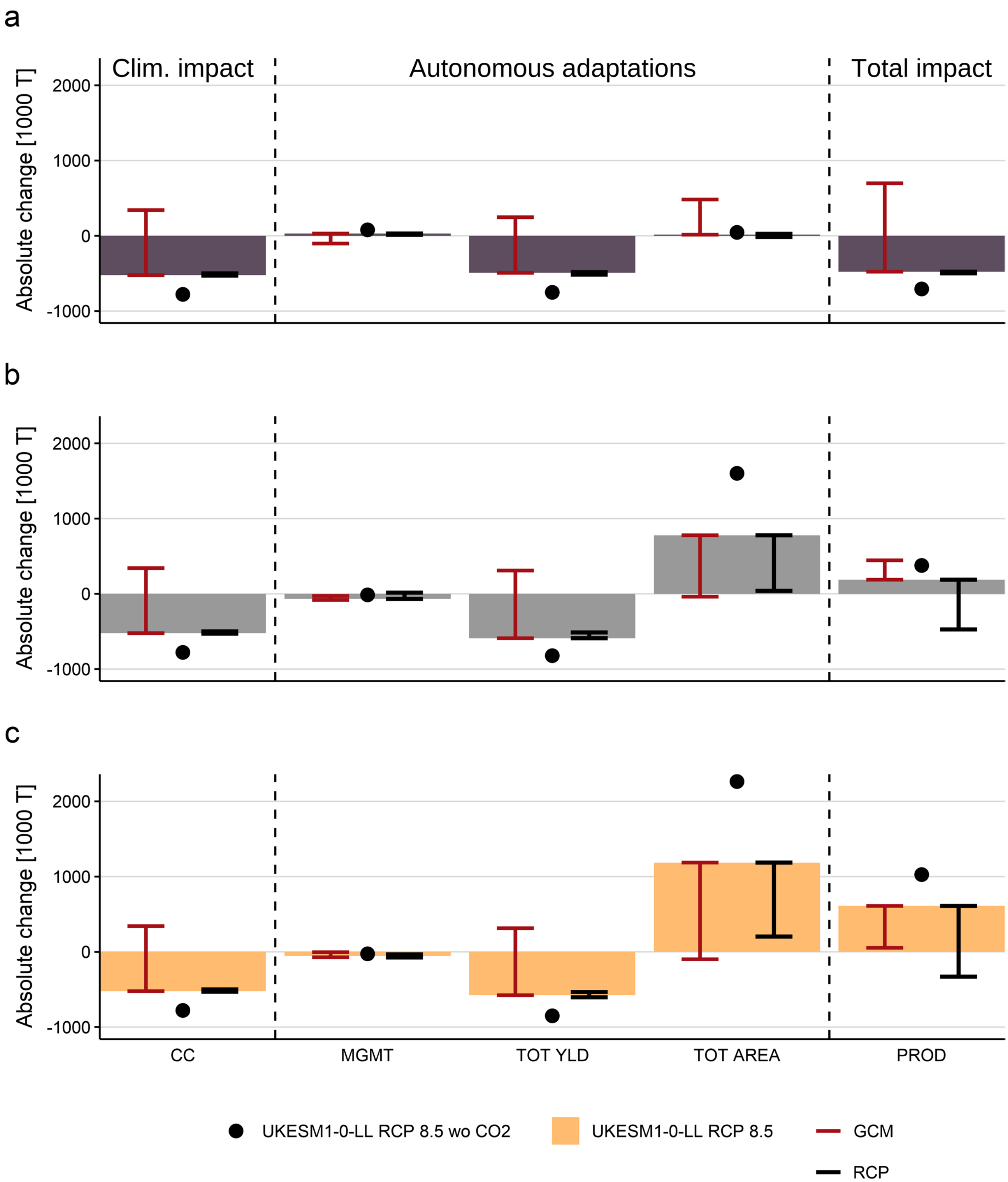

Fig. 4 Decomposition of climate change impacts, autonomous adaptations, and total effects on crop production in the Czech Republic, expressed as absolute changes relative to a no-climate change scenario (1000 tons). The results are divided into three components: (1) climate impact (CC), changes in productivity due to biophysical effects; (2) autonomous adaptations (MGMTs), adjustments through shifts in agricultural management systems; and (3) total impact (PROD), combined effects on crop production, including changes in yield (TOT YLD) and cropland area (TOT AREA) under different climate impact scenarios at the **a** national, **b** regional, and **c** global scales. The bars represent projections under the UKESM1-0-LL RCP8.5 scenario, with error bars indicating variability across GCMs (red) and RCPs (black). The black dots represent results excluding CO_2 fertilization effects

An increase in production of up to 1187 kilotons is expected because of area expansion, and the effect almost doubles when the CO_2 fertilization effect is not considered, with a gain in production of up to 2263 kilotons. The increase in production due to area expansion is enough to offset the losses due to climate change effects (last column of Fig. 4). The overall effect of autonomous adaptation has a positive effect on production by 610 kilotons, which doubles without the CO_2 fertilization effect, reaching 1027 kilotons. The final positive impact is robust across GCMs. However, under UKESM1-0-LL RCP 2.6 and RCP 7.0, there are reductions in the production of 17 and 330 kilotons, respectively.

The impacts of autonomous adaptation on production in the national and regional climate impact scenarios are shown in Fig. 4a and b, respectively. The shift in management systems remains marginal among climate impact scenarios. However, the impacts on area expansion and total impact on production differ vastly. When impacts are isolated to the Czech Republic, the overall effect on production is more negative than that under global and regional climate impact scenarios, ranging from −499 to 698 kilotons. The losses are driven by a combined effect of a slight increase in production due to management changes (from −103 to 13 kilotons) and insufficient area expansion (from −16 to 483 kilotons) to compensate for the overall losses in production due to climate change.

When the region is impacted by climate change, Czech production remains negatively impacted, declining to as much as -−473 kilotons and increasing to 446 kilotons, depending on the GCM and RCP combination. The losses are due to the limited effects of management (from −68 to 16 kilotons) and larger area expansions (from –38 to 779 kilotons) compared with those observed for the national climate impact scenario. Despite all autonomous adaptation options being available in GLOBIOM for all climate impact scenarios, the economically optimal combination of options differs when shifting from national to regional and global impacts. The area of Czech cropland progressively increased in response to new market configurations when regional and global climate change affected agricultural yields.

The net bilateral trade relationships between the Czech Republic and the rest of the EU28 and the rest of the world for aggregate crop commodities are shown in Fig. 5. The EU28 was divided into four regions to best represent the flows to and from the Czech Republic, and the trade flows outside the EU28 were determined, combined, and denoted as “the rest of the world” (RoW) (Supplementary Fig. 2). The size of the lines in the chord diagram represents the total trade flow under each climate impact scenario and the no-climate change scenario. We use the revealed comparative advantage (RCA) indicator, which is based on the Ricardian comparative advantage concept, to assess the relative positions of Czech agricultural commodities in the international market (Balassa 1965). In the RCA approach, trade flows are used to calculate a country’s relative advantage or disadvantage in the international agricultural market. A value greater than 1 indicates a comparative advantage for a commodity, whereas a value less than 1 indicates a comparative disadvantage. The RCA values for wheat, maize, barley, rapeseed, and potatoes, the primary commodities traded by the Czech Republic, are shown in Supplementary Fig. 3.

The total trade flows are greater under climate change than under the no-climate change scenario, with the greatest increase observed when climate change impacts are considered globally. The greatest export trade flow is observed between the Czech Republic and Western European countries in the regional and global scenarios and with the rest of the world in the national scenario. The Czech Republic is projected to export 2.2, 2.2, 2.3, and 2.3 million tons of product to other Western European countries under the no-climate change scenario and the national, regional, and global climate impact scenarios, respectively. The Czech Republic displays variability in terms of its RCA values under different climate change scenarios and for different crops. Barley, rapeseed, and wheat display strong to moderate RCA values, representing 80% of the total exported commodities. Wheat remains strategic for the country, especially in the EU28 market, with the Czech Republic successfully competing with Germany and France, for instance. The same pattern is present across east-central European countries for wheat.

Czech barley remains competitive in the European market, especially compared with barley from neighboring countries (Germany, Austria, Slovakia, and Poland). Rapeseed in the Czech Republic displays the greatest resilience across climate and impact scenarios and is exceptionally competitive in both the European and global markets.

The Czech Republic remains among the top-performing countries in terms of this crop. Austria, Germany, and Italy are identified as the largest importers of Czech crop commodities.

In contrast, Czech imports from neighboring countries in east-central Europe range between 1.8 and 1.9 million tons in the no-climate change scenario and global climate impact scenario, respectively. The RCA values of potatoes and maize are low, with values for potatoes being less than 1 for the Czech Republic and those for maize being lower than those for leading key players in the EU28, such as Germany, Slovakia, Hungary, Slovenia, and Romania. The Czech Republic lags behind both the EU28 and global RCA levels, highlighting its limited competitiveness in terms of maize production, with a value of approximately 1. A comparative disadvantage is projected for potatoes in the Czech Republic, where countries such as Poland and Belgium exhibit strong comparative advantages both in the EU28 and globally.

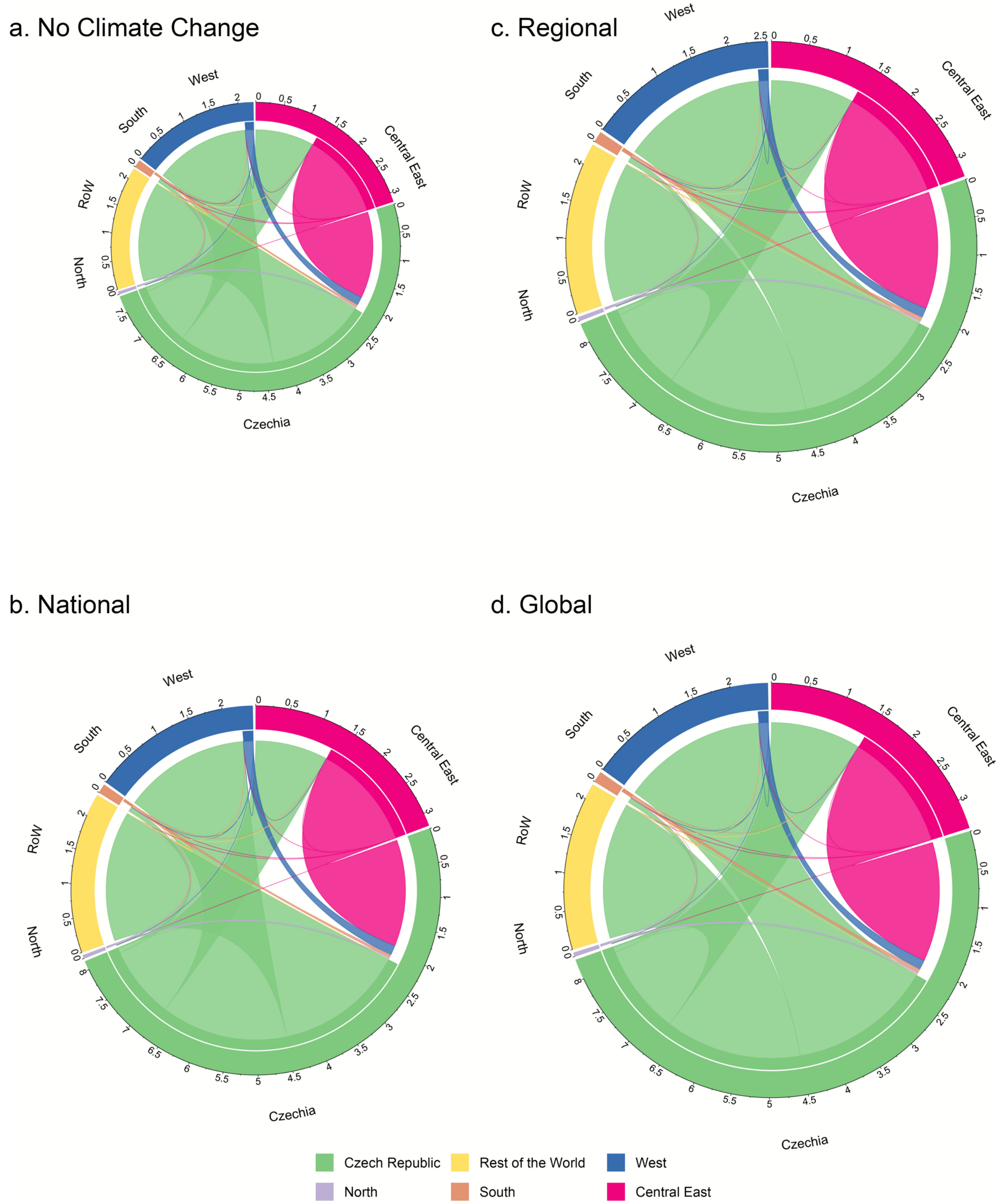

Fig. 5 Projected bilateral trade flows of cropsaggregated in 2050 under the RCP8.5 scenario (in million tons) across four climate impact scenarios. **a** No climate change, **b** national impact, **c** regional impact, and **d** global impact. The colors represent regions, with the Czech Republic (green) as the focal area. The thickness of the connecting lines indicates the trade volume

Slovakia and the Netherlands are the leading exporters to the Czech Republic, where maize and potatoes represent 75% of the total imports. When climate change impacts are isolated to the Czech Republic, the country is projected to decrease the total export of crops by 6% and increase the total import of crops by 5% compared with that in the no-climate change scenario. When climate change impacts are applied globally, the total export of crops increases by 6%, with total imports projected to decrease by 5% by mid-century. The values for each commodity are shown in Supplementary Tables 5 and 6.

Comparison with global and European results

Compared with the European Union, the Czech Republic faces more considerable projected biophysical yield reductions than the global average. The EU28 region is projected to experience relatively small reductions, mostly between −5% and −15%, while the global impacts are expected to be even less severe, typically between −5% and −10% (Supplementary Figs. 2–4, 6). Projected biophysical yields for wheat are more resilient than those for maize, ranging from −15% to 1% in the EU28 and from −10% to 3% globally, although variability increases under high-emission scenarios (RCP8.5) without CO_2 fertilization, for which the Czech Republic's decline is up to −12%. The average biophysical yield changes for the EU28 mask the heterogeneous impacts of climate change among countries. As the level of warming increases from SSP1-2.6 to SSP5-8.5, yield impacts become more extreme, particularly for some southern and eastern European countries. Compared with other EU28 countries, the Czech Republic experiences relatively modest yield changes, similar to those in other Central European countries, such as Poland (Supplementary Fig. 6). The negative extreme effects are dominated by C4 crops such as maize, with negative effects also expected in most other EU28 countries, with the most severely affected countries being Italy, France, Croatia, and Slovenia. In contrast, wheat shows a mixed pattern of impacts, with positive effects in some western and east-central European countries and negative effects in some northern and eastern European countries (Supplementary Figs. 3 and 6).

The larger reductions in the EU28 compared with the global average can be explained by both climatic and structural factors. Climatic conditions in southern and eastern Europe amplify negative impacts, whereas more temperate regions in central and western Europe sometimes benefit. At the global level, however, trade reallocation across continents helps buffer production losses, dampening the overall average. Crop type sensitivity further explains these differences: C4 crops such as maize respond more negatively to high temperatures, whereas C3 crops such as wheat display a broader range of outcomes.

Supplementary Figs. 8–10 show the economic responses to the effects of climate change globally and in the EU28 under regional and global scenarios. Like the Czech Republic, the EU28 is projected to experience more variability and severe impacts than those observed globally. In contrast, price fluctuations stand out, with changes ranging from −7.5% to + 4.5% regionally and −5.0% to + 3.2% globally. The consumer response becomes more relevant at the EU28 level than at the Czech Republic level, with changes ranging from −4% to 2% under regional impact scenarios and from −2.8% to + 1.3% in the global impact scenario. Yield and production are positively correlated with biophysical yields, which are driven by climate impacts in the EU28 and market interactions. An inverse relationship is observed for the EU28, as for the Czech Republic. Both climate and market effects are greater in the global impact scenario than in the regional impact scenario.

The overall effect of climate change impacts in the EU28 is a decrease in production despite shifts in management systems and area expansion. Changes in global indicators are relatively minor, remaining mostly within ± 1%, except for prices, which display greater variability, reaching up to 3%. Globally, trade adjustments and production compensate for the regional effects of climate change, yet crop prices are expected to surge. As in the EU28 and the Czech Republic, yield and production have a positive relationship with biophysical yields, whereas area has an inverse relationship. Strong reallocation patterns across regions, both in terms of management productivity and less so in terms of area, help buffer losses in production due to climate change impacts globally.

Discussion

We applied a multilevel framework using two globally consistent models, GLOBIOM and EPIC-IIASA, to evaluate how climate change affects Czech agriculture and how the country responds through autonomous adaptation. Unlike earlier Czech studies, such as that of Pohanková et al. (2022), which focused on biophysical outputs for specific crop rotations, and other field-based projections, our approach links biophysical yield impacts with economic and trade dynamics at the national scale. This allows us to move beyond single-crop or site-level insights (e.g., Hlavinka et al. 2015) and align our analysis with broader global frameworks. While previous intercomparison studies, such as that of Jägermeyr et al. (2021), established similar patterns globally, our study uniquely traces how yield changes in the Czech Republic are transmitted through international markets to shape production, trade, and competitiveness. Importantly, we incorporate the latest CMIP6 projections (Gier et al. 2024), providing a more realistic representation of carbon–nitrogen interactions and land use dynamics. Our contribution also complements emerging protocols that explicitly link local processes with global dynamics, such as the framework of Poláková et al. (2025). In this context, our study demonstrates the novelty of situating Czech agriculture within a multilevel framework, revealing adaptation opportunities and risks that remain hidden in national-only assessments.

Our projections show that maize is more vulnerable to climate stress than wheat is, particularly under high-emission scenarios, which is consistent with the findings of Eitzinger et al. (2013) and Trnka et al. (2018). This aligns with the findings of Pohanková et al. (2022) and Muench et al. (2024), who emphasized that potential yield gains depend on management practices and farmer adoption of adaptation. We also find that national-scale assessments may overestimate local yield shocks while underestimating the buffering role of trade. Similar outcomes have been observed in Brazil (Zilli et al. 2020), Gambia (Carr et al. 2024), the UK (Challinor et al. 2016), and Ireland (Adenaeuer et al. 2023). Importantly, our findings highlight transnational climate risks: yield shocks abroad propagate through trade and prices to influence Czech production and competitiveness. These findings echo studies on Europe's cross-border vulnerabilities, showing that droughts or losses outside the EU can significantly affect its food security and economy (Ercin et al. 2019, 2021).

Land expansion emerged as the dominant autonomous adaptation strategy, especially under global scenarios where price signals are transmitted via trade. This reflects the relatively favorable land base of the Czech Republic, which is less affected by drought than neighboring countries are (Eitzinger et al. 2013). However, the scope for expansion is limited: under the common agricultural policy (CAP), the conversion of permanent grassland is prohibited in protected areas and heavily restricted elsewhere (Ministry of Agriculture of the Czech Republic 2022), and expansion would carry environmental costs, including biodiversity loss, greenhouse gas emissions, and reduced ecosystem services (Lorencová et al. 2013; Papadimitriou et al. 2019). Thus, while land expansion provides an immediate buffer against yield shocks, it is unlikely to be sustainable. In practice, adaptation relies more on reallocating within existing arable land, maintaining ecological areas, adopting soil-conserving practices, and adjusting trade.

Reliance on a narrow set of commodities also increases vulnerability. Wheat, barley, and rapeseed dominate Czech exports (e.g., beer, feed), and while they are well captured in GLOBIOM, the model does not differentiate organic from conventional farming. This is important, as organic farming is projected to reach 21% of land by 2028, and policy measures aim to strengthen the fruit, vegetable, hops, wine, and apiculture sectors (Ministry of Agriculture of the Czech Republic 2022). Planned adaptation is therefore being reoriented toward soil, water, and biodiversity outcomes while sustaining competitiveness. Crop diversification, combined with sustainable intensification, should complement land expansion to enhance resilience and long-term competitiveness.

The implications of our results extend beyond production to the policy and institutional dimensions of adaptation. CAP regulations protect grasslands, wetlands, and ecological features, making large-scale expansion legally and economically difficult (Ministry of Agriculture of the Czech Republic 2022). Farmers also face financial and practical barriers, such as high upfront investments, uneven advisory support, and uncertainty over climate and markets. Consequently, realistic adaptation pathways in the Czech Republic will depend on CAP-compatible strategies such as reallocating existing arable land, adopting soil-conserving practices, and diversifying into resilient or higher-value crops. At the EU scale, production reallocation among member states helps buffer localized shocks but generates distributional consequences across regions. Globally, trade integration stabilizes supply and prices but exposes small open economies such as the Czech Republic to risks from regulatory mismatches or sudden disruptions. National-only assessments that ignore these dynamics risk maladaptation by overstating self-sufficiency and underestimating the benefits and trade-offs of global integration. By embedding Czech agriculture in a multilevel framework, our study shows that effective adaptation requires attention to both domestic and transnational dimensions, providing a stronger foundation for policies that enhance resilience while minimizing unintended trade-offs.

Conclusion

Our study contributes to the growing body of research that moves beyond isolated yield projections toward systemic, multiscale assessments of agricultural resilience. By situating Czech agriculture within a trade-mediated global context and complementing recent advances in local-to-global modeling, we provide a novel perspective that better captures both the opportunities and risks of autonomous adaptation. The results highlight the importance of integrating global agricultural impacts and trade dynamics into national climate change assessments. Accounting for international market interactions reveals greater adaptive capacity for the Czech Republic than suggested by national-only analyses, particularly through trade-driven responses and land use reallocation. However, the heavy reliance on land expansion raises sustainability concerns, underscoring the need for policies that balance adaptation with mitigation and environmental protection. These findings reinforce the value of multiscale approaches for informing robust adaptation planning. Policymakers should prioritize strategies that leverage trade and market responses while advancing sustainable intensification and resource-efficient practices. Overemphasis on self-sufficiency risks underestimating adaptation potential and increasing vulnerability, whereas trade-based strategies can buffer national shocks, increase resilience, and optimize resource use. For small, open economies such as the Czech Republic, recognizing the interplay between domestic responses and transnational climate risks is critical for achieving sustainable and effective adaptation.

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Author contribution JAG, PH, and MT developed the conceptual framework; JAG and EB developed the scenarios and methodological framework and improved the model (GLOBIOM). JAG wrote the initial manuscript and performed the data analysis. MT, PH, EB, IPH, and PAH edited and commented on the manuscript. IPH and PAH contributed to the discussion with JAG. MT supervised the project.

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Data availability The code and data used in the scenario analyses are available from the corresponding author upon request.

Declarations

Conflict of interest The authors declare no competing interests.

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