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Pollinator decline reveals uneven impacts of climate-driven biodiversity loss

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Pollinator decline reveals uneven impacts of climate-driven biodiversity loss

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Abstract

Ecosystems and biodiversity sustain human welfare through essential services such as pollination, collectively contributing a significant proportion to global GDP. Yet their representation in long-term socioeconomic projections remains critically limited, leading to biased outlooks, particularly under accelerating environmental change.
Here we develop a long-term, climate-driven evaluation of the macroeconomic consequences of pollination decline, integrating a multi-model ensemble of climate-driven distribution projections of wild pollinator species and 129 crops, to quantify how biodiversity loss propagates through agricultural systems into the macro-economy across 122 EU sub-national regions to 2070. EU-wide average impacts, showing GDP losses up to €57.7 billion/year (-0.18%) and agricultural sector losses of -1.5 to -6.0% by 2070, systematically conceal severe spatial concentration of damages. Under high-emission scenarios, cropland productivity losses for vegetables, fruits and nuts exceed -30% in the most exposed regions, with sectoral economic impacts spanning between -21.35% and +8.85%. Economic output polarises, with Mediterranean and eastern EU regions bearing disproportionate burdens, amplifying intra-EU economic disparities. Losses concentrate where pollinator-dependent cropping meets limited adaptive capacity, revealing critical vulnerabilities in the agricultural systems. These results demonstrate that biodiversity impacts cannot be properly captured by national-scale assessments and that spatial resolution is not a technical choice but a determinant of whether risks are visible at all. Standard integrated assessment models, typically resolved at macro-regional level, may systematically underestimate the vulnerability to climate-biodiversity impacts as aggregation conceals distributional tails by factors of 2-5×.

Main

Animal pollination significantly contributes to global crop production [56][31][6][30], with annual global economic output depending on pollinators ranging between US$235 and US$577 billion [47]. In Europe, 84% of the crops grown benefit at least partly from animal pollination [23], including almost all fruits, vegetables and nuts, oil crops (notably oilseed rape), pulses (beans, peas, lentils, etc), cotton, flax, feed and forage plants (as many protein-rich and nitrogen-fixing legumes, beans, clovers, alfalfa, vetches, lupins, etc). Ecological assessments project pollinator range shifts under climate change and land use change with increasing sophistication, leveraging Species Distribution Models (SDMs) calibrated on observed biogeographic data. Recent assessments confirm an accelerating pollinator decline due to agricultural pressures and land use[110][58][47][80][23][74]. Changes in habitat suitability driven by climatic changes pose additional threats to pollinators. These influence their geographic ranges, population

sizes, and seasonal activity patterns[25][46][121], possibly leading to extinctions of some species in the southern and northern edges of ranges and in alpine species, whilst driving the expansion of other species to colonise new areas[37][85][88][55].

This study delivers the first multi-model and multi-scenario assessment of the macroeconomic consequences of pollinator decline under climate change at sub-national resolution. We developed an integrated modelling chain, linking a multi-scenario ensemble of pollinator species distribution projections with a sub national computable general equilibrium model for the EU, to capture the propagation of ecosystem services changes through agricultural systems into the macro-economy in a spatially explicit manner.

Climate change drives spatially uneven decline in pollination potential

Projected changes in pollination service, measured by the ecosystem's ecological suitability to support wild insect pollinators, exhibit a clear and consistent pattern across the climate change scenarios considered, with significant losses occurring already in the first half of the century. By 2070, EU-wide average declines range from about -22 to -26% under low climate change trajectories (LF) to -62% to -66% under high-end trajectories (HE), with intermediate scenarios (MOD) spanning these bounds (Figure 3, 4). No scenario produces a positive EU-wide signal by 2070, confirming the directional robustness of the result even under large inter-model spread between different SDMs used. The divergence in results depends on the specific Species Distribution Model (SDM) and the radiative forcing (RCPs) underlying the pollination scenario. The model choice becomes particularly decisive under high-forcing scenarios where it builds up to 36 percentage points of spread across models.

These EU-aggregate trends hide a spatial heterogeneity that grows with the granularity of the analysis. While most regions consistently show declines across all scenarios, the magnitude of results diverge depending on the specific Species Distribution Model (SDM) or the radiative forcing (RCPs) underlying the pollination scenario (Figure 4). Pollination-service losses are highest and most widespread across Mediterranean and Eastern European regions, where average declines can exceed 30%. Only a limited number of Central-Eastern and Northern European areas, including parts of Germany, France, Romania, as well as Italy, Portugal and Spain, show negligible losses or even localized gains under low-forcing (LF) scenarios. The high spatial variability underscores the cross-regional heterogeneity of biodiversity loss; a pattern that propagates into every downstream economic outcome.

Changes in pollination services, on their turn, influence cropland productivity and are reflected in yield changes, revealing critical vulnerabilities in the EU agricultural systems.

Agricultural productivity losses show high regional and sectoral heterogeneity

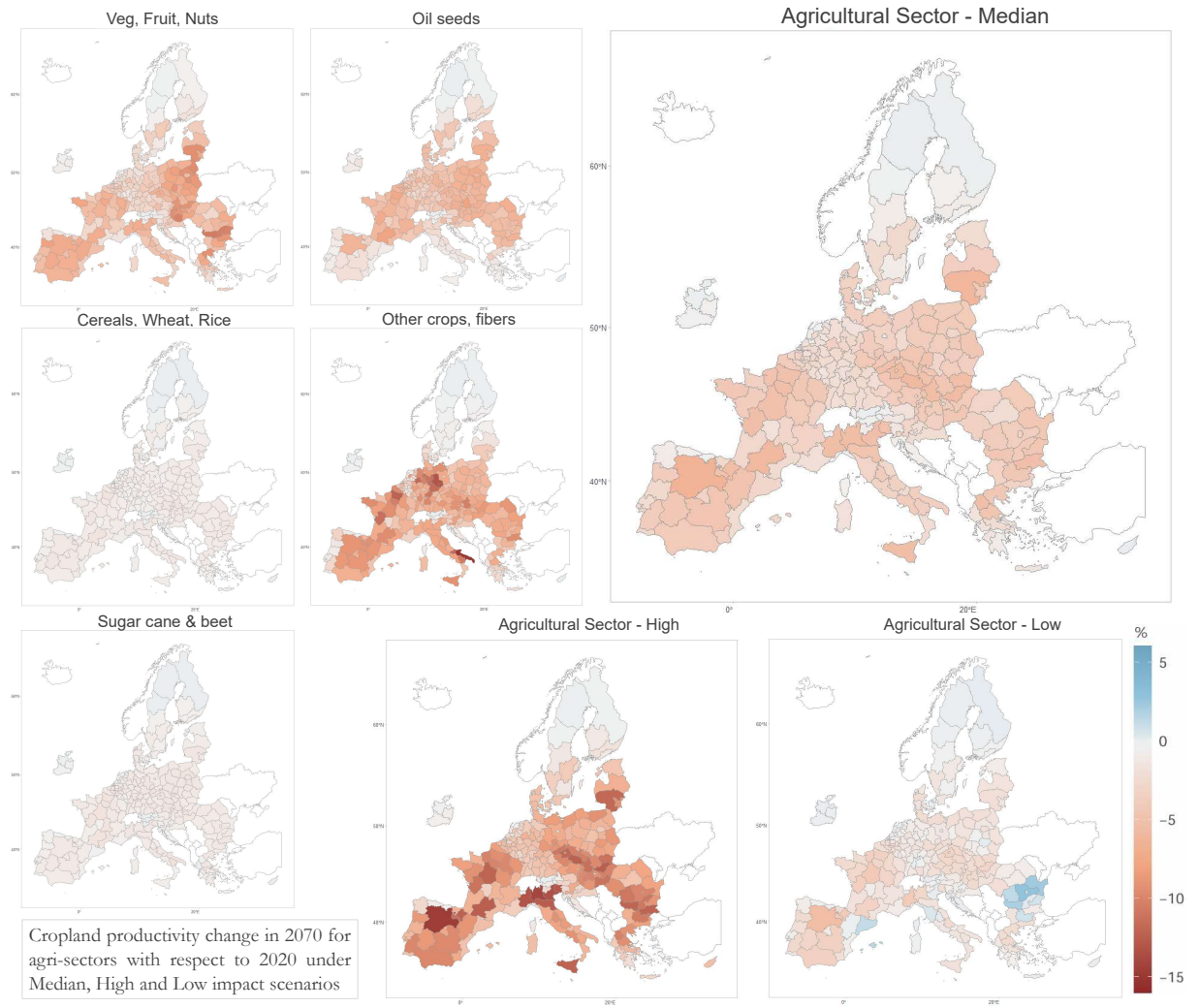
Out of the 129 analysed crops and crop categories cultivated in the EU, 103 were found to be at least partially dependent on pollination (dependency rates between 0.05 and 0.95), witnessing the widespread role of pollination services to support commercially viable yields. Within this group, 28% exhibits a high dependency (dependency rate $\geq$ 0.65), while 38% an "intermediate" one (dependency rate 0.50 - 0.25). Changes in pollination services then translate into crop-specific outcomes for cropland productivity.

When assessing cropland productivity losses on fixed 2020 agricultural areas, negative patterns prevail across all the analysed agri-sectors and scenarios (Figure 1, Table 1). Yields also replicate the pronounced heterogeneity observed in pollination projection and cropland composition, with average losses roughly doubling between lowest and highest forcing trajectories. Aggregate EU losses scale with radiative forcing, roughly doubling between the lowest and highest climate trajectories. In 2070, the average yield loss for the aggregated EU agricultural area moves from -2.4% under LF scenarios to -5.3% under HE scenarios, with the MOD group falling in between and a cross-scenario median of -3.9% (full range -2% to -8.5%). Regional responses follow the same gradient: under both MOD and HE, a few northern EU regions show limited or slightly positive changes, while southern and central regions bear the largest losses, peaking at -29% to -39% for specific crop sectors across many regions of Germany, Italy, Bulgaria and Belgium.

Crop-specific losses reflect the underlying pollination dependency and cultivation areas. Vegetables, Fruits and Nuts

are the most affected, with EU averages reaching -7.5% and maximum NUTS-3 losses of -25.5% in 2070, followed by Other Crops and Oilseeds (maximum -14.7%). Cereals, Wheat, Rice, Sugar cane and Beets show negligible impacts at all aggregation levels and across all scenario groups.
Localized yield gains are strongly scenario-dependent and fade as forcing increases from LF to HE. Under low forcing trajectories, 12.4% of NUTS-3 EU regions experience positive impacts in 2050 (0 to +2.88%) and only 7.7% in 2070 (0 to +5.22%), mostly in Finland, Germany, Poland, Romania, Spain and Bulgaria. In 2070 gains reach +5.22% for the whole Agricultural Sector, +6.3% for Oilseeds and +11.5% for Vegetables and Fruits in Bulgaria, with further gains in some regions of Romania, Germany and Italy. Positive cases become negligible under high-end emission scenarios, indicating that localized improvements are possible only under low emissions and are highly sensitive to the specific combination of socioeconomic and climate assumptions.

Under HE scenarios, the severity of these losses is masked by aggregation, with dispersion and tail losses growing systematically as spatial resolution increases. For the whole agricultural sector, losses greater than -10% in 2070 occur in 5 country-level cases (18.5%), 33 NUTS-2 regions and 155 NUTS-3 regions (13.5%); losses between -15% and -20% are entirely absent at country level and appear only at NUTS-3, with no region beyond -20%. The effect is far stronger for Vegetables, Fruits and Nuts, where 12 countries (44.4%) cross the -10% threshold against 371 NUTS-3 regions (32.2%), and 3 countries reach -15% to -20% against 129 NUTS-3 regions. The worst case, Bulgaria, deepens from -22% at country level to -32.5% at NUTS-3. Crucially, lower-tail percentiles deepen far more sharply than the standard deviation: the 1st-percentile Vegetables, Fruits and Nuts loss moves from -21.3% at NUTS-0 to -25.1% at NUTS-3 (an 18% deepening of the tail against only 1.5% growth in standard deviation), confirming that dispersion alone understates the aggregation effect. The masking is not confined to traditionally vulnerable southern regions: Germany pairs a NUTS-0 loss of -4.2% with a worst NUTS-3 value of -12.1%, nearly triple the national figure, evidence that hidden regional vulnerabilities arise even where national averages look modest.
This aggregation effect is negligible for low impacted crop sectors, but critical for Vegetables, Fruits and Nuts, Oilseeds and Other crops sectors, under high-impact scenarios, underscoring that high spatial resolution is indispensable for identifying local vulnerabilities from biodiversity loss that would otherwise be systematically masked by national averaging.



	Veg, Fruit, Nuts			Oil Seeds			Cereals, Wheat, Rice			Other crops, fibers			Sugar cane & beet			Agri sector		
	LOW	MED	HIGH	LOW	MED	HIGH	LOW	MED	HIGH	LOW	MED	HIGH	LOW	MED	HIGH	LOW	MED	HIGH
Austria	−2.1	−3.2	−6.8	−4.1	−6.2	−13.2	−0.8	−1.2	−2.6	−5	−7.4	−16	−0.9	−1.4	−2.9	−2.3	−3.5	−7.5
Belgium	−3	−4	−6.9	−4.6	−5.5	−9.8	−0.8	−1.1	−1.9	−2.7	−3.6	−6.4	−1.1	−1.4	−2.4	−2.3	−3	−5.2
Bulgaria	1.3	−9.2	−21.8	0.6	−5.9	−14.2	0.1	−1.2	−2.8	1.1	−7.6	−17.5	0.2	−1.1	−2.7	0.5	−4.5	−10.8
Cyprus	0	0	−6.1	0	0	−2	0	0	−2.1	0	0	−9.5	0	0	−2.8	0	0	−5.3
Czechia	−3.1	−5.7	−12.1	−3.2	−6	−12.7	−0.6	−1	−2.2	−4.2	−7.6	−16.3	−0.7	−1.4	−2.9	−2.8	−5.2	−11.1
Germany	−1.8	−2.9	−5.9	−2.8	−4.7	−9.8	−0.5	−0.8	−1.7	−5.1	−8	−16.6	−0.6	−1.2	−2.4	−1.8	−3	−6.1
Denmark	−1.3	−2.6	−4.1	−2	−5.3	−8.4	−0.5	−1.1	−1.7	−1.4	−2.6	−4.2	0	−0.6	−1	−1.4	−3.3	−5.2
Estonia	−1.6	−3.9	−7.9	−1.5	−3.7	−7.4	−0.2	−0.6	−1.1	−0.2	−0.6	−1.1	−0.2	−0.7	−1.3	−1	−2.4	−4.8
Greece	−3.3	−5.2	−11.6	−0.8	−1.4	−3.1	−0.6	−0.9	−1.9	−3.3	−5.4	−11.4	−0.4	−0.7	−1.6	−1.9	−3.1	−6.8
Spain	−5.1	−6.5	−13.9	−1.7	−2.2	−4.8	−0.8	−1	−2.2	−6.3	−8	−17.1	−0.9	−1	−2.4	−3.5	−4.5	−9.6
Finland	−0.4	−1.2	−2.5	−0.6	−1.9	−4	−0.1	−0.3	−0.6	−0.1	−0.3	−0.6	−0.2	−0.6	−1.1	−0.2	−0.5	−1
France	−3.4	−4.3	−9.5	−4.8	−6	−13.4	−0.8	−1.1	−2.4	−6	−7.9	−17.3	−1.1	−1.4	−2.9	−3.2	−4.1	−9
Croatia	−1.3	−3.7	−5.3	−1.4	−3.6	−5	−0.2	−0.7	−1	−1	−3.9	−5.4	−0.2	−0.6	−0.9	−0.7	−2.1	−2.9
Hungary	−4.8	−8.2	−20	−3.7	−6.3	−15.3	−0.7	−1.2	−2.9	−4.4	−7.7	−18.8	−0.8	−1.2	−2.9	−2.5	−4.2	−10.3
Ireland	−0.2	−0.7	−1.2	−0.3	−1.3	−2.4	0	−0.1	−0.3	−0.1	−0.2	−0.4	−0.1	−0.3	−0.5	−0.1	−0.3	−0.6
Italy	−2.9	−5.2	−13	−0.9	−1.6	−3.8	−0.6	−1	−2.6	−4.3	−7.5	−18.6	−0.7	−1.3	−3.4	−2.2	−3.9	−9.7
Lithuania	−3.6	−9.1	−17.8	−2.1	−6.8	−13.2	−0.4	−1.1	−2.2	−1.5	−3.9	−7.7	−0.5	−1.4	−2.7	−2.1	−6	−11.7
Luxembourg	−1	−2.4	−4.5	−2	−3.9	−7.2	−0.3	−0.7	−1.2	−3	−6.2	−11.6	−0.3	−0.9	−1.6	−0.9	−2.1	−3.9
Latvia	−2.6	−5.3	−10.2	−2.4	−5.4	−10.1	−0.4	−0.8	−1.4	−0.8	−1.6	−3.2	−0.5	−0.9	−1.7	−1.7	−3.7	−6.8
Malta	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Netherlands	−0.9	−2.2	−3.7	−1.8	−4.3	−7.4	−0.3	−0.7	−1.3	−1.4	−3.3	−5.6	−0.4	−1.1	−1.8	−0.8	−2	−3.3
Poland	−2.8	−7.7	−13.8	−2.5	−6.2	−11.4	−0.3	−1	−1.8	−2.1	−5.8	−10.5	−0.6	−1.4	−2.3	−1.5	−4	−7.2
Portugal	−5	−5.6	−14	−0.7	−0.8	−2	−0.6	−0.6	−1.7	−1.7	−2	−5.1	−0.4	−0.7	−1.7	−3	−3.4	−8.4
Romania	0.5	−5.6	−12.1	1.3	−6.2	−13.7	0.1	−1.2	−2.6	0.4	−7.7	−16.8	−0.3	−1.2	−2.6	0.5	−3.9	−8.5
Sweden	−1.3	−2.3	−3.5	−1.9	−3.4	−5.3	−0.4	−0.7	−1.1	−0.3	−0.6	−0.9	−0.5	−0.8	−1.3	−1.2	−2.2	−3.3
Slovenia	−1	−2.7	−6.2	−1.9	−4.9	−11.3	−0.4	−0.8	−1.8	−3	−6.9	−15.9	−0.5	−1.1	−2.5	−1.1	−2.7	−6.2
Slovakia	−4.4	−7.8	−16.1	−4.2	−7.5	−15.4	−0.7	−1.4	−2.9	−5.1	−8.8	−18.2	−0.6	−1.3	−2.6	−3	−5.4	−11
EU	−3.3	−5.4	−11.9	−1.8	−4.3	−9.3	−0.4	−1.1	−2.3	−3.8	−7	−15.2	−0.8	−1.3	−2.5	−2	−3.9	−8.5

Figure 1 | Cropland productivity changes in 2070 relative to 2020 for different crop categories and for the aggregate Agricultural sector, shown at the EU27 country level and for NUTS (0-2) regions. Maps display the median impact values for different crop-sectors, alongside the highest and lowest impacts across all scenarios considered for the Agricultural sector as a whole, illustrating the range of uncertainty driven by pollination and climate scenario assumptions. The table reports country-level median (50th percentile), and extreme values (low, high) for each crop category. Productivity losses are expressed as percentage change on fixed 2020 cropland areas, with no SSP-induced land use adjustments.

Macroeconomic propagation absorbs aggregate losses but concentrates regional vulnerability

The previous analysis demonstrates that aggregating biophysical impacts at the country or EU level systematically masks local extremes, particularly for high-value sectors such as Vegetables, Fruits, and Nuts. Embedding these productivity shocks in the CGE model reveals two opposing mechanisms: endogenous adjustment buffers economy-

wide losses, while regional and sectoral distress intensifies.

We estimate changes from the respective SSP baselines across 18 scenarios for the regional GDP, the value of aggregated Agricultural Sector output, and the value of agricultural sub-sectors output (Vegetables, Fruits and Nuts; Oilseeds; Cereals, Wheat & Rice; Sugar Cane & Beets; Other Crops). A comparison between EU-wide means and NUTS-level distributions reveals that the masking effect observed for physical yields is amplified for regional aggregates, while the degree of masking increases with higher levels of sectoral aggregation, becoming progressively stronger when moving from the aggregate macroeconomic variable GDP, to the sectoral aggregate Agricultural Sector, and ultimately to individual agri-sector outputs, where extremely pronounced regional differences emerge (Figure 2; Table 2).

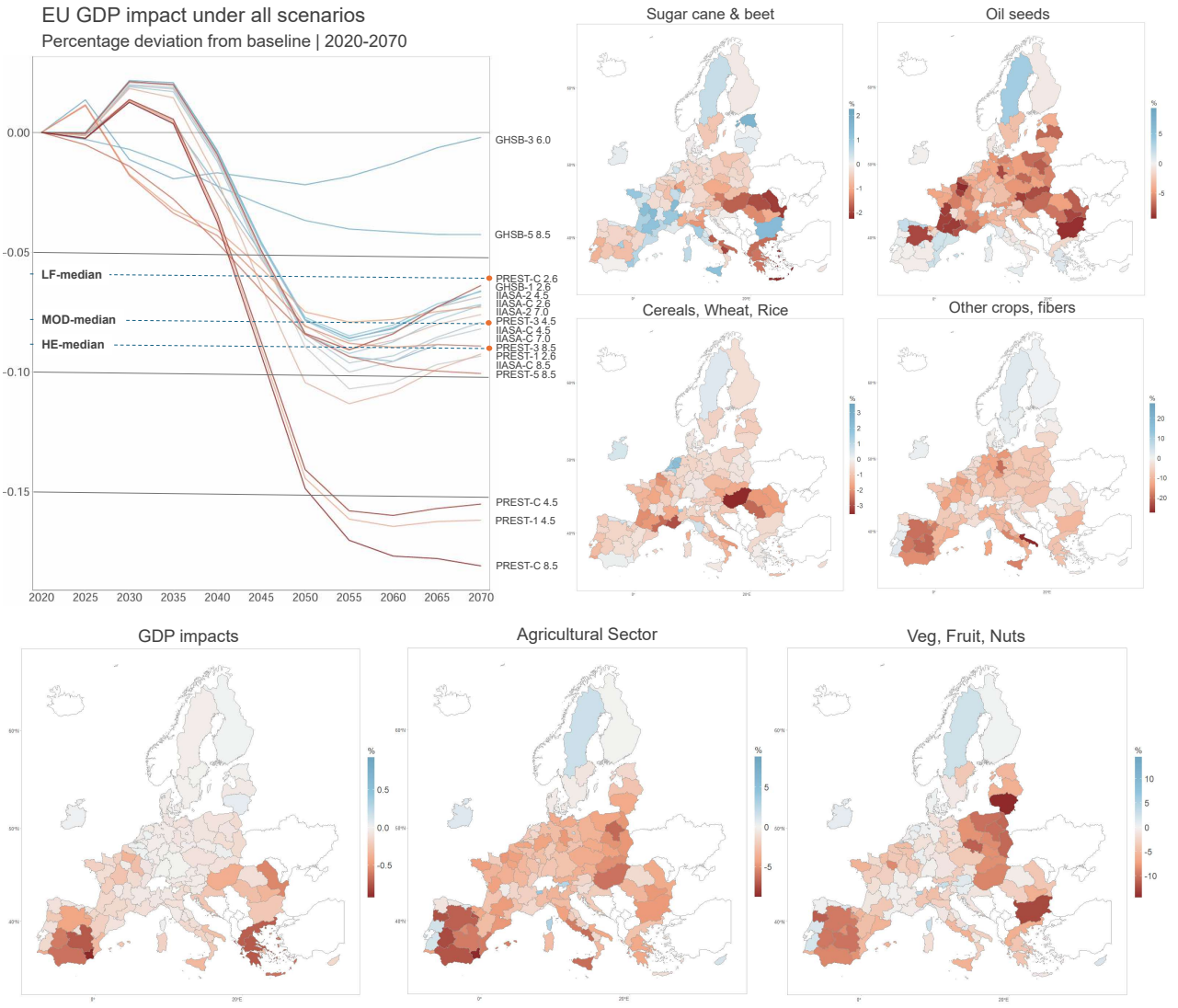


Figure 2 | Economic impacts in 2070. Maps show the median impact values (50th percentile) for individual crop sectors, the aggregated agricultural sector, and regional GDP across 122 NUTS 0–2 regions under Moderate Forcing scenarios. The line graph shows the aggregated EU GDP impact, expressed as percentage deviation from the respective baselines, for all 18 scenarios considered, as well as the median values for Low Forcing (LF), Moderate Forcing (MOD), and High-end Emissions (HE) scenarios.

By 2050, European GDP losses range between approximately -0.15% and -0.02%, even under the most severe climate scenarios, reaching -0.18% by 2070, with an average loss across all scenarios of -0.09% in both years. Although these figures may appear small, their absolute magnitude is not negligible, corresponding to a net GDP loss up to €37.85 billion (-0.15%) in 2050 and €57.7 billion (-0.18%) in 2070 for high-end scenarios, expressed in 2017 values with respect to SSP2 baseline GDP level. Low-forcing scenarios display European aggregate losses between -0.10% to

-0.08% in 2050 and -0.09% to -0.06% in 2070, with an average loss across all scenarios of -0.09% and -0.07% , thus indicating a decreasing magnitude of impacts for low climate change scenarios. These figures corresponding to up to €26.6 billion (-0.10%) in 2050 and €29.5 billion (-0.09%) in 2070, expressed in 2017 values with respect to SSP1 baseline GDP level. This apparent resilience reflects sectoral reallocation and trade adjustment, together with the limited weight of agriculture in EU GDP (1.6% in the base year), which dampens the macroeconomic visibility of even substantial agricultural shocks. The aggregate, however, conceals sharp regional divergence: under high-end forcing, regional GDP impacts range from -1.61% to +0.17% by 2070, and one quarter of EU regions face losses exceeding -0.19%, more than double the EU average.

The masking strengthens systematically with sectoral resolution. For the aggregate Agricultural sector, EU-wide losses of -1.5% to -6.0% (cross-scenario average -3.2% to -3.5%) conceal a regional distribution spanning -12.78% to +7.96% in 2070, an amplification factor (NUTS over EU average) of 2.0× to 3.6×.

For Vegetables, Fruits and Nuts the concealment is extreme: EU-wide losses of -1.9% to -7.0% mask regional losses reaching -21.35%, an amplification of 3.4× to 5.6× and an absolute gap exceeding 14 percentage points between the EU value and the worst-affected region. Under high-end scenarios this divergence becomes a polarisation that aggregate indicators cannot show. For the Agricultural Sector, between 2050 and 2070 the EU-wide mean and median improve slightly, mostly driven by gains in northern and alpine regions where warming extends growing seasons and enhances pollinator habitat suitability, while the lower tail deepens and the share of regions losing more than 10% of agricultural output nearly triples (0.7% to 1.9%). For Vegetables, Fruits and Nuts, more than one third of regions (34.7%) record gains by 2070 even as the worst-affected deteriorate to -21.35%, with 26.3% and 7.6% of regions losing more than 5% and 10% respectively. This "internal divergence", with some regions benefiting while others collapse, represents a fundamental redistribution of climate–biodiversity risk that is statistically invisible in EU-level means.

The remaining sub-sectors mapped in Figure 2 mirror the cropland-productivity ordering of Figure 1: Oilseeds and Other Crops& fibers show intermediate to very high economic deviations, while Cereals, Wheat, Rice and Sugar Cane& Beet show low to negligible negative impacts. Interestingly, the economic gain deriving from macroeconomic effects is evident even under median forcing scenarios, with many regions experiencing both sectoral impacts higher than +5/+10%, boosted by the relative smaller impact (sometimes opposite sign impact) with respect to other regions.

The emerging systematic masking results as a structural property of how spatial aggregation interacts with the joint distribution of pollination loss, crop dependency, and economic structure. Across all 18 scenarios, the amplification factor remains consistently in the 3.4-5.6× range for vegetables, fruits and nuts, substantially exceeding the 2.0-3.6× factor observed for the aggregate agricultural sector. The interquartile range of regional impacts significantly expands from GDP estimates to sectoral cropland productivity, indicating that macroeconomic adjustment mechanisms compress the visible spread of biophysical outcomes and the underlying vulnerability.

Discussion

This study delivers the first climate change-driven, multi-model and multi-scenario assessment of the macroeconomic consequences of pollinator decline at sub-national resolution. Our findings complement, and contextualise, the two established strands of pollinator economics. Stylized "catastrophic collapse" frameworks, imposing binary productivity shocks, have established the first-order economic relevance of pollinators [31][6][30]. A second stream combines static pollination-sufficiency proxies with land-use scenarios [113][52], adding endogenous land-use–economy feedback but not biodiversity-climate response. Our framework is the first to integrate both dimensions: time-evolving, climate-driven pollinator ranges, with sub-national heterogeneity in service supply and economic dependence.

In 2070, average yield losses for the aggregated EU agricultural area peak to -5.3% under high-end climate change scenarios, with a cross-scenario median of -3.9% (-2% to -8.5% range), resulting in up to €58 billion loss per year.

These results are consistent with recent literature, which estimates that catastrophic wild-pollinator collapse would cause a -7.8% (-5.2% to -10.3% range) decline in European crop yields [30]. This alignment supports the plausibility of our climate-driven trajectories as a gradual long-term realisation of the same underlying risk.

Our results reveal a structural feature of pollination decline: the propagation of biodiversity loss through the economy generates a systematic spatial masking that intensifies at every level of aggregation, so that for any given EU-wide average the most vulnerable regions experience impacts two to five times greater, losses entirely concealed in national aggregates. Three nested mechanisms produce the observed masking.

First, the composition of each region's cropland plays a pivotal role in determining the resulting sectoral shocks on agriculture. The relative share of each crop in the composition of the total output, shapes the aggregate sectoral impact according to its specific degree of dependence on animal pollination and the pollination service change in the cultivated area. This means that those regions severely affected by absolute losses in pollination service may nonetheless face comparatively smaller agricultural impacts if their cropland composition is dominated by crops that are less reliant on animal pollination, and vice versa. Furthermore, regions that register some of the largest losses at finer spatial scales (NUTS 2-3) may exhibit more moderate impacts once these effects are aggregated at broader regional or national levels as biophysical and economic exposure decouple spatially, so that negative impacts in some areas may be partially offset by positive or negligible effects in others.

Second, endogenous economic adjustment, such trade, substitution, and the reallocation of land and capital, compresses the visible spread of shocks at the aggregate level while concentrating residual vulnerability in the regions least able to adapt. The translation of severe regional biophysical impacts on cropland productivity into macroeconomic outcomes shows how endogenous economic adjustments simultaneously attenuate aggregate losses and concentrate vulnerabilities in already disadvantaged regions, rendering these risks nearly invisible in national-scale assessments.

Third, statistical aggregation mechanically conceals tail losses, an effect that grows with the size of the aggregation unit. Together these effects explain why EU GDP appears only moderately affected (average annual loss across scenarios of -0.09% in 2070) while under high-end forcing more than a quarter of regions (26.3%) experience economic losses exceeding 5% of sectoral output, and the worst affected 5% of regions lose at least 12%, for the Vegetables, Fruits and Nuts sector by 2070 (Table 2).

Because the crops that carry these concealed losses are disproportionately fruits, vegetables, nuts and other pollinator-dependent crops, the masking is not merely a statistical artefact but a redistribution of food-system risk toward the agricultural communities whose livelihoods most depend on these products, crops that are typically higher in value-added and cultural significance and that often anchor high-value or geographically protected production (PDO/PGI). Geographically, this burden falls disproportionately on Mediterranean and eastern European regions, which combine the most severe biophysical impacts (average pollination losses up to -30% in some countries) with a cropland mix highly dependent on pollination and the least economic capacity to absorb agricultural shocks. Under high-emission scenarios, parts of southern Italy, Greece, Bulgaria and the Iberian Peninsula record sectoral losses exceeding 43% for some crop categories, while northern regions remain stable or marginally positive. The concealment therefore falls hardest precisely where adaptive capacity is lowest, so that the economic burden of biodiversity loss reinforces, rather than offsets, existing structural inequalities. The emerging aggregation bias is not specific to Europe: any country-level assessment of pollination loss risks understating the exposure of precisely those agricultural communities least able to absorb productivity shocks. These dynamics constitute a sustainability trade-off that aggregate indicators are structurally unable to reveal. On one side, endogenous economic adjustment improves aggregate efficiency precisely by reallocating activity away from the worst-affected regions, so that macroeconomic resilience at the EU scale is effectively purchased at the price of a deeper concentration of loss in areas that are already structurally disadvantaged, this may implying an efficiency-equity tension of direct relevance to cohesion and rural-development policy. On the other, under high-end climate change, the agricultural output does not simply decline but polarises: northern and alpine regions gain as warming extends growing seasons and enhances habitat suitability, while southern and eastern regions deteriorate, producing clear winners and losers

within the same climatic transition. A stable or even improving EU average can therefore coexist with a widening territorial inequality in access to pollinator-dependent production.

The implications for long-term socioeconomic projections and policy information are unambiguous. Standard integrated assessment models, typically resolved at the macro-region level, are likely to ignore the spatial and sector-specific concentration of biodiversity impacts under climate change across all ecosystem services characterised by geographic heterogeneity in both service provision and economic dependence. Spatial resolution is therefore not a technical refinement but a determinant of whether critical vulnerabilities are visible in policy-relevant assessments at all. The consequence for decision-making is direct: assessments that aggregate away the tail do not merely misstate the magnitude of the climate damage, they misdirect the response, because resources allocated on the basis of national averages systematically bypass the regions where pollination deficits and economic exposure actually coincide. This systematic invisibility of regional risk is not a feature of pollination alone; it reflects a general property of how spatial aggregation interacts with biodiversity-driven productivity shocks. This distributional pattern mirrors, at sub-national scale, the cross-country inequality documented for natural capital loss under climate change [5]. The same reasoning extends to any ecosystem service whose supply is geographically concentrated, such as soil fertility, freshwater regulation, flood protection and wild-capture fisheries: wherever provision is spatially uneven and economic dependence locally concentrated, national-scale accounting will conceal precisely the communities most likely to be left behind as the service degrades. For food-system sustainability this is a general warning rather than a pollination-specific one, showing how ecosystem-loss risks are borne unevenly across regions and communities. For pollinator policy specifically, the concentration of damages in structurally disadvantaged regions argues for spatially targeted restoration and conservation under the Nature Restoration Regulation [25][26] and the Common Agricultural Policy (CAP) [12], directed to the areas where pollination deficits and economic exposure coincide. Prioritising this coincidence would let restoration and agri-environment investment double as a territorial-equity instrument, aligning biodiversity recovery with the cohesion objectives that national-scale accounting renders invisible.

On top of that, several considerations suggest that also the aggregate figures, moderate as they appear, should be read as a conservative lower bound on the true welfare cost. Because climate change enters our framework only through pollinator habitat suitability, the results capture the pollination channel in isolation: direct climate effects on yields are excluded, and the spatial concentration of damages we document should be interpreted as the pollination-specific component of a larger, partly co-located climate burden. Second, our framework propagates pollination loss only through the commercial yield of pollinator-dependent crops, and therefore omits the cascading effects of pollinator decline on the broader ecosystems in which agriculture is embedded. Pollination is not only an agricultural input but a keystone regulating service: the large majority of wild flowering plant species in the EU depend on animal pollination [72][50], so that sustained pollinator loss propagates into the reproduction and persistence of wild flora, the food webs they support and the configurational landscape heterogeneity on which other taxa depend [44][47], deepening the regional damages reported here. The macroeconomic cost we estimate is thus best understood as the lower-bound of a wider, largely non-market, loss. Extending the assessment to non-market dimensions, such as dietary quality, landscape and cultural value, and the resilience of the broader agroecosystem, is the natural next step, and would in all likelihood sharpen rather than soften the distributional conclusions drawn here.

Taken together, our results show that the macroeconomic risk of pollinator decline under climate change is real but profoundly unequal, and that its most severe manifestations are precisely those that national-scale economics renders invisible. Capturing them requires resolving biodiversity–economy interactions at the scale at which they actually occur.

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Contributions

The methodology and investigation was carried out by Campoleoni Mansi G. A.; Key contribution to the macroeconomic modelling was provided by Standardi G.; Coordination of funding, internal revision and project supervision was carried out by Bosello F.

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Extended material and data analysis

All data, including extended materials and appendices, are available on GitHub:
https://github.com/gabrielemansi/Macroeconomic-impacts-of-pollination-loss-in-the-EU

Projected yield changes are provided for 129 crops and for 6 agri-sectors in the EU at NUTS (0-3) level.
Projected economic losses are provided for 122 EU sub-national regions down to NUTS-2 level.

Appendix 1 contains Extended Framework, Methods, Materials and Data Processing, including: Baseline pollination scenarios; Climate change scenarios; Aggregation of pollination shocks to GTAP sectors.
Appendix 2 provides the background and scientific foundation of pollination loss dynamics supporting the Baseline and Impact scenario and contains the background literature of pollination current status and projected trends, including: Current Status of European Pollinators; Climate Change Impacts on Pollinators; Evidence from Species Distribution Models; Pressures on Pollinators and Conservation Responses; Agro-Ecosystems status and trend.

Research context and framework

Knowledge of how pollinators provide pollination services to crops has advanced (e.g. [96] [82], [57]), showing how this service is strongly linked to species diversity [112][34] and pollinators abundance. While some pollinator species are particularly common crop flower visitors overall, different pollinator communities are important for the pollination of different crops [33][35]. The economic value of pollination for agriculture in the EU is estimated at EUR 5–15 billion annually[23]. In 2019 pollination contributed €4.977 billion into the value of agricultural production in the EU, corresponding to €2 810 per km2, while pollinator-dependent crops are expanding at 5% per decade [24][25][63]. Over 78% of wild flowering plants in the EU rely on insect pollination [72], including many medicinal plants, with recent estimates suggesting that up to 90% of flowering plant species depend on animal pollination [50].

Without pollinators, these plants would disappear resulting in the cascading loss of biodiversity and ecosystem services, such as biological pest control provided by some hoverfly larvae, pest regulation and support of natural enemies in agriculture [44]. The number of threatened European butterfly species has increased by 76% over the last decade, with 15% of butterflies (65 out of 442 assessed species) now at extinction risk and more than 20% of bumblebee species classified as threatened[110]; nearly 40% of hoverfly species, 20% of butterflies, and 9% of bees are threatened with extinction [23]. There is evidence of current pollination deficits in crops associated with low abundance of pollinators; JRC [106] estimated 50% of pollinator-demanding crops in the EU are in pollinator-deficient areas. In the absence of restoration, the pollination gap is expected to widen, as pollination potential gradually declines while demand for pollination likely increases with the expansion of pollination-dependent crops [63].

Habitat degradation and climate change are globally acting as pivotal drivers of wildlife collapse, with mounting evidence that this erosion of biodiversity will accelerate in the following decades [37][48]. Habitat for wild pollinators, as natural and semi-natural grasslands [58][47][80], have been drastically reduced due to agricultural intensification and leads to loss of natural and semi natural habitats rich in wildflowers (which pollinators use for foraging, nesting and hibernating) [8][79][39][39][122]. Best estimates assess that in 2030, 27% of European agro-ecosystems will require management and restoration practice due habitat degradation, while the ecosystem loss is estimated at 1.5% per year. Projections of pollinators communities, as well as common farmland bird and grassland butterfly indicators, suggest that these groups will continue to decline into the future, likely driven by agricultural practices and land use [74].

Moreover, although climate change impacts to date are not likely to be among the greatest[25], they are expected to increase [49], together with indirect drivers, such as increased irrigation and production of bioenergy.

Ecological assessments project pollinator range shifts under climate change and land use change with increasing sophistication, leveraging species distribution models (SDMs) calibrated on observed biogeographic data. Ghisbain et al, 2024 [37], identifies future large-scale range contractions and species extirpations under all future climate and land use change scenarios considered, showing that temperature and precipitation have strong negative correlations with ecological suitability difference (ESD), and suggesting that warming and altered rainfall patterns are major contributors to habitat loss, especially for cold-adapted species. Around 38-76% of studied European bumblebee species currently classified as 'Least Concern' are projected to undergo losses of at least 30% of ecologically suitable territory by 2061-2080 compared to 2000-2014. Prestele at al., 2021 [85], assess the future species distribution under three RCP-SSP scenarios. They find that direct climate impacts, although variable across species, dominate responses for most species, especially under high-end climate change scenarios (up to 99% range loss). Land use may amplify, attenuate, or offset changes to suitable habitat extent expected from climate impact depending on species and scenario, especially in low-end climate change scenarios RCP2.6, indicating substantial potential for targeted conservation management. Rahimi et al., 2024 [88], 2025 [89], suggest that on a global scale approximately 65% of bees are likely to witness a decrease in their distribution, with climate change's impact on bees projected to be more severe in Europe (average reduction of 56%) under SSP585. Under the most pessimistic climate change scenario (SSP585), they estimate that Europe is expected to see a 4.7% decrease in area suitability for pollination-dependent crops by 2070. Climate change's anticipated effects on bee distributions could potentially disrupt existing pollinator-plant networks, posing ecological challenges that emphasize the importance of pollinator diversity, synchrony between plants and bees, and the necessity for focused conservation efforts. Kazenel et al., 2024 [55], document abundance patterns for a hyper-diverse bee assemblage including many bee species are ecologically and evolutionarily different from bumblebees, linking bee declines with heat and desiccation tolerances and using climate sensitivity models to project pollinators communities into the future. Models forecasted declines for 46% of species and predicted more homogeneous communities dominated by drought-tolerant taxa, even while total bee abundance may remain unchanged. Such community reordering could reduce pollination services, because diverse bee assemblages typically maximize pollination for plant communities.

While these studies produce detailed, climate-driven projections of habitat suitability changes for specific pollinator taxa, they stop short of translating ecological outputs into economy-wide consequences, leaving the macroeconomic implications of climate-biodiversity interactions unquantified. Accordingly, most economic models fail to account for the impact of biodiversity loss - particularly pollinator decline - on agricultural output, reflecting a broader gap in the representation of ecosystems and biodiversity that leads to an underestimation of their importance in future projections. Moreover, the overall impact of climate change on pollination-dependent crops, such as fruits and vegetables, is commonly not accounted for in these models. This is especially concerning given the high economic, cultural and dietary importance of such crops in the EU.

Economic assessments of pollinator decline to date have followed two distinct methodological paths, none of which fully captures climate-driven risk at high spatial resolution.
Stylized 'catastrophic loss' frameworks impose exogenous productivity shocks to the economy [31][6][30], abstracting from the spatial heterogeneity and the climate-driven dynamics of pollinator distributions. They rely on partial or general-equilibrium models to simulate economic impacts of an hypothetical collapse of wild pollinators. Feuerbacher et al., 2025 estimates crop yield reductions in Europe by 2030 of approximately 8% and global welfare losses of €34.4 billion. While these frameworks deliver important insights into the economic relevance of pollinators, they share three key limitations: (i) they impose binary or stylized loss scenarios rather than representing the climate-driven dynamics that progressively reshape pollinator ranges over time; (ii) they operate at relatively coarse spatial resolution (typically national or NUTS-1 level); and (iii) they abstract from the spatial heterogeneity of pollinator habitats and crop-specific dependencies within their aggregation units. A second stream combines static pollination-sufficiency proxies with land-use scenarios derived from integrated assessment models [113][52]. While these approaches incorporate spatial detail and consider future land allocation, they rely on aggregated indicators of pollination service rather than dynamic climate change response, limiting their capacity to represent the interactions between climate forcing, pollinator habitat suitability, and agricultural productivity.
As a result, no integrated framework has yet propagated multi-model, climate-driven pollinator projections through a spatially explicit macroeconomic model across multiple emission and socioeconomic scenarios at sub-national resolution. Our assessment aims to fill these gaps by quantifying the macroeconomic effects of expected productivity loss of the EU agricultural sector due to pollinators' decline under long-term projections of climate change. Accordingly, this study develops and applies such a framework for the EU27, delivering the first long-term evaluation of pollination impacts based on a multi-model, multi-scenario SDM projection.
Building on ecosystem accounting standards, we quantify changes in pollination ecosystem services across the European Union using observed long-term trends in wild pollinator populations and ecosystems degradation proxied by European biodiversity indicators, together with climate-driven projections derived from an ensemble of state-of-the-art species distribution models (SDMs) covering up to 153 wild pollinator species across major taxonomic groups. The resulting spatially explicit ecological projections are matched with high-resolution crop cultivation areas (0.05°) and crop-specific pollination dependency ratios for 129 European crops to estimate high-resolution agricultural productivity impacts under multiple climate scenarios (RCP2.6, 4.5, 6.0, 7.0, and 8.5) and socioeconomic pathways (SSP1, 2, 3, and 5) up to 2070. These biophysical impacts are then translated into second-order macroeconomic shocks using a regionalized version of the ICES computable general equilibrium (CGE) model, enabling the assessment of economy-wide effects down to NUTS-2 regional resolution.

Regional and sectoral heterogeneity analysis of macroeconomic results
Changes in pollination services translate into crop-specific outcomes for cropland productivity. Projected changes on fixed 2020 agricultural areas replicate the pronounced heterogeneity observed in pollination projection and cropland composition, with average losses roughly doubling between lowest and highest forcing trajectories.

Table 1: Pollination-driven cropland productivity changes relative to 2020 EU aggregate range and NUTS-3 distribution in 2050 and 2070

Var	Group	Year	EU range		NUTS-3 distribution			
			min	max	min	max	mean	median
agri	LF	2050	-2.44	-1.83	-9.38	+2.88	-2.04	-1.88
agri	LF	2070	-2.55	-1.83	-9.23	+5.22	-2.10	-1.94
agri	MOD	2050	-4.45	-2.01	-16.43	+0.20	-3.27	-2.74
agri	MOD	2070	-4.66	-2.09	-15.87	+0.60	-3.45	-2.98
agri	HE	2050	-4.91	-1.97	-16.34	+0.36	-3.37	-2.82
agri	HE	2070	-5.55	-1.96	-17.91	+1.92	-3.77	-3.16
v_f	LF	2050	-3.47	-2.65	-20.85	+6.16	-2.91	-2.36
v_f	LF	2070	-3.60	-2.56	-19.87	+11.51	-2.95	-2.44
v_f	MOD	2050	-6.31	-2.85	-28.02	+0.90	-4.62	-3.56
v_f	MOD	2070	-6.57	-2.97	-27.77	+0.65	-4.86	-3.87
v_f	HE	2050	-6.91	-2.81	-31.03	+1.04	-4.76	-3.66
v_f	HE	2070	-7.82	-2.81	-32.35	+2.49	-5.32	-4.09
osd	LF	2050	-3.28	-2.23	-11.84	+5.86	-2.67	-2.51
osd	LF	2070	-3.42	-2.39	-12.92	+6.32	-2.79	-2.62
osd	MOD	2050	-5.82	-2.68	-16.84	+0.15	-4.32	-3.86
osd	MOD	2070	-6.09	-2.79	-16.38	+0.42	-4.57	-4.14
osd	HE	2050	-6.41	-2.62	-17.62	+0.11	-4.46	-3.93
osd	HE	2070	-7.28	-2.60	-18.06	+1.19	-5.01	-4.32
ocr	LF	2050	-5.00	-3.32	-18.42	+12.64	-4.01	-3.74
ocr	LF	2070	-5.20	-3.54	-23.96	+8.06	-4.21	-3.95
ocr	MOD	2050	-9.07	-4.10	-31.47	+0.83	-6.68	-5.61
ocr	MOD	2070	-9.57	-4.27	-34.77	+1.14	-7.12	-6.02
ocr	HE	2050	-10.11	-3.98	-35.58	+1.22	-6.93	-5.76
ocr	HE	2070	-11.34	-3.89	-39.06	+2.74	-7.70	-6.28

Notes. Percentage changes in cropland productivity relative to 2020 on fixed 2020 agricultural areas. Scenario groups: low-forcing scenarios (LF) (GHSB-1 2.6, IIASA-2 2.6, IIASA-CLIM 2.6, PREST-1 2.6 and PREST-CLIM 2.6), intermediate scenarios (MOD) (GHSB-3 6.0, IIASA-2 4.5, IIASA-CLIM 4.5, PREST-1 4.5, PREST-3 4.5 and PREST-CLIM 4.5); high-end emissions scenarios (HE) (GHSB-5 8.5, IIASA-2 7.0, IIASA-CLIM 7.0, IIASA-CLIM 8.5, PREST-3 8.5, PREST-5 8.5, PREST-CLIM 8.5). **EU range**: minimum and maximum, across the scenarios of each group, of the EU-level value (unweighted mean over 1151 NUTS-3 regions). **NUTS-3 distribution**: minimum, maximum, mean and median across all NUTS-3 regions pooled over the group's scenarios. `agri` = whole agricultural sector; `v_f` = Vegetables, Fruits and Nuts; `osd` = Oilseeds; `ocr` = Other Crops. Cereals/Wheat/Rice and Sugar cane/Beets omitted as negligibly affected.

Looking at European GDP losses across all 18 scenarios considered, the divergence between extreme values and central estimates remains limited, indicating low dispersion among scenario projections. In both 2050 and 2070, the mean and median values approximate -0.09, while the standard deviation exhibits a modest increase from 0.032 to 0.043 over time. This pattern suggests that at higher levels of spatial aggregation, results tend to become more homogeneous both within and across scenarios, with scenario uncertainty correspondingly becoming less pronounced.

At the EU level, therefore, the European economic system appears relatively resilient: aggregate losses remain limited and suggest a capacity of the macroeconomic system to absorb part of the productivity shocks through sectoral reallocation and trade adjustments, also considering the limited weight of the value of agricultural production to the EU GDP (approximately 1.6% in the 2017 base year), which generally reduces the macroeconomic visibility of even substantial shocks occurring within agriculture.

Increasing the analytical granularity to NUTS 1-2 regions, the dispersion of outcomes is much wider than the EU-level aggregate suggests. Even under relatively moderate scenarios, regional impacts deviate substantially from

the EU mean. Between 2050 and 2070, the distribution of regional GDP impacts shifts downward in its lower tail while becoming more dispersed.

Under low-forcing scenarios (GHSB-1 2.6, IIASA-2 2.6, IIASA-CLIM 2.6, PREST-1 2.6 and PREST-CLIM 2.6), regional GDP impacts range from -0.79% to +0.26% in 2050 and from -1.07% to +0.42% in 2070, with pronounced spatial heterogeneity and negative tails. By 2070 the distribution becomes significantly more polarized: the median is essentially unchanged (from -0.10% to -0.08%), yet regional extremes grow substantially in both directions. Dispersion increases markedly: the 5th percentile worsens from -0.31% to -0.47%, the 10th percentile from -0.23% to -0.31%, and the bottom 1% of regions experiences a deterioration from -0.48% to -0.66%. This means that 10% of EU regions face GDP losses exceeding 0.31% in 2070, while one quarter of regions records losses of at least 0.15% in both years (P25 unchanged at -0.15%). Even 75th percentile turns slightly negative (-0.01% compared to +0.02% in 2050), indicating that more regions are experiencing losses and the small share of regions with positive impacts shrinks. The standard deviation rises from 0.112 to 0.161 (+44%), and skewness deepens from -1.34 to -1.89. The widening gap between the mean (which worsens only modestly) and the lower-tail percentiles (which deteriorate substantially) highlights increasing left-skewness: while a few regions still display modest gains, most suffer progressively worse impacts. Overall, climate damages on regional GDP become more severe and more unequally distributed over time, whereby EU-level aggregates conceal the depth of increasing impacts borne by the most vulnerable NUTS regions.

High-end emission scenarios (GHSB-5 8.5, IIASA-2 7.0, IIASA-CLIM 7.0, IIASA-CLIM 8.5, PREST-3 8.5, PREST-5 8.5, PREST-CLIM 8.5) show an even clearer worsening from 2050 to 2070, with regional dispersions ranging from -0.99% to +0.20% in 2050 and from -1.61% to +0.17% in 2070. The distribution remains strongly left-skewed in both periods, with positive values becoming rarer and smaller over time. The interquartile range widens from 0.10 to 0.15, indicating a broader structural spread of impacts. The negative tail lengthens considerably: the 5th percentile drops from -0.41% to -0.61%, the 1st percentile from -0.64% to -1.00%, while the positive tail compresses (95th percentile from +0.01% to +0.004%). The 25th percentile worsens from -0.15% to -0.19%, meaning that one quarter of EU regions records losses of at least 0.15% in 2050 and 0.19% in 2070. The 75th percentiles remain narrowly negative in both years (-0.05% and -0.04%), but the share of regions with positive impacts contracts (from 6.2% to 5.0%) and the number of regions clustering around zero grows. Mean and median diverge increasingly (median stable at -0.09%, mean worsening from -0.12% to -0.16%), reflecting a small group of regions suffering disproportionately large damages while most see persistent but moderate declines. The standard deviation grows by 58% (from 0.134 to 0.212) and the variance more than doubles (from 0.018 to 0.045), while skewness deepens from -2.28 to -2.88 and kurtosis from 7.8 to 10.8, indicating that the distribution becomes both more dispersed and more heavy-tailed. Crucially, regional GDP losses exceeding 1% are entirely absent in 2050, but appear in 1.1% of regions in 2070. The comparison confirms a clear deterioration of regional economic impacts over time, while mean and median remaining stable (near -0.10%) show that central statistics and averaged data understates the severity of the change, which materializes almost entirely in the left tail.

Increasing the sectoral detail of the analysis allows to detect significant losses even at the EU aggregate level. Economic impacts on the aggregate Agricultural Sector reveal a sectoral contraction between -5.17% to -1.78% in 2050 and -5.95% to -1.54% in 2070, with average losses across all scenarios of -3.22% and -3.47%, respectively. As for the case of GDP, the distribution between scenario is overall modest with output spread generally consistent with scenario family and radiative forcing levels. As with GDP, the variation across scenarios remains relatively modest, with the distribution of impacts broadly consistent with scenario families and radiative forcing levels.

When the spatial granularity is increased to NUTS 1-2 regions, the dispersion of agricultural sector outcomes is substantially wider than for the EU-level aggregate, and considerably larger in absolute terms than that observed for GDP. Even under moderate forcing scenarios, regional impacts deviate dramatically from the EU mean, confirming that agricultural production is more spatially heterogeneous in its climate sensitivity than the broader economy.

Under low-forcing scenarios, regional agricultural sector impacts range from -11.39% to +6.62% in 2050 and from

-11.83% to +5.31% in 2070, with pronounced spatial heterogeneity and negative tails. In 2050, 83% of EU NUTS regions record negative impacts, with a mean of -2% and a median of -2.13%. By 2070, both indicators worsen (mean -2.2%, median -2.28%), and 70% of regions deteriorate relative to 2050. The standard deviation rises from 1.95 to 2.07 (+6%) and the IQR from 2.26 to 2.42. The negative tail deepens: the 5th percentile drops from -4.68% to -5.58%, the 10th from -4.08% to -4.39%, and the 1st percentile from -7.40% to -8.41%. Regions with losses exceeding 5% of agricultural output grow from 4.4% to 6.2% between the two years, while the share recording positive impacts contracts from 16.6% to 15.2%.

Under intermediate forcing scenarios (GHSB-3 6.0, IIASA-2 4.5, IIASA-CLIM 4.5, PREST-1 4.5, PREST-3 4.5 and PREST-CLIM 4.5), extreme values exibit modest differences with low-impact, with regional distributions ranging from -10.93% to +5.63% in 2050 and -12.67% to +6.77% in 2070. The mean reaches -2.90% and the median -2.76%, while the 25th percentile stands at -4.37% in 2050, worsening to -4.68% by 2070. The standard deviation grows from 2.61 to 3.00, and the IQR expands from 3.10 to 3.80, indicating a broad structural divergence of regional trajectories. Critically, the 1st percentile deteriorates from -9.55% to -10.41%, and the share of NUTS with losses exceeding 5% rises from 18.7% to 21.7%, while regions with losses exceeding 10% more than double (from 0.7% to 1.6%), a damage class nearly absent under low-forcing conditions.

High-end emission scenarios (GHSB-5 8.5, IIASA-2 7.0, IIASA-CLIM 7.0, IIASA-CLIM 8.5, PREST-3 8.5, PREST-5 8.5 and PREST-CLIM 8.5) show the greatest structural divergence between the EU aggregate and the regional distribution. In 2050, the pooled range runs from -11.26% to +6.13%, with a mean of -2.63%, a median of -2.46%, and 85% of NUTS regions in negative territory. By 2070, the range widens from -12.78% to +7.96%, but the temporal evolution is qualitatively different from that observed under low-forcing and intermediate scenarios: the mean and median both improve slightly (+0.28 pp and +0.30 pp respectively), driven by a marked positive reorientation in northern and alpine NUTS under higher-warming conditions, while simultaneously the standard deviation grows from 2.64 to 3.13 and the IQR expands from 3.14 to 4.43. Strikingly, the 75th percentile, which stood at -0.96% in 2050, turns positive in 2070, indicating that more than one quarter of all NUTS regions now records agricultural gains under these scenarios, a structural shift that the negative mean still hides. The share of NUTS with positive impacts almost doubles between the two horizons (from 14.7% to 25.9%). At the same time, the lower tail deepens markedly: the 5th percentile drops from -7.39% to -8.11%, the 1st from -9.80% to -11.23%, and regions with losses exceeding 10% nearly triple (from 0.7% to 1.9%), a damage class entirely absent under low-forcing conditions. The skewness deepens from -0.33 to -0.46, confirming the growing asymmetry of the distribution. This dual dynamic – an improving central tendency alongside a strongly widening spread – is a clear statistical signature of deepening polarisation: a growing subset of northern and alpine regions actually benefits, while the most exposed southern NUTS deteriorate further.

The comparison across all three scenario groups highlights a systematic pattern. First, the mean and median values across groups are more similar than the scenario labels might suggest (ranging from -1.99% to -2.90% at the 2050 mean), whereas the dispersion indicators diverge dramatically: the IQR moves from 2.26 under low-forcing to 3.10 under intermediate to 3.25 under high-end forcing, widening further in all groups by 2070. Second, the share of NUTS with losses exceeding 5% – only 4.4% under low-forcing – reaches roughly 19% under both intermediate and high-end scenarios in 2050, demonstrating a threshold-like response in agricultural sensitivity to forcing level. Third, losses exceeding 10% emerge as a statistically relevant outcome class only under intermediate and high-end forcing (around 0.7-0.8% of NUTS in 2050, growing to 1.6-2.2% by 2070), and are entirely absent under low-forcing. Across all scenario groups, the EU-level aggregate consistently understates the magnitude of the worst regional impacts by a factor of 2.0× to 3.6×, with gaps growing in absolute terms as forcing increases. These results confirm that EU-level data are structurally insufficient to assess agricultural losses from pollination decline, and that NUTS-level granularity is essential to capture both the severity and the heterogeneity of the impacts.

Finally, we examine the most disaggregated agri-sectors level. By analysing the highly impacted Vegetable, Fruit, and Nuts sector, the same pattern holds. At the EU aggregate, scenario differences remain modest. The 2050 range

spans -5.86% to -1.89%, and it widens to -7.0% to -1.91% by 2070. The mean declines from -3.58% to -4.08%, and the median from -2.94% to -3.47%. The standard deviation rises from 1.37 to 1.58, indicating growing dispersion over time, while skewness is consistently moderately negative (-0.53), reflecting a slight left-skew. The 75th percentile worsens from -2.40% to -2.73%, confirming a clear negative trend across all scenarios toward 2070. The data divergence drastically increase when looking at NUTS level. Under low-forcing scenarios, regional impacts range from -15.33% to +8.37% in 2050 and from -17.22% to +6.97% in 2070, with very strong spatial heterogeneity and heavy negative tails. In 2050, 76% of EU NUTS regions record negative impacts, with a mean of -2.14% and a median of -1.80%. By 2070, the mean worsens to -2.38% while the median is essentially unchanged (-1.80%), a first signal that the bulk of the distribution shifts only marginally while the tails grow substantially. The standard deviation rises from 3.00 to 3.31 (+10%), and the IQR widens from 3.67 to 4.14. The negative tail deepens markedly: the 5th percentile drops from -7.81% to -8.44%, the 10th from -5.78% to -6.39%, and the 1st percentile from -10.97% to -12.28%. Regions with losses exceeding 5% grow from 14.6% to 19.0% between the two horizons, while regions with losses exceeding 10% almost triple (from 1.3% to 3.3%), a damage class that is essentially unknown for the broader Agricultural sector under the same scenarios. The skewness deepens from -0.77 to -0.96, confirming the growing asymmetry.

Under intermediate forcing scenarios, the regional distribution shifts substantially further, with impacts ranging from -18.04% to +6.12% in 2050 and from -18.56% to +7.78% in 2070. The mean reaches -3.12% in 2050 and the median -2.36%, while 80% of NUTS are in negative territory. The 25th percentile already stands at -5.04%, meaning that a quarter of all EU NUTS regions record losses of at least 5% in sectoral output. By 2070, although the mean marginally improves to -3.00% and the median to -2.09%, the standard deviation grows by 13% (from 3.89 to 4.40) and the IQR expands from 4.70 to 5.64. The 1st percentile deteriorates from -14.17% to -15.23%, and regions with losses exceeding 10% rise from 7.4% to 8.1%. Regions with losses exceeding -5% rise to 29.0% in 2070.

High-end emission scenarios display the most extreme structural divergence between the EU aggregate and the regional distribution. In 2050, the pooled range runs from -18.85% to +6.69%, with a mean of -2.88% and a median of -2.17%, while 77% of NUTS experience losses. By 2070 the distribution widens dramatically, ranging between -21.35% to +8.85%. The standard deviation grows by 19% (from 3.89 to 4.61), and the IQR expands from 4.77 to 5.92. As observed for the broader agricultural sector, the temporal evolution exhibits a marked dual dynamic: the mean improves slightly (+0.28 pp) and the median improves more visibly (+0.66 pp), driven by a substantial positive reorientation in northern and alpine NUTS, while simultaneously the lower tail deteriorates further. The share of NUTS with positive impacts grows from 22.6% to 34.7%, and the 75th percentile turns positive in 2070 (+0.68%) from negative in 2050 (-0.17%). At the same time, the 5th percentile drops from -10.79% to -11.79%, the 1st from -14.13% to -15.90%, and the absolute minimum reaches -21.35%. Regions with losses exceeding 10% remain stable at around 7–8% but their absolute severity intensifies; the skewness deepens from -0.93 to -1.00, kurtosis from 1.1 to 1.2.

The comparison across the three scenario groups shows that the amplification factor (NUTS over EU average) remains in the 3.4× to 5.6× range across all scenario groups, substantially higher than for Agricultural sector (2.0× to 3.6×), while the absolute gap between the EU value and the most affected NUTS reaches values of over 14 percentage points, more than double those observed for the aggregate agricultural sector. The structural pattern of polarisation observed for Agricultural sector is amplified here: under high-end scenarios, more than one third of NUTS shows positive impacts in 2070, while simultaneously the worst-affected NUTS deteriorates further, demonstrating that Vegetable, Fruit, and Nuts sector is structurally heterogeneous in its response to pollination loss under climate change and that EU-level data are unable to capture this dimension. Regions with losses exceeding 10% affect 1.3% of NUTS already under low-forcing, a value absent in Agricultural sector under same scenarios, rising to 7–8% under intermediate and high-end forcing, confirming that specific agricultural sub-sectors may be systematically most exposed to severe regional climate damages compared to the regional and sectoral aggregates.

Table 2: Summary statistics | EU aggregate vs NUTS distribution at 2050 and 2070

Var	Group	Year	EU range		NUTS distribution								Losses (%)	
			min	max	min	max	mean	median	std	IQR	P5	P95	<-5	<-10
GDP	LF	2050	-0.10	-0.08	-0.79	+0.26	-0.11	-0.10	0.11	0.09	-0.31	+0.05	0	0
GDP	LF	2070	-0.09	-0.06	-1.07	+0.42	-0.12	-0.08	0.16	0.12	-0.47	+0.02	0	0
GDP	MOD	2050	-0.14	-0.02	-0.99	+0.20	-0.13	-0.09	0.15	0.12	-0.41	+0.04	0	0
GDP	MOD	2070	-0.16	-0.00	-1.68	+0.22	-0.16	-0.09	0.23	0.16	-0.58	+0.03	0	0
GDP	HE	2050	-0.15	-0.04	-0.99	+0.20	-0.12	-0.09	0.13	0.10	-0.41	+0.01	0	0
GDP	HE	2070	-0.18	-0.04	-1.61	+0.17	-0.16	-0.09	0.21	0.15	-0.61	+0.005	0	0
agri	LF	2050	-3.16	-2.29	-11.39	+6.62	-1.99	-2.13	1.95	2.26	-4.68	+0.95	4.4	0.2
agri	LF	2070	-3.19	-2.51	-11.83	+5.31	-2.17	-2.28	2.07	2.42	-5.58	+1.04	6.2	0.2
agri	MOD	2050	-5.07	-2.05	-10.93	+5.63	-2.90	-2.76	2.61	3.10	-7.86	+1.15	18.7	0.7
agri	MOD	2070	-5.61	-2.03	-12.67	+6.77	-2.86	-2.84	3.00	3.80	-8.12	+1.65	21.7	1.6
agri	HE	2050	-5.17	-1.78	-11.26	+6.13	-2.63	-2.46	2.64	3.14	-7.39	+1.33	16.2	0.7
agri	HE	2070	-5.96	-1.54	-12.78	+7.96	-2.35	-2.16	3.13	4.43	-8.11	+1.77	17.7	1.9
v_f	LF	2050	-4.33	-2.36	-15.33	+8.37	-2.14	-1.80	3.00	3.67	-7.81	+1.69	14.6	1.3
v_f	LF	2070	-4.84	-2.59	-17.22	+6.97	-2.38	-1.80	3.31	4.14	-8.44	+1.65	19.0	3.3
v_f	MOD	2050	-5.47	-2.24	-18.04	+6.12	-3.12	-2.36	3.89	4.70	-11.08	+1.91	25.5	7.4
v_f	MOD	2070	-6.25	-2.47	-18.56	+7.78	-3.00	-2.09	4.40	5.64	-11.97	+2.58	29.0	8.1
v_f	HE	2050	-5.86	-1.89	-18.85	+6.69	-2.88	-2.17	3.89	4.77	-10.79	+2.22	24.6	6.7
v_f	HE	2070	-6.99	-1.91	-21.35	+8.85	-2.60	-1.51	4.61	5.92	-11.79	+2.94	26.3	7.6

Notes | Analysis of the percentage deviations from the respective SSP baselines across the 18 scenarios considered for projected model variables: *GDP* = regional economic output; *agri* = value of aggregated Agricultural sector output; v_f = value of agricultural sub-sector Vegetables, Fruits and Nuts. Scenario groups are: *LF* = Low Forcing (GHSB-1 2.6, IIASA-2 2.6, IIASA-CLIM 2.6, PREST-1 2.6, PREST-CLIM 2.6); *MOD* = Moderate Forcing (GHSB-3 6.0, IIASA-2 4.5, IIASA-CLIM 4.5, PREST-1 4.5, PREST-3 4.5, PREST-CLIM 4.5); *HE* = High Forcing (GHSB-5 8.5, IIASA-2 7.0, IIASA-CLIM 7.0, IIASA-CLIM 8.5, PREST-3 8.5, PREST-5 8.5, PREST-CLIM 8.5). *EU range* reports the minimum and maximum aggregate EU impacts across all scenarios. *NUTS distribution* statistics are computed across 122 NUTS regions: *std* = standard deviation; *IQR* = interquartile range; *P5* and *P95* denote the 5th and 95th percentiles of the regional NUTS distribution. Columns <-5 and <-10 report the share of regions experiencing losses greater than -5% and -10%, respectively.

Sensitivity of pollination scenarios to climate change pathways

Sensitivity analysis shows that SDMs models present heterogeneous sensitivity to emission scenarios and socioeconomic pathways (Figure 4).

PREST-CLIM and PREST-1 are highly sensitive to the RCP pathway (Figure 4c), with mean regional differences of nearly 34-40 percentage points between RCP2.6 and RCP8.5 at 2070, and with substantial spatial heterogeneity in this sensitivity (Interquartile Range IQR 30-40 pp across NUTS-2 regions). In contrast, IIASA-2 presents a low sensitivity to RCP choice, with a mean range of less than 6 pp between RCP2.6 and RCP7.0 even at 2070, as well as IIASA-CLIM (6 pp). PREST-3 occupies an intermediate position (11 pp at 2070). This indicates that for some models the emissions pathway is decisive, while for others structural assumptions dominate. Importantly, part of these differences can be explained by the different representation of species within the SDM frameworks: models vary in how they parametrise species distributions, ecological tolerances, and pollinator-crop interactions, which amplifies or dampens the sensitivity to climate forcing (see Appendix 1).

When comparing models under the same RCP, the picture shifts. At RCP2.6, models converge relatively closely (range 3-7 pp), but at RCP4.5 and RCP8.5 divergences become dramatic, reaching up to 36 percentage points at 2070 under RCP8.5. This means that model choice becomes critical in pessimistic scenarios, precisely where uncertainty is highest and policy relevance greatest.

The SSP dimension adds a further layer of uncertainty (Figure 4d). Under SSP1, inter-model spread remains moderate (mean 11 pp at 2070), reflecting that low-forcing scenarios leave little room for model divergence. Under SSP2, SSP3 and SSP5 the spread grows substantially, reaching mean values of 31, 38, and 39 pp respectively at 2070, with IQR extending beyond 45 pp in some regions. Notably, SSP3 and SSP5 are statistically indistinguishable in terms

of inter-model spread, suggesting that beyond a warming threshold the land-use variables of the socioeconomic pathway matters less than the underlying RCP and SDM structure. The eight scenarios included under SSP2 produce the widest range of outcomes in absolute terms, reflecting the diversity of model families that project into this pathway.

The full distribution of projected impacts across all NUTS-2 regions and scenarios (Figure 4e) reveals a consistently negative but highly skewed picture. In 2030, the bulk of projections cluster between -10% and -25%, with limited positive outliers confined to a handful of northern and eastern European regions under low-emission scenarios. By 2070, the distribution broadens dramatically: the median impact across scenarios sits near -30%, but the lower tail extends below -70% for PREST variants under high emissions. The overlap between the 2050 and 2070 distributions is narrow, confirming that impacts continue to accelerate rather than plateau. Critically, no scenario produces a positive EU-wide signal by 2070, reinforcing the robustness of the directional finding even in the face of large inter-model spread. These results suggest that while the direction of change is homogeneous (negative trend), the magnitude of decline is highly sensitive both to the emissions pathway and to the modelling framework. Yet, the signal-to-noise ratio varies: in some cases the decline is strong relative to model uncertainty, in others the spread between models is wide enough to weaken confidence. The convergence of GHSB and IIASA families around -25 to -35% by 2070, regardless of RCP, may represent a more conservative but robust lower bound, while PREST-family projections under high emissions should be interpreted as plausible upper-bound scenarios conditional on specific land-use change assumptions.

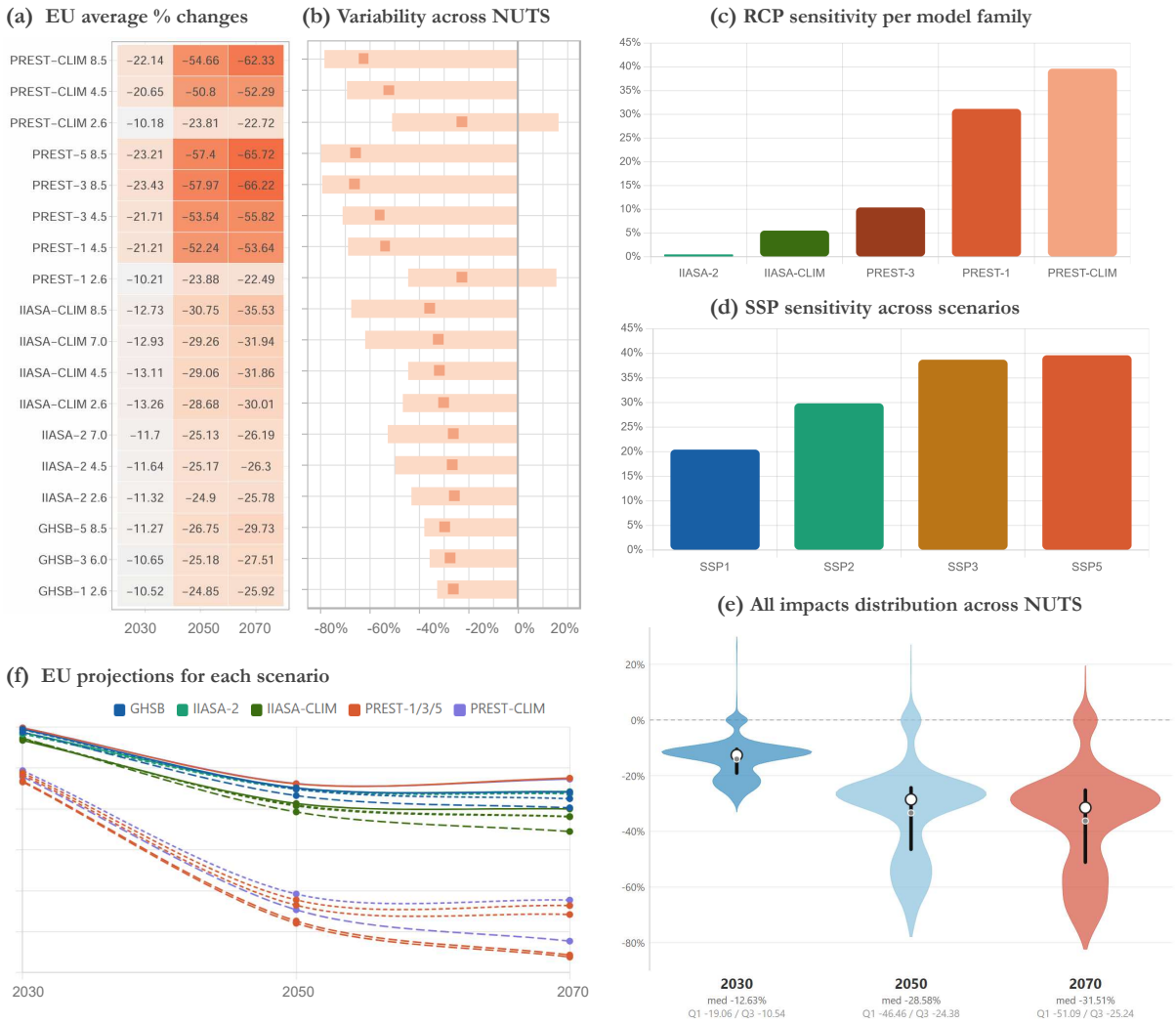


Figure 4 | Projected changes in pollination supply across EU scenarios relative to 2020. **(a)** EU-level average percentage change in pollination for 18 land-use and climate scenarios across three time horizons (2030, 2050, 2070). Colour intensity reflects the magnitude of decline, ranging from moderate losses (~10%) under low-emission scenarios to severe losses (up to -66%) under high-emission PREST variants; **(b)** Spatial variability in projected pollination change across NUTS regions for each scenario in 2070, shown as the full MIN-MAX range (shaded bar) of the regional distribution; the red square marks the EU-level average. Scenarios with low RCP (2.6) display wider ranges extending into positive values in some regions, while high-emission scenarios converge toward uniformly negative outcomes; **(c)** Mean RCP sensitivity per model family in 2070, expressed as the average range (in percentage points) between the lowest and highest RCP run within the same model. PREST-CLIM shows the highest sensitivity (~40 pp), followed by PREST-1 and 3 (~32 pp), while IIASA-2 and IIASA-CLIM exhibit near-zero RCP sensitivity (<10 pp); GHSB and PREST-5 are excluded (only one RCP per variant); **(d)** Mean SSP sensitivity in 2070 as range of EU average pp across scenarios under the same SSP (model spread at fixed SSP). Under SSP2, eight scenarios from four models are grouped. SSP1 comprises PREST-1 and GHSB-1 scenarios. SSP3 comprises GHSB-3 and PREST-3. SSP5 comprises GHSB-5, IIASA-CLIM 8.5, PREST-5, and PREST-CLIM 8.5; **(e)** Impact distribution across all NUTS (0-2) and scenarios for year 2030, 2050 and 2070 (2700 annual values). The violin shape represents the kernel density estimate (KDE) (probability density function of all values). The vertical black bar indicates the interquartile range (Q1-Q3). The white dot marks the median, and the grey dot marks the mean. **(f)** EU-level average trajectory for each scenario from 2030 to 2070, grouped by model family (colour) and RCP (line style: solid = low RCP, dashed = high RCP). All scenarios project monotonically increasing losses over time, with PREST family scenarios under high emissions reaching -65% to -70% by 2070, and IIASA and GHSB families stabilising between -25% and -35%.

Methods

The integrated modelling framework used in this study connects four sequential modules: (i) climate-driven pollination potential under 18 SSP-RCP scenarios; (ii) crop-specific yield response based on pollination dependency

ratios for 129 EU crops at a resolution of 0.05°; (iii) regionalized agricultural shocks aggregated to NUTS 0-3 levels; and (iv) macroeconomic propagation and assessment in 122 EU regions through the application of a CGE model resolved at the NUTS-2 level. The framework operates as a sequential, modular cascade, in which outputs from each ecological and agricultural module are consistently propagated as inputs into subsequent economic modules, enabling an internally consistent assessment of ecological and socioeconomic impacts. While the framework does not explicitly model endogenous feedbacks from economic outcomes to ecological dynamics [4], it captures the one-way propagation of ecosystem services changes through agricultural systems into the macro-economy in a spatially explicit manner, consistent with the production-function method of the SEEA-EA ecosystem accounting standards (United Nations, 2024; Markandya et al., 2022).

Baseline pollination potential scenario

The KIP-INCA framework [105, 63] developed a set of ecosystem services accounts including crop pollination. The service is provided by the functional match between pollination potential, defined as the ecosystem's ecological suitability to support wild insect pollinators, and pollination demand, defined as the spatial extent of pollinator-dependent crops (the use area). The spatial co-occurrence of pollination potential and pollination demand is used to quantify the actual flow of the service and to identify priority areas where restoration or conservation interventions are most needed to mitigate pollination deficits.

The KIP-INCA datasets [107] classifies EU land surface into categories of pollination potential based on a highly detailed assessment of land-cover composition and land-use patterns, aimed at identifying habitat elements suitable for pollinators. This classification enables us to project how future changes will differentially affect different regions based on projected future climate and land-use trends (see sections below). The assessment is based on an indicator of the environmental suitability to support wild insect pollinators which integrates two different models: an Expert-Based Model for solitary bees and a Species Distribution Model (SDM) for bumblebees. Both models are based on land use, land cover and on the distance to semi-natural areas, being the most important drivers, while their relative importance differs among the taxonomic groups. The presence of semi-natural areas in agricultural landscapes (such as hedgerows, wildflower strips, and fallow land) is included as an element providing food resources and nesting sites, based on Garibaldi et al. (2011) which shows that the stability of pollination services decreases with isolation from natural areas. LULC data, CORINE data and TeleAtlas® Maps, are used to identify semi-natural areas and areas that cannot provide floral resources or nesting sites to insect pollinators. Current climate is also considered as an important driver of the large-scale occurrence of the groups of pollinators, but other pressures affecting pollinators are not considered, such as the use of pesticides, climate change and invasive alien species.

To build the pollination potential baseline (2020-2070), the initial level of Pollination Potential for the year 2020 relies on data from the INCA (2018) potential [105], normalized to a 0-1 scale. To ensure consistency with existing literature, we compared this metric against the 2015 Pollination Sufficiency baseline from Von Jeetse et al. (2023) [113], which incorporates similar ecological and spatial elements. The two metrics proved to be broadly comparable, with closely aligned mean values across the EU (See Appendix 1).
The INCA pollination potential represents a snapshot of current ecological conditions and does not explicitly incorporate temporal trends. Likewise, species distribution models (SDMs) generally omit several relevant stressors, including pollutant exposure. Future changes are modelled by scaling down the 2020 baseline potential up to 2050 to match observed historical trends in wild pollinator abundance (see Appendix 1, 2). This degradation is applied uniformly across space, so all spatial heterogeneity in our results originates from the SDM ensemble. In the absence of future climate change effects, no further decline is projected between 2050 and 2070, implying a stabilisation of pollination potential in the long run under the baseline scenario. The assumption is deliberately conservative, intended to avoid overstating long-term losses under substantial uncertainty in ecological trajectories and policy effectiveness. In particular, it reflects the fact that existing policy interventions, such as the EU Pollinators

Initiative and earlier reforms under the Common Agricultural Policy (CAP), may not yet have fully translated into observable trends. Extrapolating current declines over extended horizons would otherwise rely on a strong and potentially unjustified assumption of persistence, with a risk of systematic overestimation of long-run impacts. In the absence of an established convention for baseline pollination trajectories, the rate is anchored on the EU Science and Technology for Pollinating Insects (STING) project (Potts et al., 2024 [83]), long-term projections of agro-ecosystem degradation reported by the European Commission [24][25], and the EU Grassland Butterfly Index [110][28]; independent corroboration of continent-wide decline is provided by European Red List assessments and by modelled reconstructions of historical habitat suitability [66][37][116][90][71]. We acknowledge that these indicators proxy pollinators habitat suitability status rather than pollination service delivery, and they are not fully independent to already occurred climate-change effects, so the baseline partially embed past climate channel carried by the SDM ensemble.

Climate change scenarios

Projected declines in pollination potential due to changing climate are derived from an ensemble of state-of-the-art multi-model, multi-scenario species distribution models (SDMs) for key pollinator taxa (wild bees, hoverflies, butterflies, beetles), based on the most recent and robust data currently available. This framework enables the assessment of multiple climate change scenarios (RCP2.6, 4.5, 6.0, 7.0, 8.5) and socioeconomic pathways (SSP1, 2, 3, 5) [93, 111], accounting for future impacts on pollinators up to 2070 (Figure 3). In the CLIM experiments, the input data used only capture climate-induced environmental changes such as temperature and precipitation patterns, while in the other experiments the datasets also embed land-use dynamics under different SSPs. Data sources were selected to ensure full consistency with the KIP-INCA and Status and Trends of European Pollinators (STEP) frameworks. The selected data sources provide information on the future probability of presence for different species based on projected habitat suitability for up to 153 wild pollinator species across two major taxonomic groups: Hymenoptera (including bumblebees, wild bees, wasps, and ants) and Lepidoptera (including butterflies and moths). The expected probability of presence is then averaged across species within each SDM-scenario considered. These are standard assumptions in economic modelling of pollination services[40][52][113], reflecting current data constraints. A composite indicator combining species distribution, abundance, and functional trait diversity would provide a more comprehensive measure of pollination capacity[87], yet such data remain unavailable for large-scale, long-term projections. Nonetheless, our approach is grounded in substantial empirical evidence demonstrating that species richness, even as a first-order approximation, captures critical dimensions of pollination service provision. A full description of data sources and data elaboration is provided in Appendix 1.

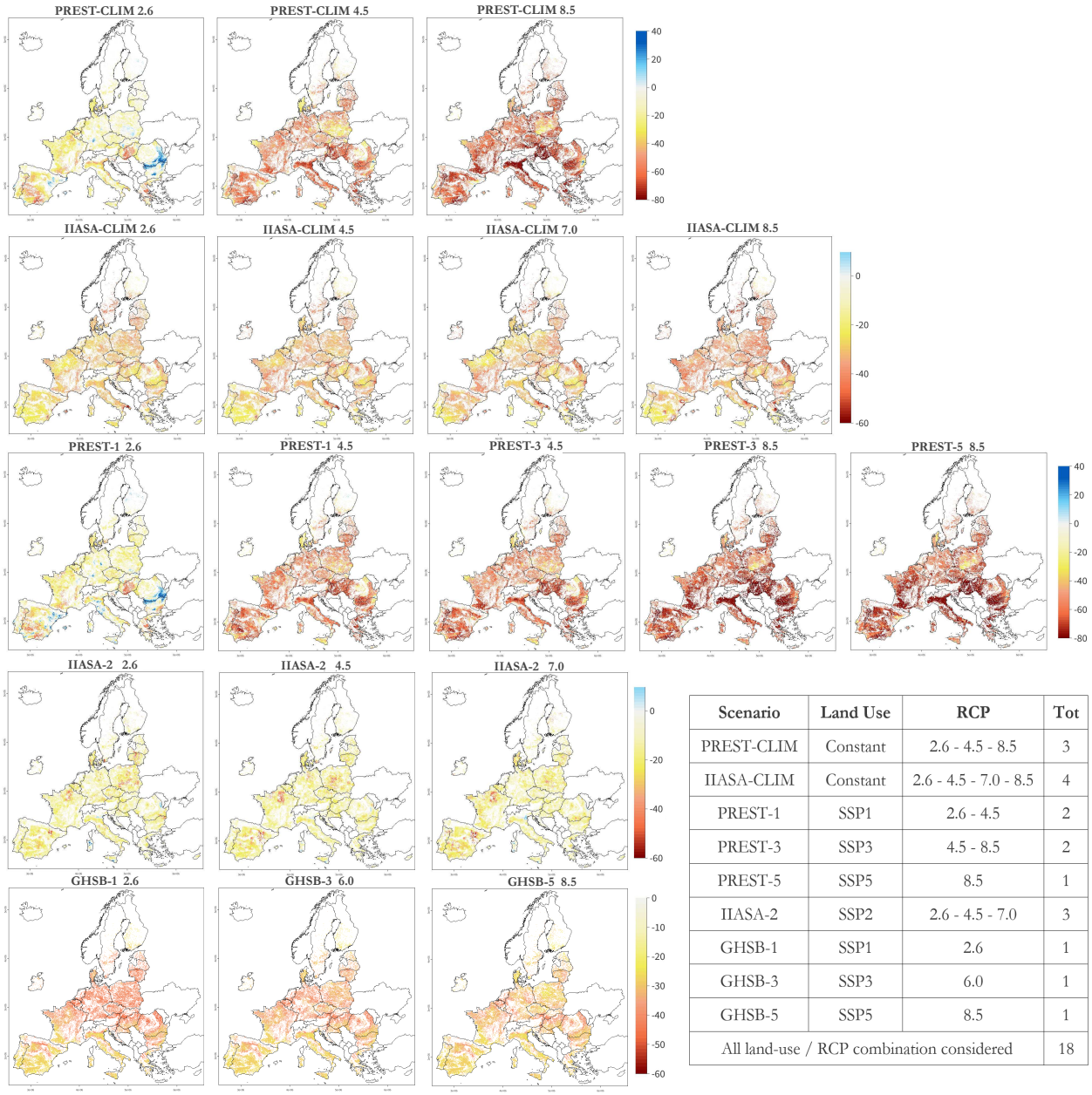
Spatially referenced information are provided at a level of granularity comparable to that of the INCA datasets, and capture both increases and decreases in pollinator distributions due to habitat suitability as driven by projected regional climate conditions under several SSP-RCP combinations. Consequently, some areas are expected to experience gains in pollination potential, while others will face substantial declines. This spatial heterogeneity reflects the inherently local nature of climate impacts: current evidence suggests that many wild pollinator species may shift towards northern ranges, whereas most bumblebee species are projected to undergo substantial range contractions (Potts et al., 2015).
The projected per-period shocks are then cumulated pixel by pixel to obtain, for each scenario and five-year step τ, the cumulative percentage change in habitat suitability $\Delta\tilde{p}_{n,\tau}$ relative to the 2020 reference value. This cumulative shock is applied multiplicatively to the corresponding baseline value to obtain the climate-adjusted pollination potential:

$$P_{n,\tau} = \left(1 + \frac{\Delta\tilde{p}_{n,\tau}}{100}\right) \cdot P_{b,n,\tau}, \qquad P_{n,\tau} \in [0,\ 1] \tag{1}$$

where $P_{b,n,\tau}$ is the baseline pollination potential in pixel n at time step τ, and $\Delta\tilde{p}_{n,\tau}$ is the cumulative percentage change in habitat suitability relative to 2020 (negative values indicate a decline). $P_{n,\tau}$ is clamped to the unit interval

[0, 1] after application of the shock.

By imposing the projected, spatially explicit climate-induced changes in habitat suitability onto the baseline pollination potential, we estimate future pollination potential and its percentage change in each time step at a high spatial resolution of 1 km $\times$ 1 km across all SSP–RCP combinations considered (Figure 3).



Scenario	Land Use	RCP	Tot
PREST-CLIM	Constant	2.6 - 4.5 - 8.5	3
IIASA-CLIM	Constant	2.6 - 4.5 - 7.0 - 8.5	4
PREST-1	SSP1	2.6 - 4.5	2
PREST-3	SSP3	4.5 - 8.5	2
PREST-5	SSP5	8.5	1
IIASA-2	SSP2	2.6 - 4.5 - 7.0	3
GHSB-1	SSP1	2.6	1
GHSB-3	SSP3	6.0	1
GHSB-5	SSP5	8.5	1
All land-use / RCP combination considered			18

Figure 3 | Projected pollination potential change in 2070 with respect to 2020 values under all scenarios considered. The table shows the combination of SSP-consistent land use variables and climate radiative forcing (RCPs) used by the species distribution models (SDMs) in each scenario. These scenarios has been divided in the following three categories in the study to distinguish between different climate change pathways: low-forcing scenarios (LF) (GHSB-1 2.6, IIASA-2 2.6, IIASA-CLIM 2.6, PREST-1 2.6 and PREST-CLIM 2.6), intermediate scenarios (MOD) (GHSB-3 6.0, IIASA-2 4.5, IIASA-CLIM 4.5, PREST-1 4.5, PREST-3 4.5 and PREST-CLIM 4.5); high-end emissions scenarios (HE) (GHSB-5 8.5, IIASA-2 7.0, IIASA-CLIM 7.0, IIASA-CLIM 8.5, PREST-3 8.5, PREST-5 8.5, PREST-CLIM 8.5).

Impacts on agriculture

We assess the agricultural impacts due to yield reduction for specific crop following a well established methodology based on the dependency of specific crops to pollination [31][6][30], and on the expected reduction of pollinator habitat suitability (potential) in the cultivation area [40][113][52]. The overlap between the pollination potential

and demand for pollination is used to quantify the area generating the actual flow of service (i.e. the use area) [63]. This can be defined as the number of hectares of pollinator-dependent crops covered by areas with different pollination potential levels. Consequently, changes in crop areas (service demand) or declines in pollination (service supply) translate into variations in agricultural output. As we do not assess climate-change impacts arising from other sources (such as droughts or wildfires), this implies that in our framework climate change affects agricultural production through reductions in pollination potential. Accordingly, the impact of pollination decline is modelled as a decrease in cropland productivity for specific crops, based on each crop's dependency on pollination and its cultivated area. Agricultural impacts are then represented as the percentage change in crop yield (crop-specific cropland productivity) relative to the baseline, across the various SSP-RCP scenario combinations considered.

To determine use areas at the highest possible spatial resolution, agricultural land (cultivated hectares) for 129 crops and crop categories from FAO CROPGRIDS [99] is mapped at the grid level and then overlapped with raster layers representing projected percentage changes in pollination under each SSP–RCP scenario combination for the period 2020-2070 relative to the baseline values with no pollination impacts. Only crops whose average pollination dependency exceeds 0.05 are retained in the analysis, as crops below this threshold generate yield shocks too small to be resolved within the macroeconomic model. This enables us to quantify the extent to which the 2020 cultivation areas of specific crops in the EU are affected by pollination decline, prior to evaluating potential SSP-driven land use changes.

The impact of pollination changes is modelled as decreased cropland productivity based on the dependency of specific crops on pollination, which measures the fractional reduction in crop yield associated with a loss of animal pollination [56] [10] [96](See Appendix 1). For example, a pollination dependency of 0.05, means that a 100% decrease in pollination results in a 5% decrease in crop yield. The impact on production for a specific crop in a given area is therefore determined by the projected change in pollination service in the area where the crop is cultivated and by that crop's dependency on animal pollination.

$$\text{yield}_{c,n,t_1} = \text{yield}_{c,n,t_0} \cdot \left(1 + \text{dependency_p}_c \cdot \Delta\text{p}_{n,t_1}\right) \tag{2}$$

where:

c the specific crop;
n the specific spatial unit of production area (grid cell);
Δp the variation ($t_0 - t_1$) of pollination potential in n;

For each crop c and NUTS region r, the area-weighted mean cumulative percentage change in pollination potential is computed across all pixels n belonging to that region:

$$\overline{\Delta\tilde{p}}_{c,r,\tau} = \frac{\sum_{n \in r} A^0_{c,n} \cdot \Delta\tilde{p}_{n,\tau}}{\sum_{n \in r} A^0_{c,n}} \tag{3}$$

where $A^0_{c,n}$ is the baseline cultivated area (hectares) of crop c in pixel n from FAO CROPGRIDS (2020), and $\Delta\tilde{p}_{n,\tau}$ is the cumulative percentage change in pollination potential in pixel n at time step τ (equation 1). The yield shock for crop c in region r at time τ is then expressed as a fractional change in yield (negative values indicate a yield loss):

$$S_{c,r,\tau} = \text{dependency_p}_c \cdot \frac{\overline{\Delta\tilde{p}}_{c,r,\tau}}{100} \tag{4}$$

In this way, the resulting shocks fully embed spatial information on habitat-specific suitability shifts, crop-specific pollination dependency, and the spatial distribution of crop areas.

Assessing macroeconomic impacts on agricultural sub-sectors

The projected gridded percentage changes in yield for each crop and climate scenario are mapped and aggregated at NUTS levels (0 to 3) and then used as land-productivity shocks in the macroeconomic model. Macroeconomic impacts are then estimated using a regionalized version of the ICES Computable General Equilibrium (CGE) model based on GTAP11 database [1], which provides detail for 122 regions down to NUTS-2 level across the EU27, while the rest of the world is represented as a macro-regional aggregate.

Since the agricultural sector in ICES is relatively aggregated, we averaged the projected yield percentage changes based on the relative weight of each crops cultivated in each region, aligning them with the 5 crop categories (agricultural sub-sectors) used in the model. These are: Vegetable, Fruit, Nuts ; Oil seeds ; Cereals, Wheat, Rice ; Sugar cane & Sugar beet ; Other crops, Fibers (See Appendix 1 for full crops detail). This approach is also convenient because the GTAP crop-sectors categories generally correspond to similar levels of pollination dependence; for example, Vegetables and fruits have, on average, high dependence, Oil seeds medium, while Cereals and Rice low to negligible dependence. To do this, we compute a weighted average in which the weight of crops in each grid cell within a NUTS region is proportional to the number of hectares cultivated in that cell. These results are then further aggregated to match the crop categories used in the economic model, taking into account the relative contribution of each crop within the NUTS region of interest.

With the exception of the CLIM scenarios, which are based on a constant 2020 land use exercise, we incorporate projected crop-specific land-use changes from Goebel and Britz (2025)[38], both in the baseline runs and in the impact scenarios to account for future demand changes and crop expansion within each crop-sector under different SSPs [93, 111], at the highest resolution available. These changes reflects how population, GDP and demand dynamics evolve within each SSP scenario, and how these dynamics translate into agricultural sector expansion and land-use patterns across different cropland categories in the EU. Projections are made ensuring full consistency with our modelling framework, as they also rely on a Computable General Equilibrium platform built on the GTAP v11 Power Database [1, 14]. The database represents the global economy in 2017 and includes LULC information, with regional land-use extents adjusted using additional datasets such as the 2018 European CORINE land-cover (LC) data [16]. Cropland and yield developments are calibrated to projections from the Food and Agriculture Organization of the United Nations (FAO, 2018)[29], thereby maintaining full alignment across all components of our modelling chain.

Land-use change information is provided at the NUTS-2 level for eight land-cover types (e.g., cropland, forests, pastureland, shrubland) and for 65 land-use categories corresponding to individual crops and crop aggregates, which are matched to the FAO CROPGRIDS crop categories used in this study. Since information on future cropland expansion is available only at the NUTS-2 level, a grid-level spatial overlap is no longer feasible, as the exact spatial distribution of future crops within each polygon is unknown. The shock is therefore recalibrated proportionally to the expected cropland shares in each crop-sector, NUTS region, scenario, and year, so that the percentage change in crop area is applied uniformly across the entire polygon, assuming that future land allocation within each NUTS-2 region occurs in areas close to the original ones, with no significant deviations in the projected changes in pollination potential for each crop-NUTS-scenario-year combination. The resulting agricultural region and category-specific shocks are then imposed in each run of the recursive-dynamic macroeconomic model as a percentage change of land productivity specific to each agricultural crop-sector and NUTS, reflecting the impact on regional yields in each time step due to pollination loss.

In the SSP-based recalibration of cropland areas, future cultivated areas are therefore computed by applying the percentage changes associated with each SSP. Where $\Delta_{c,r,s}^{SSP}$ the projected percentage change in cultivated area, r NUTS regions, and s SSP scenario–year combinations. Each crop c belongs to one GTAP category g. Baseline cultivated areas $A_{c,r}^{0}$ are obtained from FAO CROPGRIDS (2020).

$$A_{c,r,s} = A^0_{c,r} \cdot \left(1 + \frac{\Delta^{SSP}_{c,r,s}}{100}\right) \tag{5}$$

Total cultivated area for each GTAP sector g, region r, and scenario–year s, is defined as:

$$A_{g,r,s} = \sum_{c \in g} A_{c,r,s} \tag{6}$$

In the dynamic crop weighting, crop-specific weights are computed as the share of each crop area on total GTAP crop category area:

$$w_{c,g,r,s} = \frac{A_{c,r,s}}{A_{g,r,s}} \tag{7}$$

By construction, weights vary across scenarios and years and satisfy:

$$\sum_{c \in g} w_{c,g,r,s} = 1 \tag{8}$$

In the weighted aggregation of pollination shocks, let $S_{c,r,s}$ denote the pollination shock at crop level. The GTAP-sector shock is obtained as a weighted average:

$$S_{g,r,s} = \sum_{c \in g} w_{c,g,r,s} \cdot S_{c,r,s} \tag{9}$$

Substituting the weights yields,

$$S_{g,r,s} = \sum_{c \in g} \left(\frac{A_{c,r,s}}{\sum_{c \in g} A_{c,r,s}}\right) \cdot S_{c,r,s} \tag{10}$$

this formulation ensures that changes in cultivated areas across SSP scenarios and years directly affect both the magnitude and the composition of GTAP crop categories shocks.