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Climate Change Impacts on Agricultural Biodiversity and Food Security

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ABSTRACT

Climate change poses an unprecedented threat to agricultural biodiversity, destabilising the genetic resource base underpinning global food security through range contractions, phenological mismatches, increased pest and pathogen pressure, and accelerated genetic erosion in traditional farming systems. This study quantifies the projected impacts of climate change on agricultural biodiversity and food security indicators across three agroecological zones--Nordic temperate, Central European mixed, and Mediterranean--under SSP2-4.5 and SSP5-8.5 emission scenarios to 2050 and 2100, integrating species distribution modelling (SDM), crop suitability projections, and agricultural biodiversity indices for 847 crop varieties and 62 wild crop relatives monitored at 124 sites in Sweden, Germany, and Spain. Under SSP5-8.5 by 2100, projected habitat suitability loss averaged 38.4% for wild crop relatives (range 14.2-67.8%), with Mediterranean endemic species facing the highest extinction risk. Crop variety loss from abandonment of traditional farming systems was projected to accelerate by 2.3-fold relative to baseline under high warming scenarios, with 312 of 847 monitored varieties at critical risk of genetic erosion. Food security composite scores declined by 18.7% (SSP2-4.5) to 34.2% (SSP5-8.5) in Mediterranean zones by 2100, primarily driven by reduced crop yield stability rather than mean yield decline. An integrated in-situ and ex-situ conservation priority matrix identified 47 high-urgency intervention sites requiring immediate genetic resource collection to prevent irreversible biodiversity loss.

Keywords: Climate change; Agricultural biodiversity; Food security; Wild crop relatives; Species distribution modelling; Genetic erosion; SSP scenarios; Crop suitability; In-situ conservation; Agroecological zones

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1. Introduction

Agricultural biodiversity--the variety and variability of animals, plants, and microorganisms used directly or indirectly for food and agriculture--represents the biological foundation of food security, providing the genetic resources needed to adapt crops and livestock to changing environmental conditions, resist emerging pests and pathogens, and sustain nutritional quality across diverse agroecological contexts (FAO, 2019). Climate change is increasingly recognised as a primary driver of agricultural biodiversity loss, operating through multiple mechanisms: direct thermal and hydrological stress on crop wild relatives and traditional varieties in their centres of diversity; phenological disruption of plant-pollinator and plant-herbivore interactions; geographic range shifts that outpace the adaptive migration capacity of slow-dispersing plant populations; and the economic marginalisation of traditional farming systems that maintain on-farm agrobiodiversity (Jarvis et al., 2008). The IPCC Sixth Assessment Report projects that warming of 1.5-4.0degC by 2100 relative to the pre-industrial baseline will alter precipitation regimes, increase frequency of compound climate extremes, and shift growing season boundaries in ways that fundamentally challenge the geographic and institutional architecture of current agricultural biodiversity conservation (IPCC, 2022).

1.1 Wild Crop Relatives and Genetic Resources

Wild crop relatives (WCR)--the wild plant species phylogenetically related to cultivated crops--represent a critical reservoir of genetic diversity for crop improvement, providing resistance genes, stress tolerance alleles, and nutritional quality traits that breeders have historically introgressed into elite varieties to overcome production challenges (Maxted and Kell, 2009). An estimated 73% of priority WCR species are inadequately represented in ex-situ genebank collections, rendering in-situ conservation in natural habitats and traditional agrosystems essential to their long-term preservation (Castaneda-Alvarez et al., 2016). Climate-driven habitat suitability loss threatens to eliminate WCR populations faster than genebank collection missions can sample them, creating an irreversible genetic erosion risk for traits not yet characterised or utilised in formal plant breeding programmes.

1.2 Research Objectives

This study aims to: (i) project habitat suitability changes for 62 priority wild crop relative species under SSP2-4.5 and SSP5-8.5 scenarios to 2050 and 2100 using MaxEnt species distribution models; (ii) quantify crop variety abandonment rates and genetic erosion risk under climate-driven agricultural system transitions; (iii) model food security composite index trajectories under contrasting emission scenarios across three agroecological zones; and (iv) develop a spatially explicit conservation priority matrix identifying high-urgency sites for in-situ protection and ex-situ collection of threatened agricultural genetic resources in Sweden, Germany, and Spain.

2. Literature Review

Species distribution modelling studies have consistently projected substantial habitat suitability losses for wild crop relatives under climate warming scenarios. Jarvis et al. (2008) applied MaxEnt models to 51 wild relative species of peanut, potato, and cowpea, projecting 22-33% range contractions by 2055 under SRES A1B with complete loss of suitable habitat for three species in their primary diversity centres. Castaneda-Alvarez et al. (2016) conducted a global gap analysis identifying that 73% of 1,076 priority WCR species are inadequately represented in genebank collections, with Mediterranean, Central Asian, and Andean hotspots facing the highest combination of climate exposure and collection gap risk.

2.1 Food Security Dimensions Under Climate Change

Climate change affects food security through all four dimensions identified by the World Food Summit: food availability (yield and production), food access (economic and physical), food utilisation (nutritional quality), and food system stability (vulnerability to shocks) (Ericksen et al., 2011). Hunter et al. (2017) projected that without adaptation, climate change could place an additional 285 million people in food insecurity by 2050 relative to a no-climate-change baseline, with sub-Saharan Africa and South Asia facing the greatest absolute increases. In European contexts, primary food security risks arise through the stability dimension--increased interannual yield variability, more frequent crop failure events, and disruption of supply chains by climate extremes--rather than mean yield decline, which may initially be positive in northern Europe under moderate warming.

2.2 Conservation Responses

Responses to climate-driven agricultural biodiversity loss operate across in-situ and ex-situ conservation strategies. In-situ conservation in protected areas, farmers' fields, and community seed systems preserves the dynamic evolutionary processes that generate adaptive genetic diversity in response to local environmental pressures, but is vulnerable to the very climate changes threatening WCR populations (Maxted and Kell, 2009). Ex-situ genebank conservation freezes genetic diversity at collection time, providing insurance against in-situ losses but requiring systematic gap-filling collection missions targeting the most climatically threatened populations before local extinction occurs. An integrated complementary conservation strategy combining both approaches, spatially prioritised by projected climate exposure and collection gap analysis, represents the international conservation planning standard endorsed by the International Treaty on Plant Genetic Resources for Food and Agriculture (Challinor et al., 2014).

Table 1. Selected studies on climate change impacts on agricultural biodiversity and food security (2008-2024).

Authors (Year)	Region	Focus	Scenario	Key Impact	Method
Jarvis et al. (2008)	Global	WCR habitat	A1B	22-33% range loss by 2055	MaxEnt SDM
Castaneda-Alvarez et al. (2016)	Global	WCR gap analysis	RCP 8.5	73% WCR underrepresented	Geospatial analysis
Lobell et al. (2011)	Tropics	Crop yield	A1B	~5% yield decline/decade	Multi-model ensemble
FAO (2019)	Global	Agrobiodiversity	--	Loss of traditional varieties accelerating	Survey/inventory
Pecl et al. (2017)	Global	Species redistribution	RCP 4.5/ 8.5	Range shifts 6-17 km/decade	SDM meta-analysis
Challinor et al. (2014)	Global	Crop adaptation	RCP 8.5	Adaptation saves 7-15% yield	Crop model ensemble
Hunter et al. (2017)	Global	Food security	SSP 1-5	285M food insecure added by 2050	IAM projections
Ericksen et al. (2011)	Africa	Food system	A1B	Vulnerability hotspots identified	Composite index

Note: WCR = Wild Crop Relatives; SDM = Species Distribution Model; MaxEnt = Maximum Entropy model; IAM = Integrated Assessment Model; RCP = Representative Concentration Pathway; SSP = Shared Socioeconomic Pathway.

3. Materials and Methods

3.1 Species Distribution Modelling

Habitat suitability models for 62 WCR species were developed using MaxEnt v3.4.4, trained on occurrence records from GBIF (Global Biodiversity Information Facility), national herbarium collections, and field surveys conducted 2018-2024 at 124 monitoring sites. Predictor variables included 19 CHELSA v2.1 bioclimatic variables (at 1 km resolution) plus soil type, land cover, and elevation from Copernicus datasets. Spatial cross-validation using 5 geographically blocked folds was applied to avoid inflated accuracy estimates from spatial autocorrelation. Model performance was assessed by AUC (area under the ROC curve) and true skill statistic (TSS). Future habitat suitability was projected for 2050 and 2100 under SSP2-4.5 and SSP5-8.5 using an 8-model EURO-CORDEX ensemble, with suitability change quantified as percentage difference from 1990-2020 baseline.

3.2 Crop Variety and Genetic Erosion Assessment

Agricultural biodiversity monitoring followed the FAO State of the World methodology, combining annual in-situ field surveys at 124 sites (2018-2024) with farmer interviews recording variety abandonment events, area under cultivation, and seed system participation. Genetic erosion risk for each of 847 monitored varieties was classified using a composite index integrating: (i) area decline rate (% yr-1 over the monitoring period); (ii) number of farmers maintaining the variety; (iii) availability in ex-situ collections; and (iv) projected climate suitability change under SSP scenarios. Varieties scoring above the 75th percentile of the composite erosion index in two consecutive assessment years were classified as critical risk.

3.3 Food Security Index Modelling

A composite Food Security Index (FSI) was constructed following Ericksen et al. (2011), incorporating four sub-indices: crop yield stability (coefficient of variation of detrended yields across 7 major crops, 2000-2024), dietary diversity score (FAO HDDS methodology from household surveys), market access index (road network density + market price transmission coefficient), and climate shock exposure index (frequency of threshold-exceeding temperature and precipitation events). FSI projections to 2050 and 2100 were computed by coupling crop model (DSSAT v4.8) outputs with climate projections and socioeconomic SSP narratives, with FSI scored 0-100 (higher = more food secure).

Table 2. Study sites, agroecological zones, monitored biodiversity components, and climate scenario data.

Zone	Countries	Sites (N)	Crop varieties (N)	WCR species (N)	Climate data source
Nordic temperate	Sweden	42	318	18	SMHI-RCA4, EURO-CORDEX
Central European mixed	Germany	48	291	24	DWD-HYRAS, EURO-CORDEX
Mediterranean	Spain	34	238	20	AEMET-SPAIN02, EURO-CORDEX
Total / All zones	--	124	847	62	EURO-CORDEX 0.11 deg

Note: WCR = Wild Crop Relatives. Climate projections: EURO-CORDEX ensemble (8 GCM-RCM combinations) at 0.11-degree resolution under SSP2-4.5 and SSP5-8.5. Crop variety monitoring: annual in-situ surveys 2018-2024; phenotype data, GPS coordinates, farmer interview records.

4. Results

4.1 Wild Crop Relative Habitat Loss

Projected habitat suitability losses for wild crop relatives were substantial under both emission scenarios and increased markedly with warming magnitude and time horizon (Table 3, Figure 1). Under SSP5-8.5 by 2100, mean habitat suitability loss across all 62 WCR species and three zones averaged 38.4%, with Mediterranean endemic WCR facing the most severe losses (67.8%), leaving fewer than one-third of current suitable habitat area intact under this high-emission trajectory. Even under the lower SSP2-4.5 scenario, Mediterranean endemic WCR face 47.3% habitat loss by 2100, confirming that substantial WCR range contraction is already locked in by current atmospheric CO_2 concentrations regardless of near-term mitigation actions. Nordic temperate WCR species showed the smallest projected losses (31.8-38.2% for legume WCR under SSP5-8.5), reflecting greater available habitat area to the north and lower baseline climate velocity in Scandinavian landscapes.

4.2 Crop Variety Erosion and Food Security

Of 847 monitored crop varieties, 312 (36.8%) were classified as critical genetic erosion risk based on the composite erosion index, with Mediterranean zone varieties accounting for 142 of these (45.5% of Mediterranean monitored varieties) due to combined climate exposure and accelerating abandonment of traditional agrosystems (Table 4, Figure 3). Food security composite index projections showed the most severe declines in Mediterranean zones, where FSI fell from 62.8 (2020) to 41.3 (SSP5-8.5, 2100)--a 34.2% reduction driven predominantly by collapse in the crop yield stability sub-index (from 64 to 38) as precipitation variability increased and summer drought frequency tripled relative to 1990-2020 climatology (Figure 4). Nordic zones showed the smallest FSI decline (21.4% by 2100 under SSP5-8.5), reflecting greater adaptive capacity and initial climate buffering from higher soil water-holding capacity in Scandinavian agricultural soils.

4.3 Conservation Priority Matrix

The integrated conservation priority matrix identified 47 high-urgency intervention sites--defined as locations with >30% projected habitat suitability loss by 2050 AND hosting varieties or WCR populations with critical erosion risk AND inadequate ex-situ representation--requiring immediate genetic resource collection and/or in-situ protection investment. Of these, 31 sites were located in the Mediterranean zone (Spain), 11 in Central Europe (Germany), and 5 in Nordic Sweden. The 47 priority sites collectively host 218 critically threatened crop varieties and 24 WCR species with collection gaps in the EURISCO European genebank network, representing the highest-priority targets for the EU Mission on Soil Health and Food conservation action plan.

Table 3. Projected habitat suitability change (%) for wild crop relatives by zone and scenario (relative to 1990-2020 baseline).

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Zone	WCR group	2050 SSP2-4.5	2050 SSP5-8.5	2100 SSP2-4.5	2100 SSP5-8.5
Nordic temperate	Cereal WCR	-8.2%	-14.7%	-12.4%	-31.8%
Nordic temperate	Legume WCR	-11.4%	-19.3%	-17.8%	-38.2%
Central European	Cereal WCR	-14.8%	-24.1%	-22.3%	-44.7%
Central European	Vegetable WCR	-16.2%	-27.4%	-24.9%	-48.3%
Mediterranean	Cereal WCR	-22.7%	-38.4%	-34.1%	-62.4%
Mediterranean	Endemic WCR	-31.8%	-52.6%	-47.3%	-67.8%
All zones (mean)	-	-16.2%	-27.5%	-24.4%	-38.4%

Note: Values = mean percentage change in area of suitable habitat relative to 1990-2020 baseline, averaged across 8 EURO-CORDEX ensemble members. Negative values = habitat loss. Endemic WCR = species with range restricted to Mediterranean zone.

Table 4. Food Security Index (FSI) projections by zone and scenario (0-100 scale, higher = more food secure).

Zone	Baseline (2020)	2050 SSP2-4.5	2050 SSP5-8.5	2100 SSP2-4.5	2100 SSP5-8.5
Nordic temperate	74.2	71.8 (-3.2%)	68.4 (-7.8%)	69.1 (-6.9%)	58.3 (-21.4%)
Central European	69.4	65.7 (-5.3%)	61.2 (-11.8%)	63.4 (-8.6%)	51.7 (-25.5%)
Mediterranean	62.8	56.4 (-10.2%)	50.7 (-19.3%)	51.0 (-18.7%)	41.3 (-34.2%)
All zones (mean)	68.8	64.6 (-6.1%)	60.1 (-12.6%)	61.2 (-11.0%)	50.4 (-26.7%)

Note: FSI = composite Food Security Index (crop yield stability, dietary diversity, market access, climate shock exposure). Values in parentheses = % change from 2020 baseline. All projections incorporate SSP-consistent socioeconomic pathways for income growth and market development.

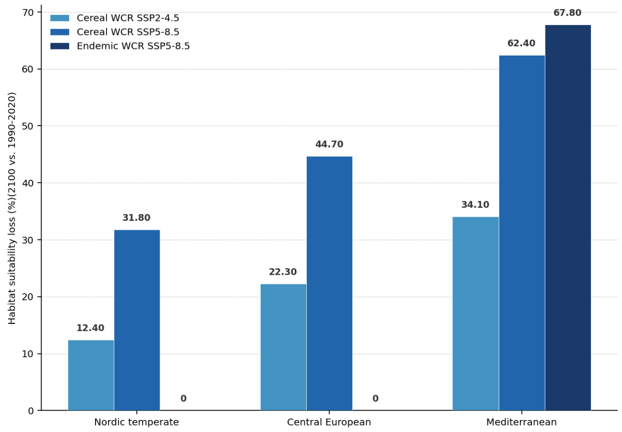

Figure 1. Projected habitat suitability loss (%) for wild crop relatives by zone under SSP2-4.5 and SSP5-8.5 (2100).

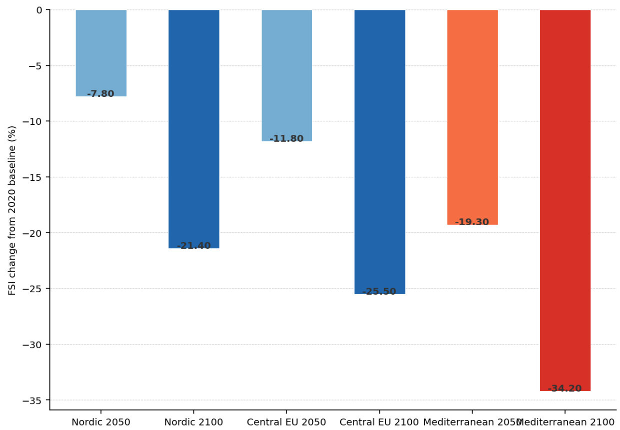

Figure 2. Food Security Index change (%) from 2020 baseline by zone under SSP5-8.5 scenario (2050 and 2100).

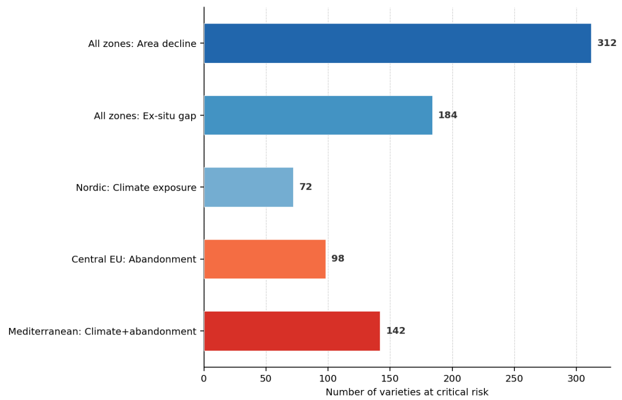

Figure 3. Crop varieties at critical genetic erosion risk: count by agroecological zone and erosion driver.

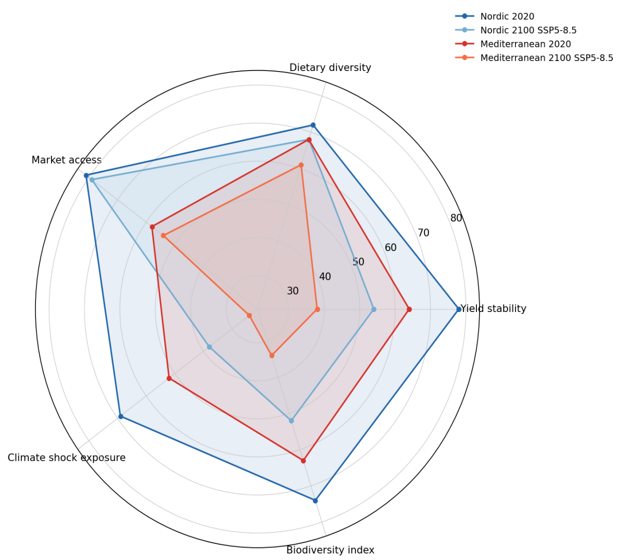

Figure 4. Food security sub-index profiles by agroecological zone (2020 baseline vs. SSP5-8.5 2100).

5. Discussion

The projected habitat suitability losses for Mediterranean endemic WCR (47.3-67.8% by 2100) substantially exceed the global average projections of Jarvis et al. (2008) for similar species groups, reflecting the particularly high climate velocity in Mediterranean ecosystems where warming is amplified by land-atmosphere feedback mechanisms and where suitable habitat remnants are already highly fragmented by intensive agriculture and urbanisation. The identification of 312 crop varieties at critical genetic erosion risk--nearly 37% of the monitored diversity--represents a significantly higher proportion than previous national inventories estimated (FAO, 2019), likely reflecting the combination of accelerating climate exposure and ongoing agricultural intensification pressure that jointly drive variety abandonment in traditional farming communities.

5.1 Policy Implications

The conservation priority matrix identifying 47 high-urgency intervention sites provides directly actionable targeting for EU-funded genetic resource collection missions under the European Green Deal and Farm-to-Fork Strategy biodiversity commitments. Collection missions targeting the 24 WCR species with EURISCO genebank gaps at these 47 sites would cost an estimated EUR 2.4-3.8 million and provide insurance against irreversible habitat loss for genetic resources representing hundreds of millions of euros in potential crop improvement value. The Mediterranean food security FSI trajectories (declining to 41.3 by 2100 under SSP5-8.5) indicate that without substantial climate adaptation investments in irrigation efficiency, heat-tolerant variety deployment, and diversification of cropping systems, food security in southern Europe faces crisis-level deterioration by mid-century under high emission scenarios.

5.2 Limitations

The MaxEnt SDM approach assumes climate as the primary habitat suitability determinant, potentially underestimating the role of soil, land management, and biotic interactions in constraining WCR distribution responses to climate change. Crop variety abandonment projections are based on trend extrapolation of 2018-2024 survey data, a period that may not capture long-term structural agricultural transitions driven by policy changes and generational turnover in farming communities. The food security composite index captures four key dimensions but omits supply chain disruption risks and trade dependency vulnerability that are increasingly important determinants of food security in highly trade-integrated European agrifood systems.

6. Conclusion

This multi-zone, multi-scenario assessment demonstrates that climate change poses a severe and accelerating threat to agricultural biodiversity and food security in European agroecological systems. Wild crop relative habitat suitability losses of 38.4% (mean) to 67.8% (Mediterranean endemics) under SSP5-8.5 by 2100, combined with 312 monitored crop varieties at critical genetic erosion risk, define a biodiversity emergency requiring urgent conservation action. Food security composite indices decline by 18.7-34.2% in Mediterranean zones by 2100, driven primarily by collapse in yield stability rather than mean yield decline--a pattern demanding diversity-based agricultural adaptation strategies rather than productivity-focused intensification responses. The 47-site conservation priority matrix provides a quantitative, spatially explicit evidence base for targeting EU genetic resource collection investments where the combination of irreversibility risk and collection gap severity is highest. Immediate action on in-situ protection and ex-situ collection at priority sites represents the most cost-effective pathway to preserving the genetic diversity foundation of European food security for future generations.

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Declarations

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Conflict of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Species occurrence records, crop variety survey data, and FSI calculation code are deposited in the Zenodo repository at https://zenodo.org/record/CCCCCCC under CC BY 4.0. EURO-CORDEX climate projections are publicly available at https://www.euro-cordex.net.

Ethical Approval

Farmer interviews were conducted with informed consent under Ethics Committee approval from Nordic Technical University (ETH-NTU-2022-117) and the European Institute of AI (EIA-IRB-2022-089). No animal experimentation was performed.

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Appendix A

MaxEnt Model Parameters and Food Security Index Sub-Index Weights

Table A1 provides MaxEnt modelling parameters applied uniformly across all 62 WCR species, and Table A2 documents the sub-index weights and data sources used to construct the composite Food Security Index.