



Agrometeorological risk of *Epitrix papa* in Europe under climate change using ERA5-land and EURO-CORDEX projections

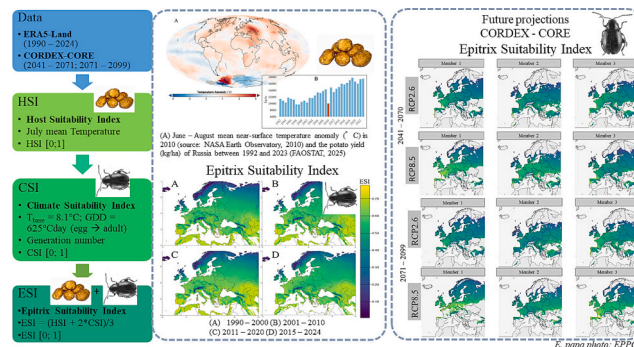
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HIGHLIGHTS

- Climate-stable potato zones shifted northwest in Europe (1990–2024).
- Optimal habitat for *E. papa* now is Iberia, as evidenced by ERA5-Land and records
- There will be limited habitat shift before 2070 across all scenarios (RCP2.6/8.5).
- By 2071–2099, RCP8.5 drives a marked northward expansion of suitable habitat.
- The ESI hotspots are now in W/C Europe; N Europe emerges under high emissions.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:

Host suitability index
Climate suitability index
Epitrix suitability index
Climate change
Potato flea beetle

ABSTRACT

The European distribution range of the recently described potentially threatening potato flea beetle *Epitrix papa* remain unknown. Understanding its potential range and future spread dynamics requires a host-specific thermal niche assessment. We developed an Epitrix Suitability Index (ESI) by combining a potato Host Suitability Index (HSI), proxied by July mean air temperature with a Climate Suitability Index (CSI), derived from degree-day accumulation between 1 March and 30 September (base 8.1 °C, 625 °Cday per generation). Past conditions were reconstructed from ERA5-Land for 1990–2024; while future projections based on CORDEX-CORE (EUR-22) RegCM4 downscaling of three GCMs under RCP2.6 / SSP1–2.6-TYPE LOW FORCING and RCP8.5 / SSP5–8.5-TYPE HIGH FORCING for 2041–2070 and 2071–2099. Present-day patterns reproduce known potato belts and show high model-agreement across Western and Central Europe, with greater spread across complex terrains such as Alps, the Carpathians, and Fennoscandia, as well as at transition zones. Projections indicate a possible northward shift of suitability of the host and pest, with the strongest shift under RCP8.5 / SSP5–8.5-TYPE HIGH FORCING during 2071–2099. This shift is accompanied by an increasing ESI across the British Isles, southern Scandinavia and the Baltic region, while parts of the Mediterranean may become less suitable as a result of heat stress affecting the host plant. The poleward displacement of the “optimal” belt is robust across members, although the magnitude of the change varies substantially, with uncertainty concentrated along mountainous areas. These results identify regions where adaptation efforts are most needed in terms of surveillance and integrated pest management, and provide a transparent, farm-aware framework for mapping emerging pest risks under climate change.

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1. Introduction

Potato (*Solanum tuberosum* L.) ranks among the world's most important staple crops, with annual production exceeding 370 million tonnes globally. Cultivation extends from cool temperate to subtropical zones, but optimal tuber bulking occurs between 15 °C and 20 °C, with pronounced reductions above 25 °C due to disrupted carbohydrate partitioning (Guillemette et al., 2025). Concurrently, several flea beetles of the genus *Epitrix* (Coleoptera: Chrysomelidae: Alticinae) have emerged as key pests of potato in North America and, increasingly, Europe. Of these, four out of the five species such as: *Epitrix tuberis* Gentner, 1944, *Epitrix cucumeris* Harris, 1851, *Epitrix subcrinita* LeConte, 1857 and *Epitrix papa* Orlova-Bienkowskaja (2015) are subject to quarantine or official control measures owing to their economic impact (Bieńkowski and Orlova-Bienkowskaja, 2016; European Food Safety Authority (EFSA) et al., 2019). Early reports of *Epitrix similis* Gentner, 1944 in Iberia were subsequently re-identified as *E. papa* (Orlova-Bienkowskaja, 2015). Eyre and Giltrap also call the attention to the potential and new threats of *Epitrix* species in Europe (Eyre and Giltrap, 2013).

In North America, *E. tuberis* ("tuber flea beetle") and *E. cucumeris* ("potato flea beetle") have long been recognized as widespread defoliators and tuber-scarring agents: outbreaks can cause heavy foliage feeding and shallow grooves/scarring in tubers that can render produce unmarketable (Eyre and Giltrap, 2013; EPPO, 2025a), however their present in Europe was observed around 2004 (Boavida and Germain, 2009). *E. subcrinita*, historically a minor pest in western U.S. potato belts are absent from Europe (European Food Safety Authority (EFSA) et al., 2019). Emergency EU measures now mandate non-EU seed and ware potatoes originate from pest-free areas or be brushed/washed to ≤ 0.1 % soil carryover (Bieńkowski and Orlova-Bienkowskaja, 2016). Two out of the five *Epitrix* species shown in Fig. 1 are present in Spain, Europe (EPPO, 2025a, 2025b). Namely, *E. cucumeris* and *E. papa* have already observed, while *E. similis*, *E. tuberis* and *E. subcrinita* have not yet reported.

All five *Epitrix* species share a strong affinity for potato but also attack other Solanaceae, including tomato (*Solanum lycopersicum*),

eggplant (*Solanum melongena*) and tobacco (*Nicotiana tabacum*) (Boavida et al., 2013; Bieńkowski and Orlova-Bienkowskaja, 2016). Adults overwinter in crop debris or soil in or near potato fields and become active in late winter–spring as temperatures rise, before moving onto potato plants as foliage develops (European Food Safety Authority (EFSA) et al., 2019). Larval feeding in *Epitrix* species is typically focused on below-ground tissues. In the case of *E. cucumeris*, the larvae primarily feed on potato roots (with only occasional, shallow entries into tubers). In contrast, *E. tuberis* and *E. papa* have been documented as the cause of superficial, serpentine galleries on potato tubers. *E. subcrinita* has also been documented to cause superficial tuber tracking; however, its tuber-damaging potential has been reported as variable. (EPPO, 2025a; EPPO, 2025b; Boavida and Germain, 2009; Boavida et al., 2013). *Epitrix* larvae undergo pupation in earthen cells within the soil. The development period from egg to adult is typically 3–7 weeks, contingent on temperature, generation and soil conditions (European Food Safety Authority (EFSA) et al., 2019). In the case of *E. cucumeris*, this period is often 4–5 weeks (EPPO, 2025b), whereas in the case of *E. tuberis*, it may extend to 7 weeks (Vernon and Thomson, 1993; EPPO, 2025a).

Although, these *Epitrix* species are widespread, there is a lack of information about their biological traits and threshold temperatures. The most comprehensive laboratory rearing of *E. papa* demonstrated rapid development: at 30 °C egg-to-adult took just 29.7 days, and at 25 °C females laid a lifetime total of ~190 eggs (Boavida et al., 2019). *E. subcrinita* has been observed to complete its development within a period of approximately 49 days under laboratory conditions set at 21 °C (Jones, 1944). It has been hypothesised that this species may be capable of producing two generations annually in certain geographical regions. However, research pertaining to the exact degree of fecundity and developmental parameters exhibited by the species at elevated temperatures within the existing literature is limited. For *E. tuberis* and *E. cucumeris* there is no reliable and exact data for developmental threshold temperatures in the literature, the EPPO description of the pests mentions its possible generation numbers, one or two generations for both pests in North America (EPPO, 2025a; EPPO, 2025b). All in all, *E. papa* has the most comprehensive knowledge of life development and the associated thresholds. Although this species has only been observed

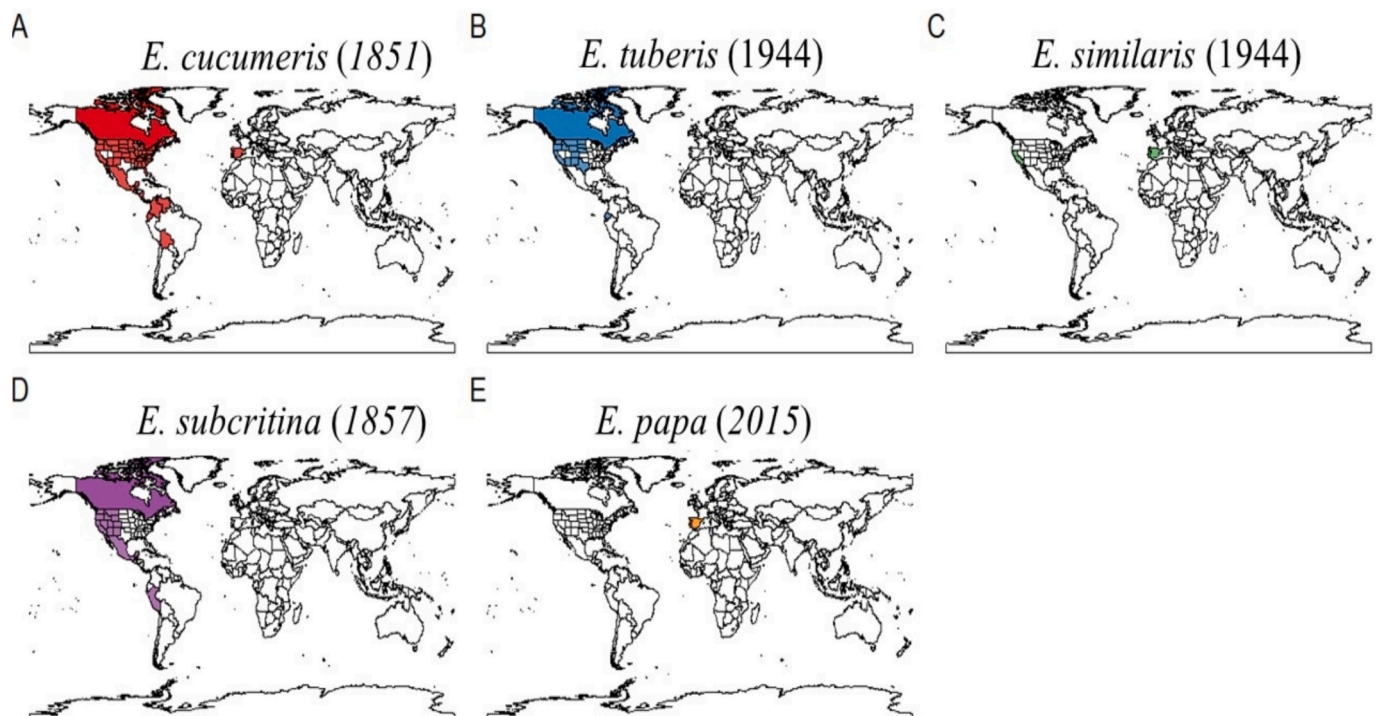


Fig. 1. Registered Distribution of *Epitrix* species based on EPPO database with the dates of the first records (EPPO, 2025a, 2025b).

in Spain and Portugal so far, Orlova-Bienkowskaja (2015) states that the species' origin and native range are still unknown. Therefore, within the geographical confines of the EPPO region, the presence of *E. papa* has been substantiated in Spain and Portugal (including the Azores and Madeira). The precise origins of this pest remain uncertain, and the potential for undetected presence beyond the current focus areas cannot be discounted.

Potato physiology is highly temperature-sensitive: tuber initiation peaks at 15–20 °C, declines steeply above 25 °C, and stops beyond 30 °C due to altered hormonal balance (Tavakoli et al., 2014). Foliage photosynthesis likewise suffers at day–night temperature differentials, with high nighttime minima exacerbating yield losses (Kim and Lee, 2019). In contrast, *Epitrix* species development accelerates under higher temperatures: *E. papa* requires 625 accumulated degree-days above 8.1 °C per generation (Boavida et al., 2019). Climate projections (+1.0–4.8 °C by 2100) predict shortened generation times and potential for up to three, or even four generations per year in southern Europe (Skendzić et al., 2021). This mismatch, i.e. heat-induced potato stress versus heat-accelerated pest phenology, creates a paradox: regions becoming less suitable for tuber bulking may simultaneously become hotspots for *Epitrix* outbreaks (Anu and Meena, 2025). Enhanced voltinism may overwhelm host-resistance and integrated pest management strategies, underlining the urgency for models that couple host crop phenology with pest thermal-time and distribution forecasts.

Comparative niche modelling, such as CLIMEX and MaxEnt, has been applied successfully to the potato tuber moth (*Phthorimaea operculella* Zeller, 1873 (Lepidoptera: Gelechiidae) to forecast current and future risk zones under climate change (Jung et al., 2020). Using CLIMEX for modelling the distribution and threats of different agricultural pests suggest potential northward expansion and altitudinal shifts worldwide (Jung et al., 2017; Early et al., 2022).

As a new and unique approach of climatic suitability of different plants, Sadeghfam et al. (2024a) formulated an AI-based probabilistic framework for rainfed medicinal plants in which they fit site-specific probability distributions to daily precipitation and temperature, interpolate occurrence probabilities via GIS processes, and then apply Particle Swarm Optimization clustering to derive a Climate Suitability Index for each grid cell. In a companion study, Sadeghfam et al. (2024b) developed a Shannon-Entropy Catastrophe Scheme for rainfed wheat, wherein they calculate occurrence probabilities of desired climate thresholds by frequency-based PDF fitting, spatially distribute these via inverse distance weighting, and combine the resulting layers through a series of catastrophe functions to map a Cultivation Potential Index.

In our study we explicitly rely on EURO-CORDEX high-resolution regional climate projections. A number of studies have applied RCM-ensemble workflows to insect pests at national scale e.g. winter survival/temperature suitability in Switzerland (Schneider et al., 2023) and to viticultural pests with explicit EURO-CORDEX forcing (Comte et al., 2024). Furthermore, EU-level assessments and project deliverables demonstrate the potential of EURO-CORDEX to underpin agricultural risk mapping and agro-climatic indices across Europe (Marcinkowski et al., 2023). In this study, the environmental changes for the potato and its pest, *E. papa*, were analysed from 1990 to the present based on ERA5-Land data, in order to assess changes in the environmental conditions relevant to *E. papa*, including decades prior to its establishment in Europe. However, Orlova-Bienkowskaja (2015) stated that the place of origin and its current distribution are unclear. In order to ensure the prevention and security of crops, it is essential to examine the future spread of the pest. To achieve this goal, we used EURO-CORDEX multimodel ensemble and different climate scenarios (RCP2.6 / SSP1–2.6-TYPE LOW FORCING and RCP8.5 / SSP5–8.5-TYPE HIGH FORCING) applying three GCMs and one RSM. The objectives of the present study are as follows:

1. Map the past and current optimal habitat for both potato and *E. papa* at a European scale.
2. Identify regions where potato yield declines and beetle pressure

coincide in the near and far future, highlighting priority areas for proactive pest management.

2. Material and methods

2.1. Description of climate data

ERA-5 Land database: daily four near-surface air temperature data (00; 06; 12; 18 UTC) were downloaded and daily mean were calculated for 1 March – 30 September from ERA5-Land database (Copernicus Climate Change Service, 2019). Spatial resolution was $0.1^\circ \times 0.1^\circ$. The reanalysis domain matches the EURO-CORDEX (Jacob et al., 2014) EUR-22 domain; accordingly, data were retrieved for longitudes -25° to 45° and latitudes 30° to 72° .

EURO-CORDEX database: July mean temperature and daily near-surface air temperature were downloaded for 1 March–30 September from the CORDEX-CORE (Jacob et al., 2014; <https://www.euro-cordex.net/> last access: 17. July 2025) multi-model ensemble over the EUR-22 domain ($\approx 0.11^\circ$). Data were subset to longitude -25° to 45° and latitude 30° to 72° . The coordinate system was EPSG:4326 – WGS84 geographic coordinate system (lat/lon). We used a single regional climate model, RegCM4 (ICTP), driven by three CMIP5 global models—NorESM1-M, MPI-ESM-LR, and HadGEM2-ES—under two emission scenarios, RCP2.6 / SSP1–2.6-TYPE LOW FORCING and RCP8.5 / SSP5–8.5-TYPE HIGH FORCING. Processing was performed with the CAVAanalytics package (Soldan et al., 2025) in R statistical and visualization software (R Core Team, 2021); for each scenario we obtained three members, with Member 1 = NorESM1-M, Member 2 = MPI-ESM-LR, and Member 3 = HadGEM2-ES. Analyses focused on two projection periods: 2041–2070 and 2071–2099.

Bias correction: An explicit bias correction was not applied to the EURO-CORDEX/CORE daily 2-m air temperature, but several studies have already estimated the bias of temperature in EURO-CORDEX. A multitude of evaluations of the EURO-CORDEX ensemble have been conducted in comparison to gridded observations, and these have reported modest warm-season temperature biases over a substantial proportion of Europe (typically within approximately ± 1 – 2°C) (Vautard et al., 2021). However, larger and more spatially structured errors have been observed over the Mediterranean region and in complex terrain (linked to soil-moisture/precipitation errors and elevation effects) (Matiu et al., 2024). For instance, an evaluation of the substantial EURO-CORDEX ensemble by Vautard et al. (2021) reveals summer median biases of typically less than 2°C across extensive regions, with more pronounced warm biases observed in the vicinity of the Mediterranean, while mountainous areas exhibit augmented errors attributable to elevation and lapse-rate representation. Over the Iberian Peninsula, daily temperature performance falls mostly within ± 1 – 2°C , depending on the reference and sub-region (Herrera et al., 2020). Studies over the Pannonian/Carpathian region, however, document a characteristic summer warm-dry bias (Torma and Kis, 2022). Elevation-dependent assessments further demonstrate that temperature biases increase with altitude in the Alps and other ranges (Smiatek et al., 2016; Matiu et al., 2024).

RCP–SSP scenario mapping: In this study we use regional climate projections from the CORDEX-CORE ensemble, which is driven by CMIP5 Representative Concentration Pathways (RCP2.6 / SSP1–2.6-TYPE LOW FORCING and RCP8.5 / SSP5–8.5-TYPE HIGH FORCING). Although these scenarios belong to the earlier RCP framework, they can be interpreted as predecessors of the CMIP6 Shared Socioeconomic Pathway (SSP) scenarios. Following Meinshausen et al. (2020), SSP1–2.6 and SSP2–4.5 are approximately the successors of RCP2.6 / SSP1–2.6-TYPE LOW FORCING and RCP4.5, while SSP5–8.5 is closely comparable to RCP8.5 / SSP5–8.5-TYPE HIGH FORCING, mainly differing in lower methane concentrations. Thus, RCP2.6 / SSP1–2.6-TYPE LOW FORCING and RCP8.5 / SSP5–8.5-TYPE HIGH FORCING used here can be regarded as representing SSP1–2.6-type low-forcing

and SSP5-8.5-type high-forcing futures, respectively. Throughout the paper, we therefore refer to our scenarios as ‘RCP2.6 / SSP1-2.6-TYPE LOW FORCING / SSP1-2.6-type’ and ‘RCP8.5 / SSP5-8.5-TYPE HIGH FORCING / SSP5-8.5-type’ to facilitate comparison with recent SSP-based studies.

2.2. Host suitability index (HSI)

The objective was to identify a method that would both reproduce the current distribution of potato-growing areas in Europe and rely exclusively on predictors available in the EURO-CORDEX archive. Consequently, the July mean temperature was utilised as a solitary indicator to delineate the potential potato-growing zones. In order to demonstrate the adequacy of this approximation, a comparison was made between our calculations and the FAO Potato Suitability Index (FAO IIASA, 2010) (Fig. 2). The classification of each grid cell into one of eight Suitability Category was based on the mean temperature in July (Table 1). This permitted a direct comparison to be made between the FAO Suitability Index for Potato categories and a temperature-based potential suitability map (Fig. 2).

Numerous studies have addressed potato-growing areas in Europe (Daccache et al., 2012; Goffart et al., 2022), yet our understanding of the stability of these regions remains incomplete. In accordance with this, an investigation was conducted into the climatic stability of potato cultivation, and the Potato Production Stability Index was created. Accordingly, the climatic stability of potato cultivation was examined by setting up the following 10-year intervals between 1990 and 2024: 1991–2000, 2001–2010, 2011–2020, and 2015–2024. The subsequent step involved the enumeration of categories, with the objective of ascertaining the maximum value. The cultivation of potato is considered to be stable if it falls into the same suitability category in a minimum of seven out of the ten years (Table 1). If it remains in the same category for five or six years, it is considered moderately stable; if it is in the same category for four years, it is considered low stability. The mathematical background of these calculations can be seen as follows.

Modal frequency (number of times the most frequent category occurred) is calculated by

Table 1

Temperature intervals and potato suitability categories based on the the categories derived from the July mean temperature. The name of the first column is presented as a variable in a subsequent calculation (Eq. 3).

$c_{mod,i}$	Temperature intervallum	Suitability category
1	$(-\infty, 13.0)$	Not suitable
2	$[13.0, 15.0)$	Low
3	$[15.0, 16.0)$	Moderate
4	$[16.0, 18.3)$	High
5	$[18.3, 20.6)$	Good
6	$[20.6, 22.8)$	Moderate
7	$[22.8, 24.0)$	Low
8	$[24.0, \infty)$	Not suitable

$$f_{max,i} = \max_k(count_i(k)) \quad (1)$$

where $count_i(k)$ is the number of occurrences of the k^{th} category in the i^{th} grid on the European domain. Based on Eq. 1, a stability code was assigned based on the modal frequency:

$$s_i = \begin{cases} 1, & 0 \leq f_{max,i} < 5, \\ 2, & 5 \leq f_{max,i} < 7, \\ 3, & 7 \leq f_{max,i} \leq 10. \end{cases} \quad (2)$$

In the case of category $s_i = 3$, it is a crucial information whether the highest return modal frequency is in the low, moderate, or good/high suitability category. Therefore, based on Eq. 2, we defined three additional subcategories as follows:

$$s'_i = \begin{cases} 31, & s_i = 3 \wedge c_{mod,i} \in \{2, 7\} \\ 32, & s_i = 3 \wedge c_{mod,i} \in \{3, 6\} \\ 33, & s_i = 3 \wedge c_{mod,i} \in \{4, 5\}. \end{cases} \quad (3)$$

where $c_{mod,i}$ was defined in Table 1, while $\wedge$ operator denotes the logical AND operator, i.e. both conditions must be satisfied simultaneously. Important to note that this stability of the potato growing areas was calculation only in the reanalysis fields, because it would not be appropriate to consider annual data in the context of climate

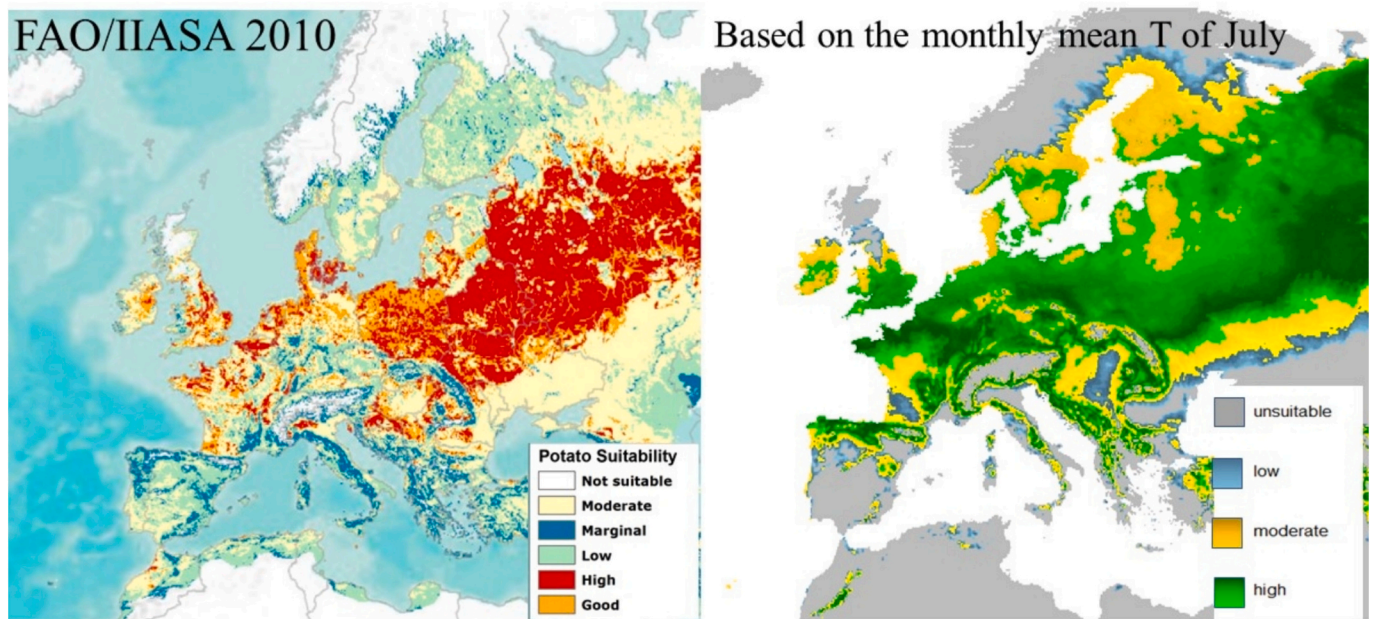


Fig. 2. Comparison of FAO/IIASA, 2010 Potato Suitability Index and our Potato Suitability based on the monthly mean temperature of July (FAO IIASA, 2010). The colours indicate the potato suitability categories, while lighter and darker shades are used only to enhance visual distinction and do not carry additional quantitative meaning.

projections.

Subsequently, the Host Suitability Index (HSI) was created based on the July temperature. The HSI is a dimensionless value that ranges from 0 to 1. The function was divided into four sections based on the average July temperature (Fig. 3). The function assumes a value of 1 between 16 °C and 18.3 °C, which is considered to be the optimal range for potato cultivation and tuber development. The suitability of potato production decreases more slowly at temperatures below 16 °C and more rapidly at temperatures above 18.3 °C. This is due to the fact that potatoes tolerate lower temperatures better than high temperatures (Merzlaya et al., 2008). In conditions of temperature below 13 °C and above 24 °C, the HSI value is recorded as zero, indicating that the region is deemed unsuitable for potato cultivation. The values of the function are described by Eq. 4.

$$HSI(T) = \begin{cases} 0, & T \leq 13^\circ\text{C or } T \geq 24^\circ\text{C} \\ \sqrt{\frac{T-13}{3}}, & 13^\circ\text{C} < T < 16^\circ\text{C} \\ 1, & 16^\circ\text{C} \leq T \leq 18.3^\circ\text{C} \\ 1 - \sqrt{\frac{T-18.3}{24-18.3}}, & 18.3^\circ\text{C} < T < 24^\circ\text{C} \end{cases} \quad (4)$$

2.3. Climate suitability index of *Epitrix papa*

The Climate Suitability Index (CSI) was computed from daily mean air temperature for each grid cell over the season 1 March–30 September, using a base temperature of $T_{\text{base}} = 8.1^\circ\text{C}$ (Boavida et al., 2019). The daily effective temperature (T_{eff}) was calculated by

$$T_{\text{eff}} = \max(T_{\text{daily}} - T_{\text{base}}, 0) \quad (5)$$

i.e. the negative daily heat values were considered to be zero. The seasonal Growing Degree Days were determined using the following:

$$GDD = \sum_{1 \text{ March}}^{30 \text{ September}} T_{\text{eff}} \quad (6)$$

where it must be noted that the reanalysis dataset contained the appropriate month lengths, while the EURO-CORDEX projections used a unified 30-day months, however, the difference between the two calculation methods is four days in a growing season. The egg-to-adult Growing Degree Days necessary for germination were 625 °C.

Calculating the number of germinations in a growing season (GEN), the Climate Suitability Index (CSI) for *E. papa* was calculated by the following:

$$CSI = \begin{cases} 0, & GEN < 1 \\ \frac{GEN-1}{3}, & 1 \leq GEN < 4 \\ 1, & GEN \geq 4 \end{cases} \quad (7)$$

i.e. this index is a dimensionless value ranging from 0 to 1.

2.4. *Epitrix* suitability index

While the values of both CSI and HSI fall in the [0; 1] interval, so ESI takes its values from this interval, as well. The Climate Suitability Index was weighted by two, because the presence of host plant is less crucial as only potato was taken into account, but other possible hosts was left out of consideration. So, the *Epitrix* Suitability Index (ESI) can be calculated as the following:

$$ESI = \frac{2 \cdot CSI + HSI}{3} \quad (8)$$

The suitability categories based on Jung et al. (2020) can be seen in Table 2.

2.5. Statistical methods

The processing of reanalysis data was implemented using the packages of “terra”, “ncdf4” and “tmnp” in R statistical software (R Core Team, 2021). The processing of climate projections and the visualization were achieved by the Climate and Agriculture Risk Visualization and Assessment (CAVA) (Soldan et al., 2025) and the packages of “ncdf4”

Table 2
Epitrix Suitability Index categories.

ESI	Category
ESI < 0.20	not suitable
0.20 ≤ ESI < 0.40	low suitability
0.40 ≤ ESI < 0.60	moderate suitability
0.60 ≤ ESI < 0.80	good suitability
0.80 ≤ ESI ≤ 1	high suitability

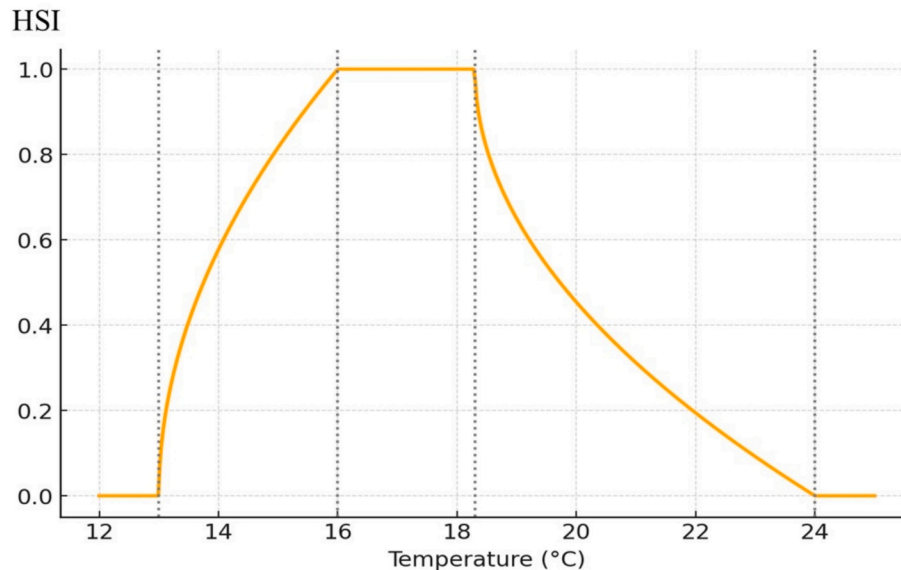


Fig. 3. the function of the Host Suitability Index (HSI) based on the mean July temperature, based in Eq. 4.

(Pierce, 2025), “terra” (Hijmans, 2025), “sf” (Pebesma and Bivand, 2023), “loadeR” (Rodriguez, 2023), “tmap”, “climate4R” (Iturbide et al., 2019) in R statistical software.

3. Results

3.1. Past climate suitability patterns for potato and *Epitrix papa*

A number of studies have addressed the environmental changes and challenges facing potato production using different indices (Daccache et al., 2012). For this reason, only a few years have been highlighted in Fig. 4 as examples of potato cultivation, with the aim of facilitating comprehension of the results of the Potato Production Stability Index. As demonstrated, certain regions, including parts of France and Germany, have exhibited a consistent high level of suitability across all the years examined. Conversely, there are areas where the suitability category exhibits significant variability.

For instance, 2010 was a remarkable year, when meteorological conditions proved disadvantageous for potato production across substantial regions of Ukraine and western Russia (Fig. 4/C). In that year, Russia experienced significant heat waves in July, which is further confirmed by Fig. 5/B on potato production (kg/ha) based on FAOSTAT data from 1992 to 2024. It clearly demonstrates the crop losses caused by the heatwave, due to the exceptionally hot summer of 2010 in Russia. In contrast, other regions of Europe did not encounter such substantial positive temperature anomalies (Fig. 5/A).

This is indeed the rationale behind the development of the Potato Production Stability Index, which employs a three-tier categorisation system comprising “low stability,” “moderate stability,” and “stable.” Within the “stable” category, it was necessary to assess whether

favourable or unfavourable growing conditions indicated stability. This resulted in the creation of three subcategories: high suitability – stable, moderate suitability – stable and low suitability – stable. Between 1990 and 2000 (Fig. 6/A), the high suitability – stable category was typical in Western Russia and Ukraine, as well as in South-Eastern Europe, the Balkan region and the cooler climates of Western Europe. The topography of Germany and Poland was typified by moderate and low stability areas. Low stability – stable category, i.e. where conditions for potato cultivation would have been unfavourable in at least 7 out of 10 years, did not occur in any decade. Since the 2000s (Fig. 6/B – D), the high suitability – stable regions have shifted westward. In particular, we see large areas of stable high suitability categories in Germany and Poland. It is also worth keeping an eye on the Mediterranean, as potato cultivation is also present in these areas. Significant changes can be observed in Italy and in the Balkan region. However, the growing environment was not necessarily optimal between 1990 and 2000 and 2001–2010 (see Fig. 6/A and Fig. 6/B), but moderate suitability can be seen in stable areas. Later, in both Italy and Greece, there has been a notable increase in the area designated as unsuitable between 2015 and 2024 (Fig. 6/D).

It is imperative to analyse the shift in relationship between the low stability and high suitability – stable categories, as these two extremes constitute the stability categories. For this reason, the focus has been on these two categories in Fig. 7 for the periods 1990–2000 (Fig. 7/A) and 2015–2024 (Fig. 7/B). The arrows indicate the change in the geographical location of the two categories. The change is pronounced, with the two categories exchanging places based on data from the periods 1990–2000 and 2015–2024. The high suitability-stable category has undergone a geographical shift, moving from its previous location in western Russia to the regions of Germany and Poland. In contrast, the

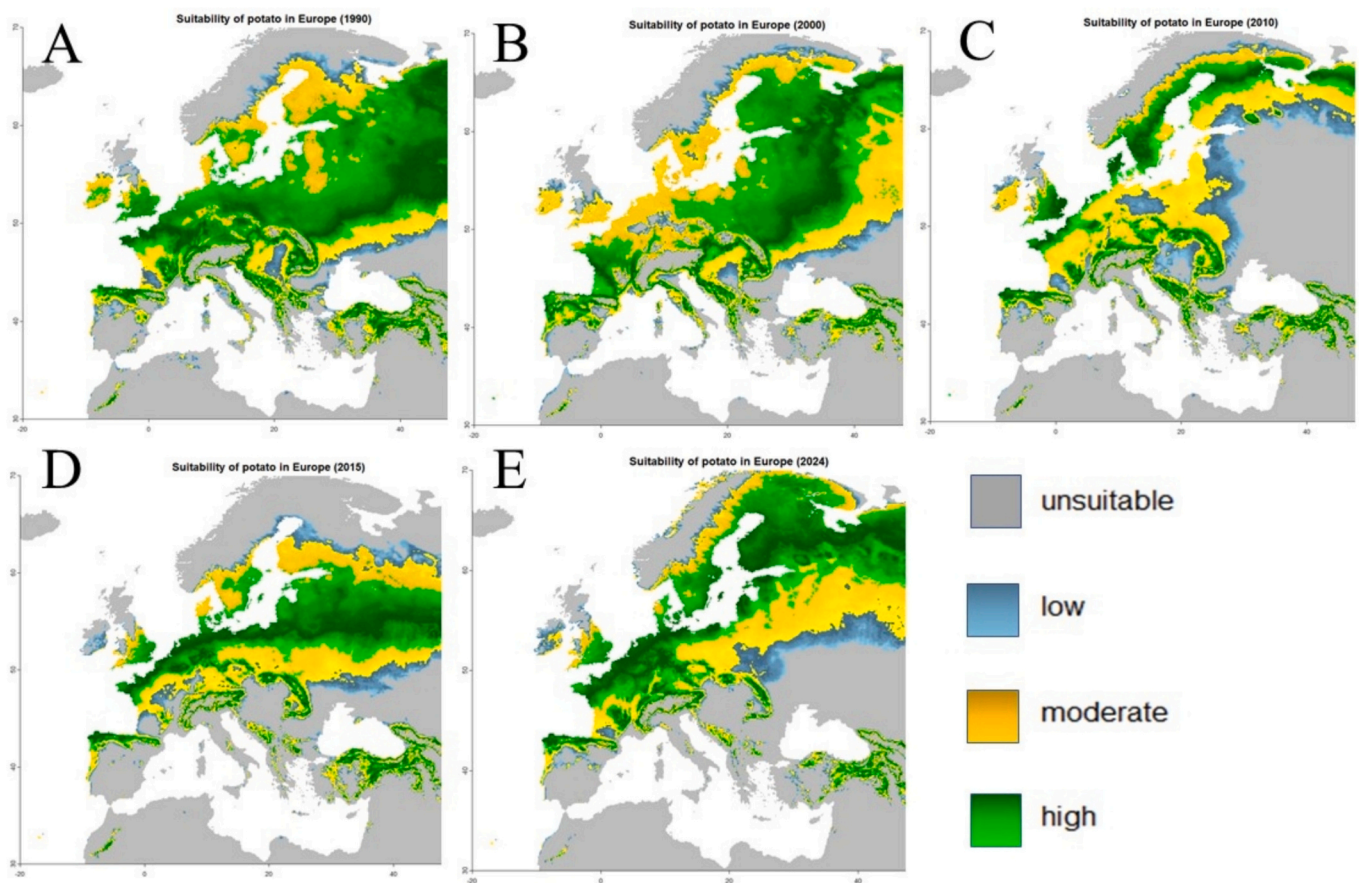


Fig. 4. Categories of potato suitability in Europe in certain years: (A) 1990, (B) 2000, (C) 2010, (D) 2015, (E) 2024. The primary colours indicate the potato suitability categories, while lighter and darker shades are used only to enhance visual distinction and do not carry additional quantitative meaning.

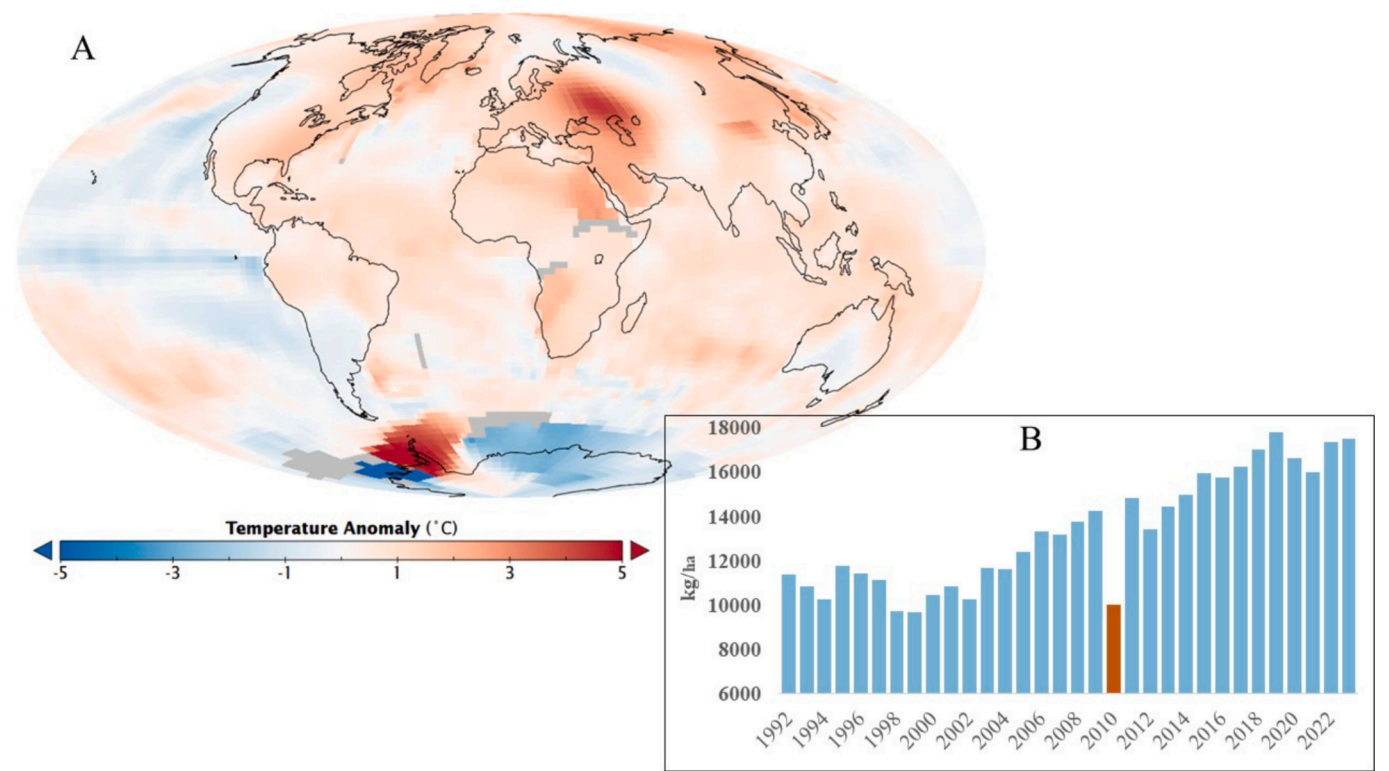


Fig. 5. (A) June – August mean near-surface temperature anomaly ($^{\circ}\text{C}$) in 2010 (source: NASA Earth Observatory, 2010) and the potato yield (kg/ha) of Russia between 1992 and 2023 (FAOSTAT, 2025).

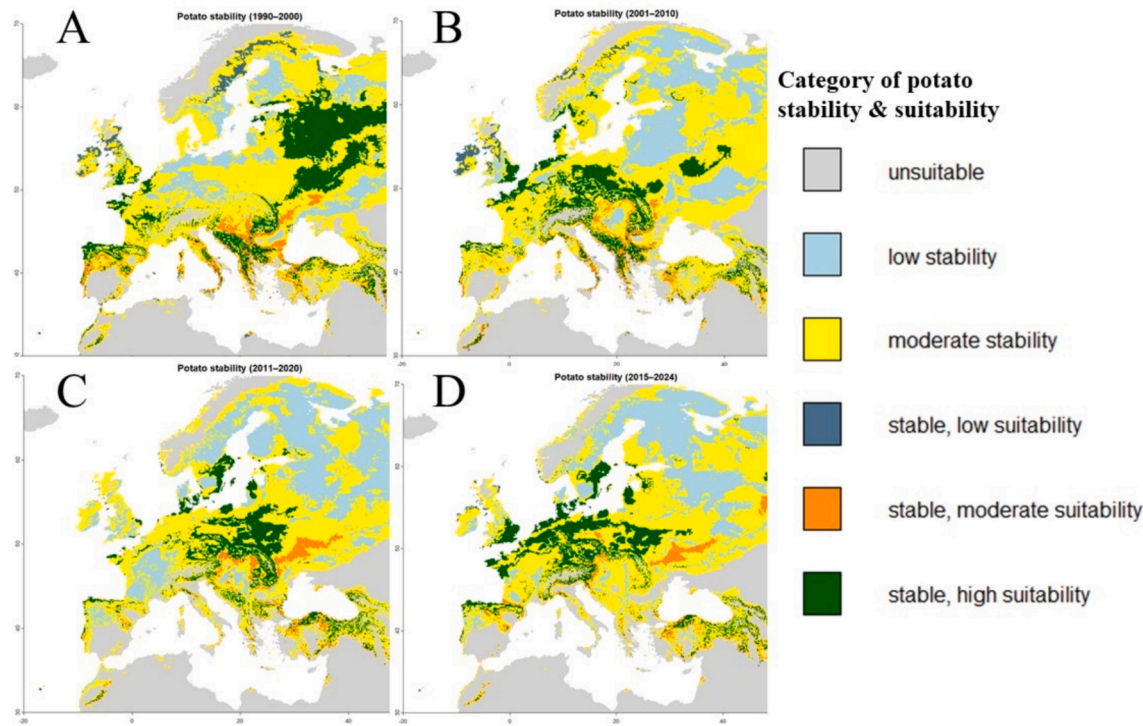


Fig. 6. Categories of potato production stability in (A) 1990–2000 (B) 2001–2010 (C) 2011–2020 (D) 2015–2024.

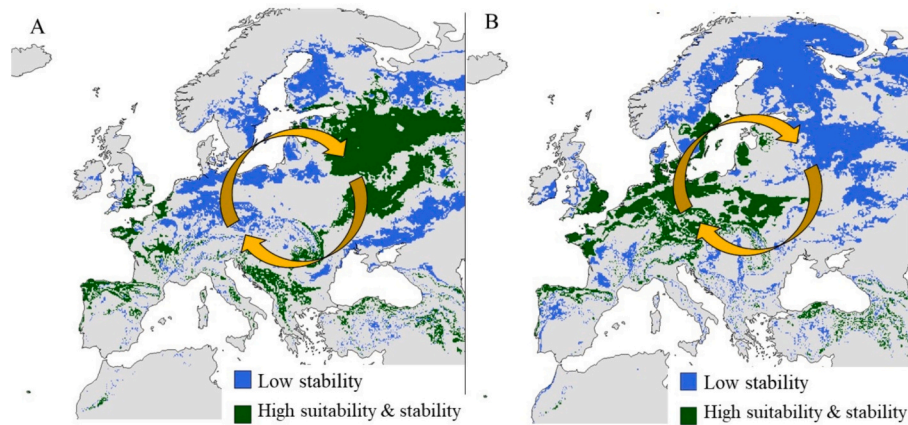


Fig. 7. The geographical location of the high suitability – stable and low stability categories over the period 1990–2000 and 2015–2024. The yellow arrows symbolize the change in position between the two categories.

low stability areas have experienced a shift towards western Russia.

3.2. Historical climatic suitability of *Epitrix papa* in Europe

To date, only a limited number of *Epitrix* species have been introduced in Europe: *E. cucumeris*, *E. similaris*, and *E. papa*. It is noteworthy that only one species of this group, *E. papa*, has undergone comprehensive physiological examination and description (Boavida et al., 2019). Despite the fact that *E. papa* was identified only in 2015, making it the most recently described species among the *Epitrix* species, its climatologically possible habitat must be examined even in the past decades in Europe, as it is the only way to become possible to describe habitat shifts related to climatological changes up to 2099. A study of CSI values based on ERA5-Land reanalysis data reveals a shift in climatologically suitable habitat ($CSI > 0.5$) northwards between 1990 and 2024 (Fig. 8). The shift was smallest in Western Europe and the easternmost areas, while the largest shift occurred in the region from Ukraine (1990) to the Baltic states, where the habitat shifted northward over the examined four decades (Fig. 8/D). The black lines represent the

line north of which climatic conditions are no longer conducive to the appearance of *E. papa*.

The *Epitrix* Suitability Index (ESI) is the weighted average of the two indices presented above, with twice the weight given to the Climate Suitability Index and once the weight given to the Host Suitability Index, i.e. the presence of host plants, as we did not examine the effects of irrigation and other agrotechnical operations during potato cultivation, which would allow us to exclude areas where potatoes or other alternative host plants (e.g. tomatoes) are actually present. ESI values above 0.7 indicate favourable conditions, where both the host plant and the pest have the necessary temperature conditions. Fig. 9 shows that the *Epitrix* Suitability Index (ESI) values are currently highest in southern Europe, mainly in western Spain and Portugal. Compared to 1990–2000, the ESI value has increased in Western Europe, mainly in France and the Benelux countries. The territorial changes in ESI categories can be clearly seen in Fig. 10, where, in addition to Western Europe, Central Europe and the Balkan Peninsula should also be mentioned as past potential habitats for the pest, however in the last decade its habitat has shrunk in Central Europe and its centre of focus has shifted to Western

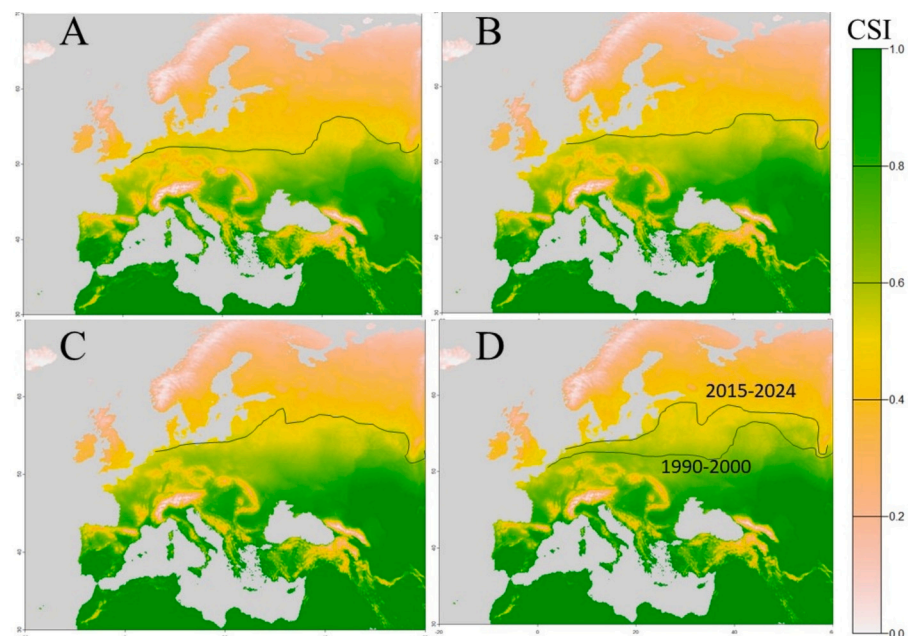


Fig. 8. The climatic suitability of *E. papa* in the last four decades to demonstrate the poleward shift of suitable areas due to the temperature rise in the growing season in (A) 1990–2000 (B) 2001–2010 (C) 2011–2020 (D) 2015–2024.

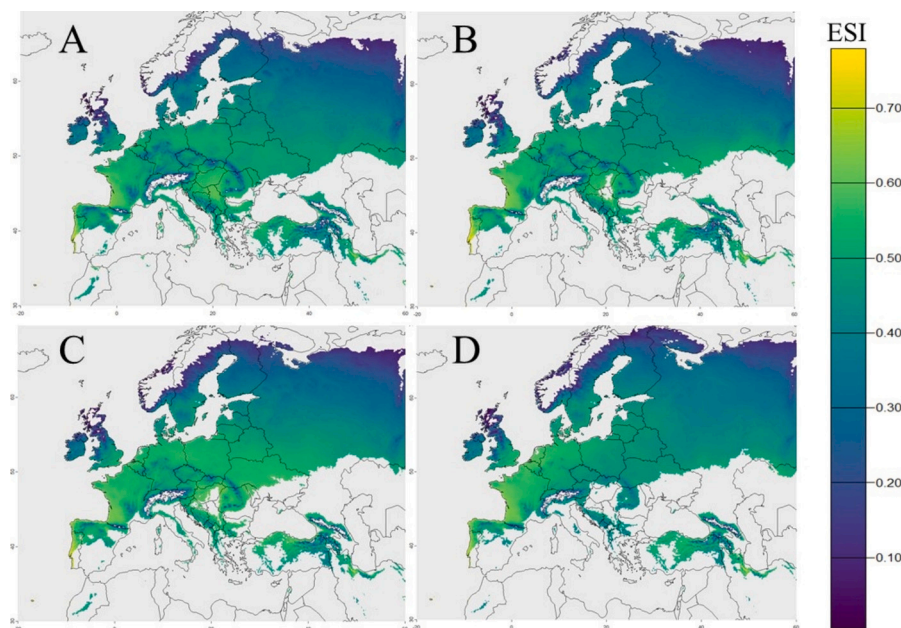


Fig. 9. Epitrix Suitability Index (ESI) in Europe in (A) 1990–2000 (B) 2001–2010 (C) 2011–2020 (D) 2015–2024.

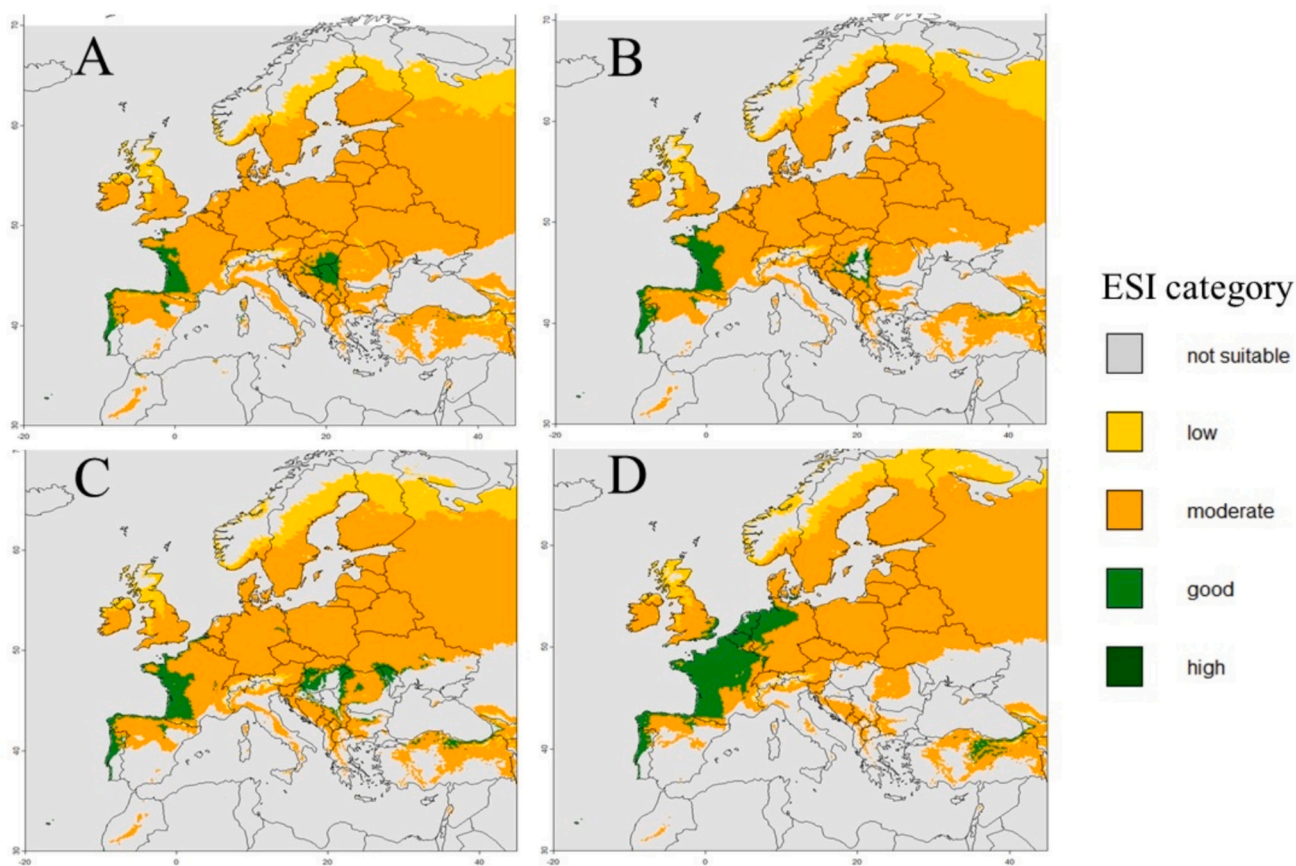


Fig. 10. Historical Epitrix Suitability Index (ESI) categories in Europe in (A) 1990–2000 (B) 2001–2010 (C) 2011–2020 (D) 2015–2024.

Europe, where the conditions are favourable to spread over a large area. However, there have been still no official sightings in these areas to date. A good example of change detection is the Carpathian Basin and Romania. The entire area would have been suitable for pest habitats between 1990 and 2000 (Fig. 10/A). In the next decade, spatial

continuity began to break down and, in the last decade, the Carpathian Basin became too warm for optimal potato cultivation, thus reducing habitat potential for the pest. The same process can be seen in Romania. A northward shift has been evident over the last four decades.

3.3. Future distribution possibilities of potato and *Epitrix papa* in Europe

3.3.1. Climate projection of HSI

The present study has thus far examined past habitat suitability, with a discussion of the stability of potato cultivation conditions and *Epitrix* Suitability Index based on ERA5-Land reanalysis data. The subsequent study will examine the results of the EURO-CORDEX climate projections, with climate data being sourced from the CAVAanalytics postprocessed database. Fig. 11 illustrates the suitable growing areas for potatoes (HSI – Host Suitability Index) for the periods 2041–2070 and 2071–2099, under the RCP2.6 / SSP1–2.6-TYPE LOW FORCING and

RCP8.5 / SSP5–8.5-TYPE HIGH FORCING scenarios, based on the results of the three RCMs (Member 1–3). In the context of RCP2.6 / SSP1–2.6-TYPE LOW FORCING, a substantial moderate-to-high HSI belt extends across Western and Central Europe, encompassing the British Isles, France, the Benelux countries, and northern Germany, with Poland also falling within this region. In contrast, the Mediterranean fringe exhibits predominantly low levels of HSI. In the context of RCP8.5 / SSP5–8.5-TYPE HIGH FORCING, the favourable zone undergoes a shift in direction towards the northeast, accompanied by a strengthening of the meridional gradient. This shift is characterised by higher HSI values in regions such as Scandinavia, Scotland/Iceland, and northwestern Russia, in

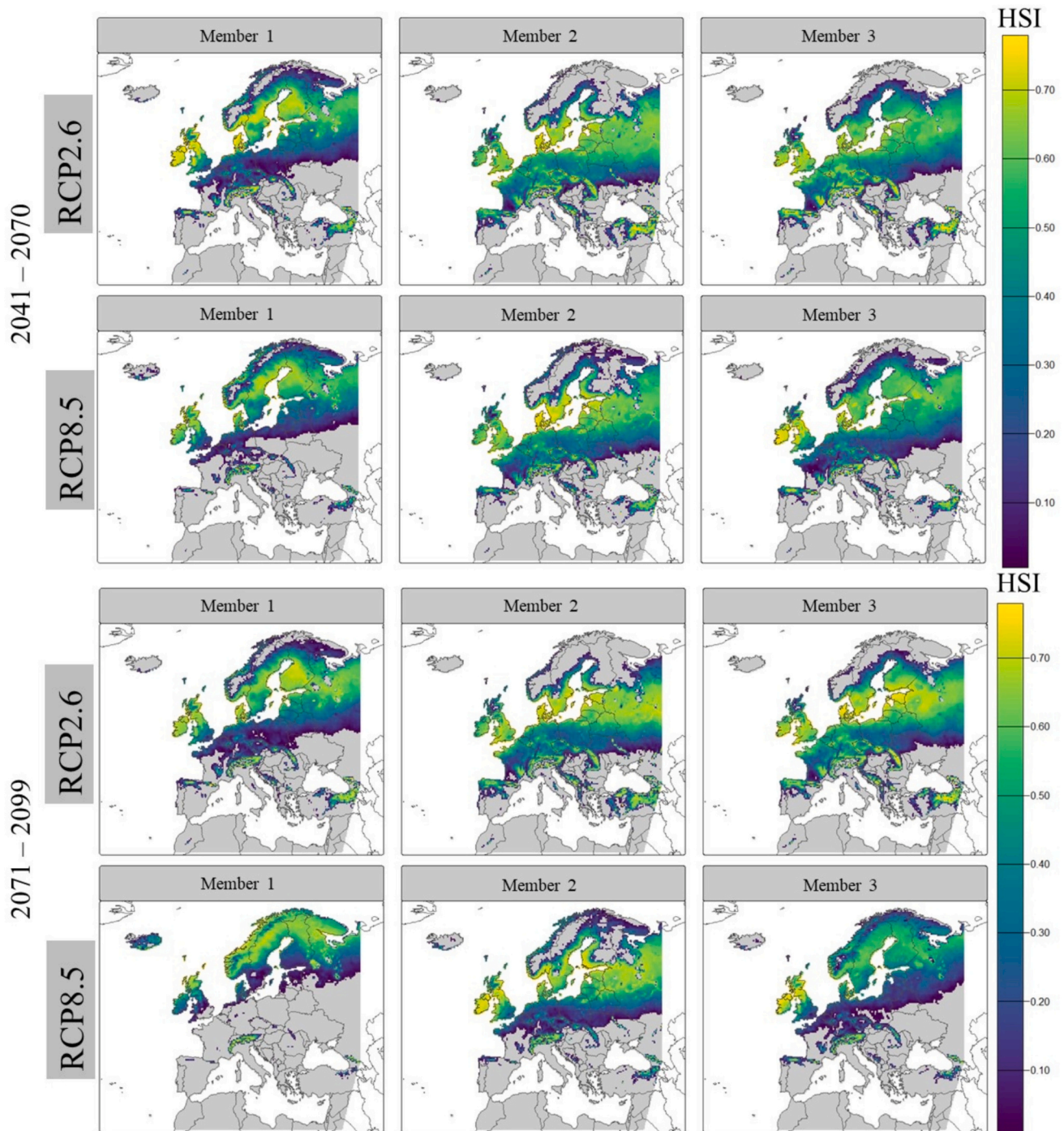


Fig. 11. Future projection of Host Suitability Index (HSI) for RCP2.6 / SSP1–2.6-TYPE LOW FORCING and RCP8.5 / SSP5–8.5-TYPE HIGH FORCING for three ensemble members for 2041–2070 and 2071–2099. Member 1 = NorESM1-M, Member 2 = MPI-ESM-LR, and Member 3 = HadGEM2-ES.

conjunction with pronounced declines across the Mediterranean basin. However, even in the most favourable regions, HSI values generally peak around 0.6–0.75, and extensive “very high” areas (≥ 0.8) are rare, concentrating only in a narrow line in Denmark, Ireland, and some parts of the Baltic region. A comparison of Fig. 11 with ERA5-Land reanalysis (Fig. 4) data reveals values in excess of 0.8 HSI, with dark green colours, albeit in a very narrow band, extending across Europe from Western Europe to Russia. The largest inter-member spread is observed along transition zones, where the HSI gradient is high, including southern Scandinavia and the Baltic region, the eastern European margins, and the Balkans-Carpathian Basin. In these regions, the northward

displacement of suitability is member-dependent. The topography of the region is characterised by a mosaic pattern, which is further compounded by the presence of the Alps, the Carpathians, and the Scandinavian highlands. This topography is consistent with orographic temperature and precipitation gradients, which amplify the differences between the constituent members. In contrast, oceanic Western Europe and the core of Central Europe demonstrate the most stable signals among members. As illustrated in Fig. 11 (below), the 2071–2099 projections under the RCP2.6 / SSP1-2.6-TYPE LOW FORCING scenario demonstrate relatively modest changes. The region exhibiting a moderate to high HSI consolidates and shifts northeastwards, exhibiting an

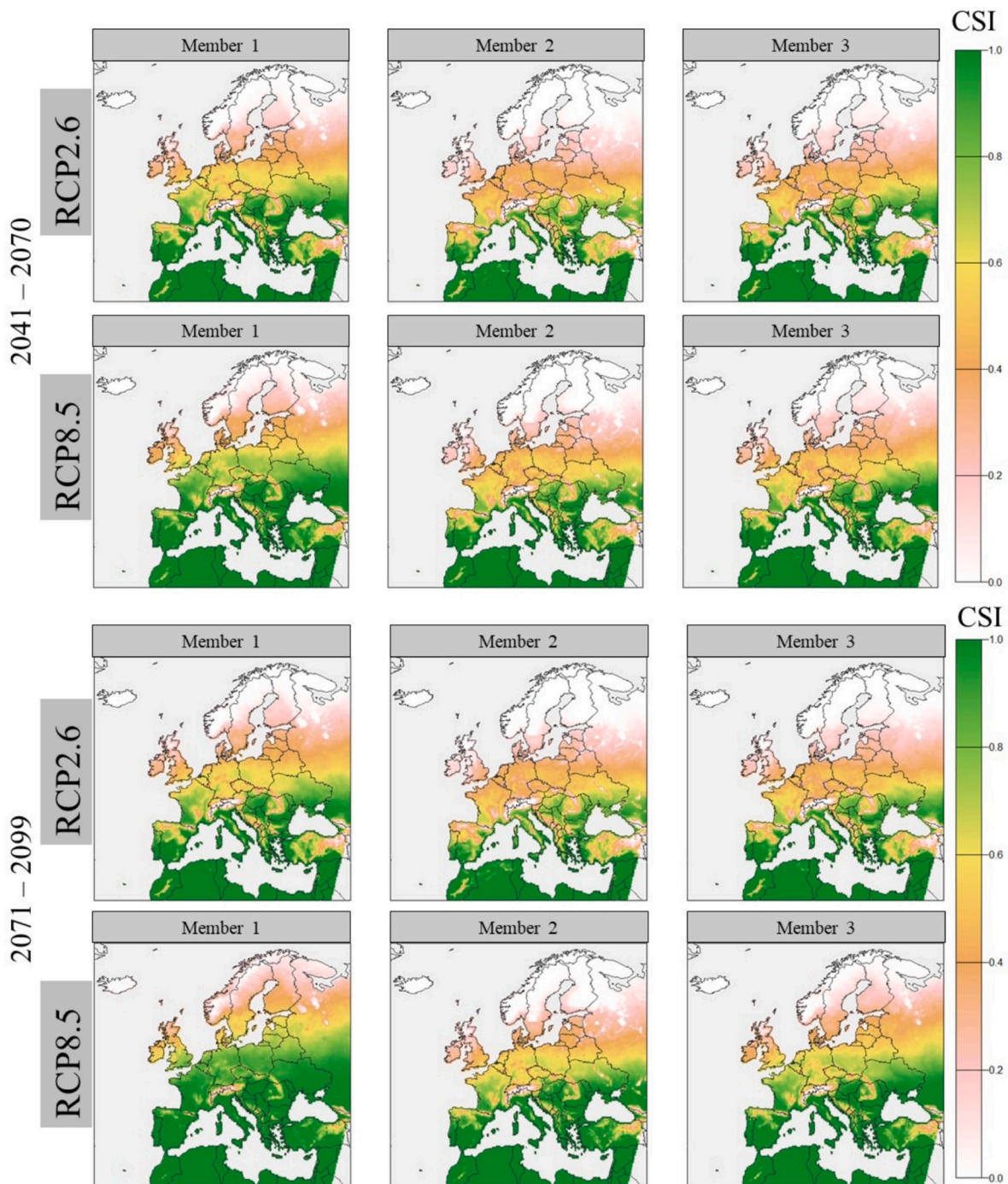


Fig. 12. Future projection of Climate Suitability Index (CSI) for RCP2.6 / SSP1-2.6-TYPE LOW FORCING and RCP8.5 / SSP5-8.5-TYPE HIGH FORCING for three ensemble members for 2041–2070 and 2071–2099. Member 1 = NorESM1-M, Member 2 = MPI-ESM-LR, and Member 3 = HadGEM2-ES.

increase in intensity over Scandinavia and northwestern Russia. Concurrently, the Mediterranean region experiences a slight retreat. In the context of RCP8.5 / SSP5–8.5-TYPE HIGH FORCING, the shift is characterised by a marked intensification and expansion of the favourable belt across the British Isles and Fennoscandia, accompanied by a coherent decline over the Mediterranean Basin. Inter-member differences remain largest along transition regions (Southern Scandinavia/Baltic area, the eastern European margins and the Balkans-Carpathian region) and over complex topography (Alps, Carpathians, Scandinavian Highlands), where minor thermodynamic/orographic perturbations result in substantial alterations. It is important to note that Member 1 is an outlier in terms of spatial pattern. It is evident that the suitability belt is pushed unusually far poleward by this member, resulting in significant regions of Germany, Poland and the Baltic states falling below the moderate class when compared with the other members.

3.3.2. Climate projection of CSI

Following an analysis of the changes in potato production areas, now the discussion will move on to the determination of the future areas possibly favourable for pests. The number of generations has been determined by calculating the GDD, and a linear index number between [0;1] has been created based on the number of generations to determine the most favourable areas. In this instance, in contrast to the HSI, it is anticipated that a north-south gradient will be observed, with a maximum CSI = 1 value in the south and a CSI = 0 value in the north (Fig. 12). During the period 2041–2070, there is a negligible discrepancy between the members and the RCPs. In southern regions, including France, Italy, the Carpathian Basin, and areas south and east of the Carpathians, where up to four generations can develop during the growing season, this results in GDD exceeding 2500 °C with a threshold temperature of 8.1 °C. This phenomenon is also evident in the ERA5-Land data (Fig. 8), although a northward shift is observed between the periods 1990–2000 and 2015–2024. The CSI = 1 category is shown in the RCP8.5 / SSP5–8.5-TYPE HIGH FORCING members for 2071–2099 in Fig. 12. Across the two projection periods, the CSI maps indicate a systematic northward expansion of high suitability, with areas that are unsuitable (white) contracting. As demonstrated in Fig. 12, under

RCP2.6 / SSP1–2.6-TYPE LOW FORCING, this shift is modest, but it becomes pronounced under RCP8.5 / SSP5–8.5-TYPE HIGH FORCING in 2071–2099. At this point, the green belt advances by several degrees of latitude into the British Isles, northern Germany–Poland, the Baltic region. Many of the former transition belts turn from orange to green. Understandingly, the Mediterranean region remains highly suitable (CSI = 1). The most significant uncertainty remains in the following regions: transition fronts (Southern Scandinavia/Baltic Rim, margins of Eastern Europe, the Balkans–Carpathian Basin); and complex topography (Alps, Carpathians). In these regions, minor thermodynamic/orographic variations among members result in the formation of mosaic patterns. The headline result is clear: It is projected that between 2071 and 2099, under the RCP8.5 / SSP5–8.5-TYPE HIGH FORCING scenario, the highest suitability zone will undergo robust northward expansion.

In order to observe the difference between the scenarios, Fig. 13 presents the number of grid points falling into the CSI ≥ 0.8 (high suitability) category between 2041 and 2099. The shaded area indicates a standard deviation of ± 1 SD, based on the member tags. RCP2.6 / SSP1–2.6-TYPE LOW FORCING does not yet demonstrate a substantial alteration in the spatial extent of the high suitability area until the turn of the century, while RCP8.5 / SSP5–8.5-TYPE HIGH FORCING diverges markedly from RCP2.6 / SSP1–2.6-TYPE LOW FORCING after the 2050s and commences an upward trend.

3.3.3. Climate projection of ESI

The Epitrix Suitability Index, a composite value derived from the weighted average of two indices (HSI and CSI), is depicted in Fig. 14. The upper segment of the figure delineates the period 2041–2070, while the lower segment delineates the period 2071–2099, with each segment exhibiting two distinct scenarios. It is evident that the geographical extent of the ESI is also affected by the limitation of the HSI from both the north and south, despite the latter having been assigned a lesser weight in the calculation. The distribution of *E. papa* does not exhibit any substantial changes in area or suitability under the RCP2.6 / SSP1–2.6-TYPE LOW FORCING scenario. In southern regions, the decline of host plants is constrained due to rising temperatures, while in the north, the heat sum during the growing season is insufficient. In

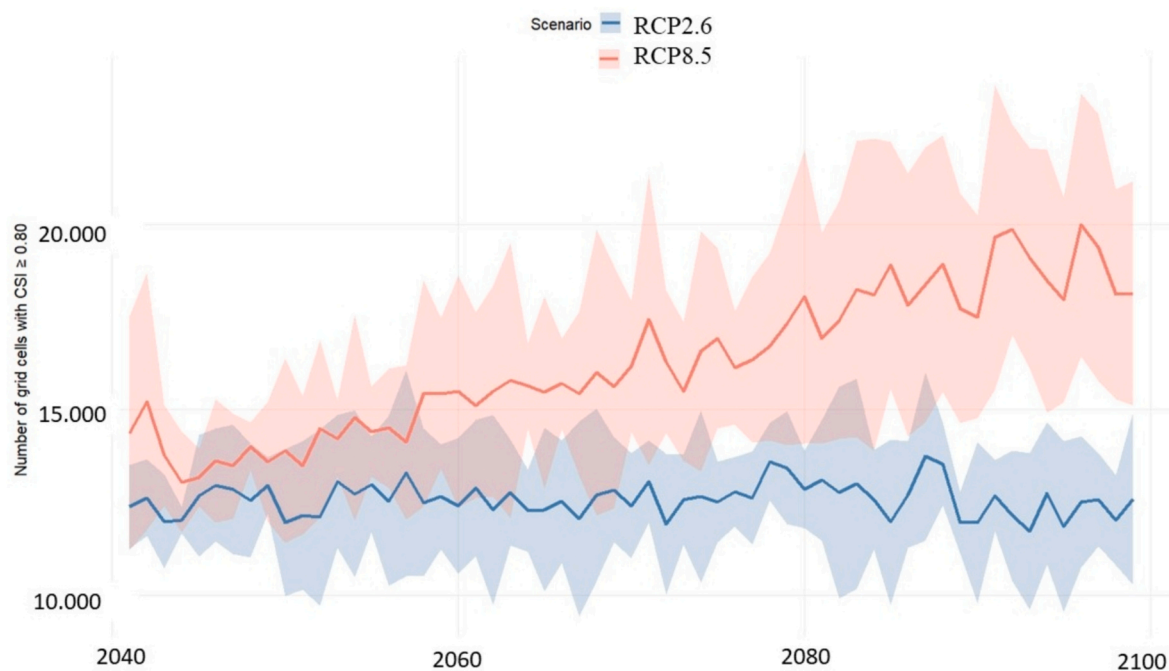


Fig. 13. Geographical expansion of “high suitability” category of Climate Suitability Index (CSI ≥ 0.8), number of grid points between 2041 and 2099. The line is the ensemble mean, the shaded are the ± 1 SD. Blue line: RCP2.6 / SSP1–2.6-TYPE LOW FORCING, red line: RCP8.5 / SSP5–8.5-TYPE HIGH FORCING.

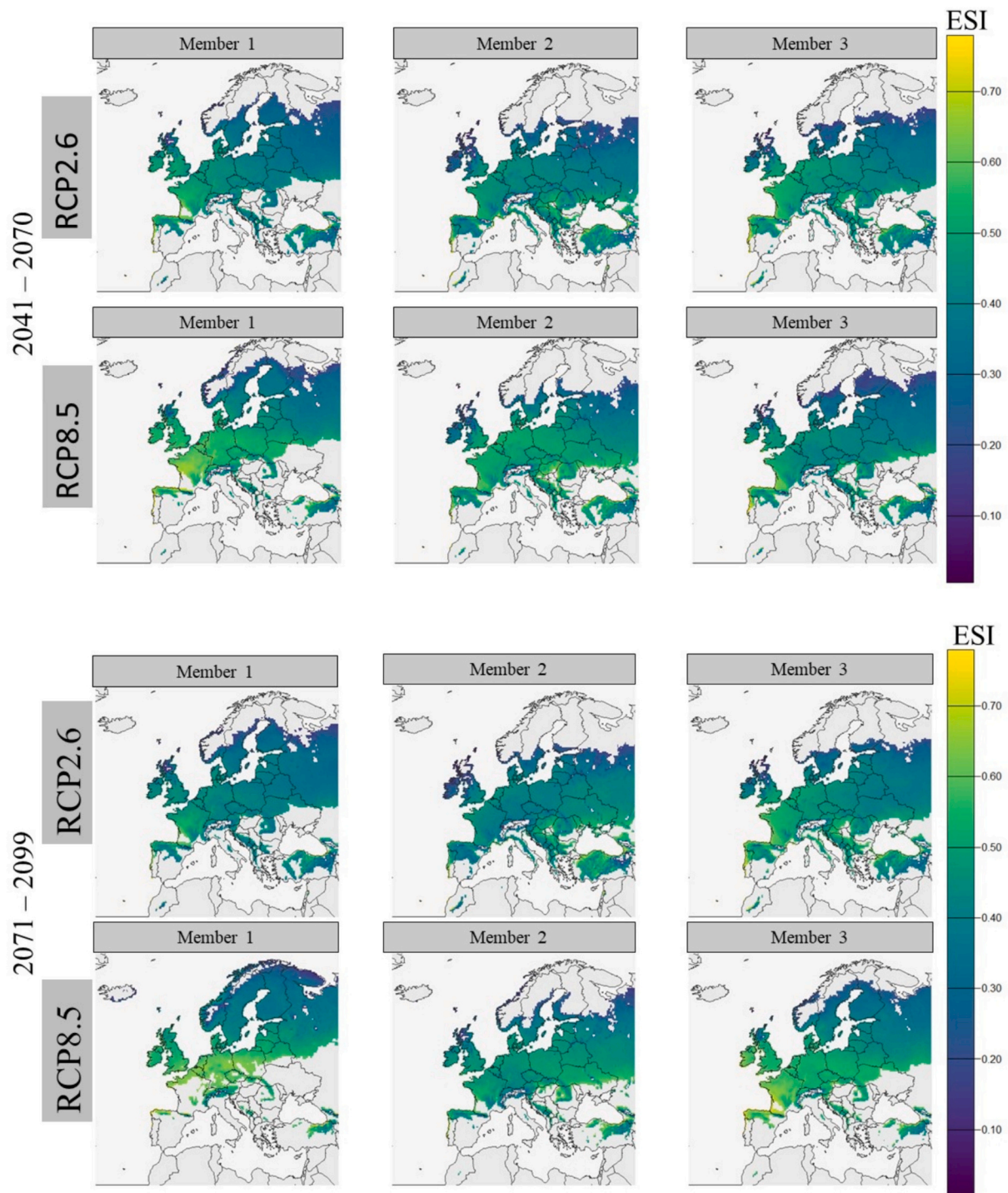


Fig. 14. Future projection of Epitrix Suitability Index (ESI) for RCP2.6 / SSP1-2.6-TYPE LOW FORCING and RCP8.5 / SSP5-8.5-TYPE HIGH FORCING for three ensemble members for 2041–2070 and 2071–2099. Member 1 = NorESM1-M, Member 2 = MPI-ESM-LR, and Member 3 = HadGEM2-ES.

contrast, the RCP8.5 / SSP5-8.5-TYPE HIGH FORCING scenario exhibits a more pronounced shift towards the north, an observation that was previously hinted at by the HSI and CSI results (Fig. 11 and Fig. 12). In southern areas, the decline of host plants is limited by rising temperatures, while in the north, the seasonal heat amount during the growing season is insufficient. In the RCP8.5 / SSP5-8.5-TYPE HIGH FORCING scenario, however, we see a more pronounced shift to the north, which could already be expected from the HSI and CSI results (Fig. 11 and Fig. 12). The extent of the suitability zones do not change, but shifts uniformly northward, extending to high latitudes on the Scandinavian

Peninsula and in western Russia to the Barents Sea coastline. Fig. 15 shows the ESI categories created based on the ESI. The “moderate suitability” category is the most extensive in Europe in all RCPs and periods. What is interesting is that in the period 2071–2099, under the RCP8.5 / SSP5-8.5-TYPE HIGH FORCING scenario, the “good suitability” category appears in two members (Member 1 = NorESM1-M and Member 3 = HadGEM2-ES) over a larger area, although there is no consensus on the geographical location between the members. However, it can be seen that more favourable conditions will develop in the western and northwestern parts of France by the end of the century in

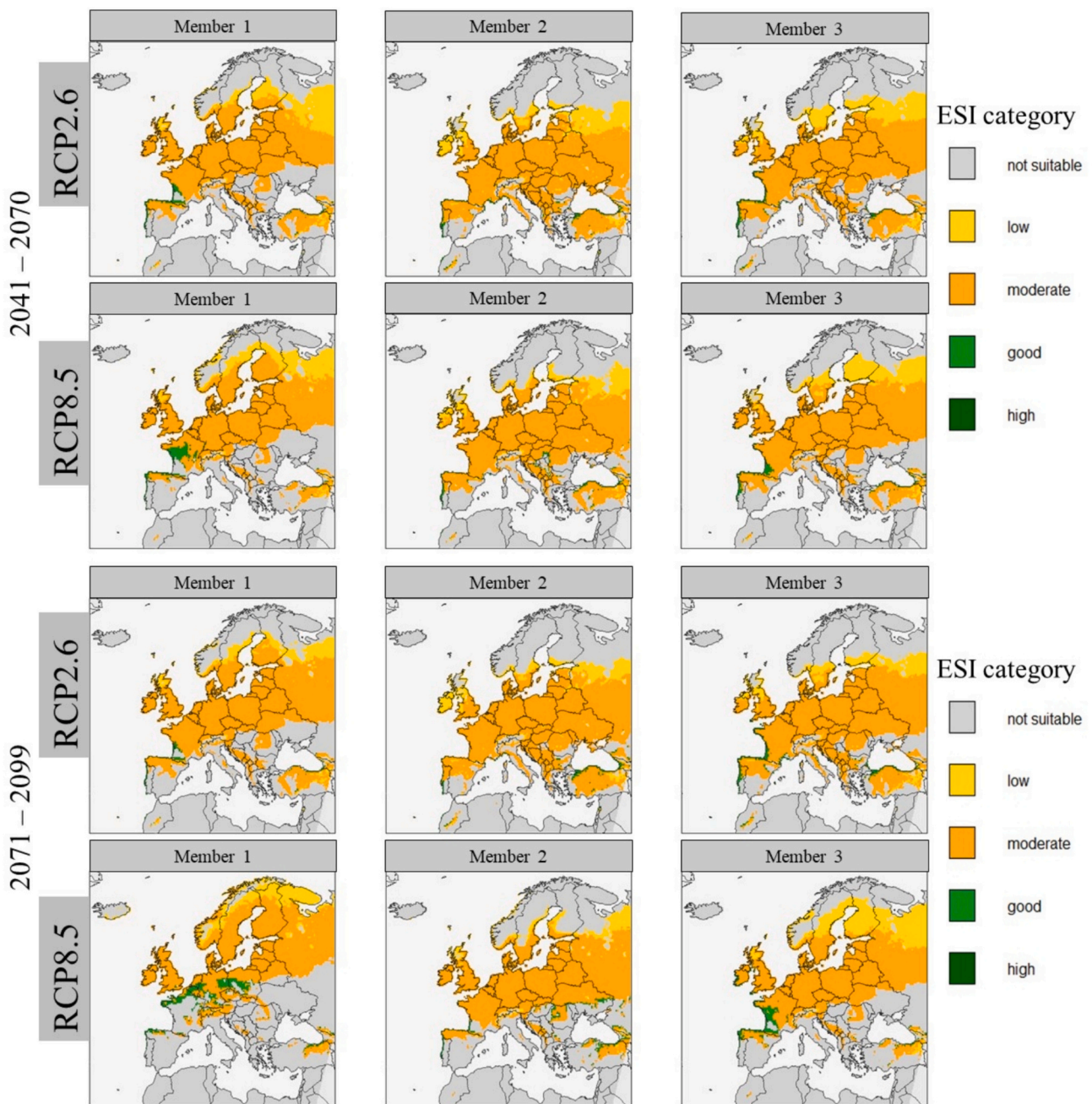


Fig. 15. Future projection of *Epitrix* Suitability Index (ESI) categories for RCP2.6 / SSP1–2.6-TYPE LOW FORCING and RCP8.5 / SSP5–8.5-TYPE HIGH FORCING for three ensemble members for 2041–2070 and 2071–2099. Member 1 = NorESM1-M, Member 2 = MPI-ESM-LR, and Member 3 = HadGEM2-ES.

terms of the spread of *E. papa*, with the area of “good suitability” increasing significantly in the two members mentioned.

4. Discussion

In this study, we sought to delineate the geographic areas favourable to *E. papa*, both historically and using climate projections, through the end of the century. It is important to note that *E. papa*, as a species, was only identified in 2015 (Orlova-Bienkowskaja, 2015), whereas the present analysis begins in the 1990s. The rationale underpinning this approach was twofold: firstly, to detect the displacement of areas favourable for potato cultivation, and secondly, to ascertain the variability arising in potato cultivation. This is of particular importance given the role of potato as the host plant, which is closely linked to the

life cycle of *E. papa* (Kroschel et al., 2020). Secondly, the spatial changes of the ESI index, as a long-term process, can be studied in this manner and used to draw inferences. Not to mention the fact, that the area of origin of *E. papa* are unknown (Orlova-Bienkowskaja, 2015), so it might possible that the species is also present elsewhere in Europe. The findings of our investigations underscore the climatically most optimal areas.

Our results obtained can be divided into several sections. Firstly, the potato production index (Host Suitability Index – HSI) was analysed in detail. Secondly, the number of generations of *E. papa* was computed based on heat accumulation, from which the so-called Climate Suitability Index (CSI) was derived.

For the HSI component, host-plant availability was approximated by summer (particularly July) thermal conditions, given that the optimal

growth of potato typically occurs in an average temperature range of 15–20 °C. It has been demonstrated that temperatures that are too low or too high rapidly impair performance (Lal et al., 2022). This approach pragmatically links host-plant climate to the pest's heat-time requirement; concurrently, it is emphasised that regional differences in irrigation, soil moisture and cultivar use may refine this picture (Ierna, and A., Mauromicale, G., 2023). The contemporary “potato belt” in Western and Central Europe remains robust, as indicated by the HSI (host) (FAO/IIASA, 2010). Conversely, unfavourable (heat-related) deviations are more frequent along the Mediterranean margin (Lal et al., 2022). By 2015–2024, the centre of gravity of the optimal–good categories has clearly intensified towards the cooler zones of Western and Central Europe (this study). In some areas of Italy and Greece, however, the share of “unsuitable/poor” has increased (FAO/IIASA, 2010). This finding is further substantiated by the observations of Goffart et al. (2022), who indicate that regions exhibiting favourable climatic conditions for potato cultivation are located in Great Britain, the French–Belgian border regions, the Netherlands, and northern Germany. The security of potato sites was examined using the Potato Stability metric with the ERA5-Land database. The number of years with favourable or unfavourable conditions according to the HSI value was determined in 10-year periods. The stability was derived strictly from an environmental/climatic perspective. The primary conclusion of this study is that the geographical distribution of the “high suitability – stable” regions, i.e. the areas that demonstrate optimal conditions across all evaluated criteria, has undergone a shift during the period spanning from the 1990s to the 2000s, from western Russia to Western and Central Europe, with a notable concentration around Germany and Poland, as observed in the 2015–2024 timeframe. Converging conclusions were ascertained by other researchers in the field, including Goffart et al., 2022. An analysis of climate projections indicates that, under the RCP2.6 / SSP1–2.6-TYPE LOW FORCING scenario, the optimal areas for potato cultivation do not shift northward; rather, a contraction of the optimal zones is observed, centred on Denmark, northern Germany, and northern Poland. As demonstrated in Fig. 1, under the RCP8.5 / SSP5–8.5-TYPE HIGH FORCING scenario, particularly between 2071 and 2099, the optimal belt shifts much more markedly to the north and northeast (i.e. towards Scotland, Ireland, southern Scandinavia and north-western Russia). Concurrently, host suitability declines across vast parts of the Mediterranean due to heat and potential water stress. Furthermore, inter-member differences (especially in transition zones and mountainous regions) are larger. This conclusion was also drawn by Daccache et al. (2012).

The CSI component is grounded in the species' temperature-dependent laboratory development curve. Available experimental data indicates that the lower developmental threshold is approximately 8.1 °C, and 625 degree days are required to complete one generation. In Portugal, this enables three (or four) generations per year (Boavida et al., 2019). These values provide the biological basis for our degree-day calculations and the timing of the ESI. It is important to note that medium-term projections indicate that the easing of winter minima critical for overwintering (Bale and Hayward, 2010; Skendžić et al., 2021) increases the probability of successful overwintering, particularly in current boundary zones. This may result in higher ESI values and faster generation turnover in the subsequent season. A multi-species comparison of Swiss data also confirmed that trends in winter temperature are increasingly favourable for a number of agricultural and forest pests. This is a relevant mechanism for human beings as well (Schneider et al., 2021). For CSI values, under RCP2.6 / SSP1–2.6-TYPE LOW FORCING, a moderate northward shift is probable, though in many regions the thresholds of the high (≥ 0.8) categories are not exceeded by 2070. In the distant future, under RCP8.5 / SSP5–8.5-TYPE HIGH FORCING emissions, a robust northward expansion is likely, with high CSI (sufficient heat sum for multiple generations) extending towards the British Isles, northern Germany–Poland, and the Baltic region; the white/unsuitable belts are predicted to shrink drastically. Independent

studies in Europe also indicate increases in annual GDD and expected rises in voltinism, thereby providing support for the results obtained in this study (Schneider et al., 2023). The Colorado potato beetle (*Leptinotarsa decemlineata*) is the focus of a study of phenological synchrony that is Europe-focused and uses RCP8.5 / SSP5–8.5-TYPE HIGH FORCING. This study indicates an increase in the number of generations and a northward expansion of pressure; temperature thresholds have a critical influence on the outcome (Jönsson et al., 2013), which may also be a sensitive point for *E. papa* and may require further investigation. Nevertheless, it is important to note that these processes are not only valid for Europe, but can also be observed on a global scale. For instance, in the case of the potato tuber moth (*Phthorimaea operculella*) research has shown that its distribution exhibits a robust, warming-supported expansion and an increase in voltinism. Furthermore, under higher emission pathways, the magnitude of these changes is amplified (Kroschel et al., 2013).

The main limitation of our work is the restricted possibility for formal validation of the model outputs. *Epitrix papa* is a recently emerging pest in Europe, and long, spatially comprehensive time series of georeferenced occurrence or damage data are not yet available for a rigorous, quantitative evaluation. In the present study we therefore focus on process-based consistency: the index formulation is directly linked to the known biology of the species (temperature-dependent development and survival thresholds) and to the spatial distribution of its main host crop, and the resulting high-risk areas are qualitatively consistent with regions where the pest has already been reported and where climatic conditions are known to be favourable for other related species. As more detailed monitoring data and systematic surveys become available, future work should include a dedicated validation step, comparing predicted risk classes against observed occurrence and damage records and exploring alternative formulations of the index in a formal benchmarking framework.”

A further methodological limitation pertains to the omission of probability of entry pathways of *E. papa* around Europe and the impact of regulatory measures, such as quarantine and production protocols, within climate-suitability maps. This is particularly relevant given that the primary channels of long-distance spread of *E. papa* can be influenced by regulation and commercial practices. In the context of risk management, it is imperative that the ESI is integrated with analyses of commercial pathways and the development of surveillance programs. In the context of future developments, it is imperative to (i) address heat-stress thresholds explicitly (alongside the degree-day model, the harmful effects of high daytime maxima), (ii) incorporate water availability and soil moisture (in drought years, host limitation may reduce HSI), and (iii) refine the photoperiodic, thermal, and cover-crop dependencies of diapause/overwintering.

5. Conclusion

Our study interprets the European risk of *E. papa* in a host-sensitive thermal niche framework: the HSI based on July temperatures reliably reflects current potato crops, while the CSI calculated with parameters $T_{base} = 8.1$ °C and 625 °Cday captures the spatial-temporal variation in potential generation number. The combination of these (ESI) indicators demonstrates a recent strengthening of the core regions in Western and Central Europe, which is in parallel with the centre of gravity of the ‘high suitability – stable’ zone shifting to the Germany–Poland region for the period 2015–2024 compared to 1990–2000. In terms of future projections, the RCP2.6 / SSP1–2.6-TYPE LOW FORCING scenario anticipates a moderate shift in climate patterns. The northern boundary will undergo a limited displacement, primarily constrained by the heat sum limit, while in the southern regions, crop stress is expected to result in a local reduction of the HSI. Conversely, under RCP8.5 / SSP5–8.5-TYPE HIGH FORCING—particularly between 2071 and 2099—a marked northern shift is anticipated. It is anticipated that ESI will increase in the British Isles, southern Scandinavia, and the Baltic rim, while in the

Mediterranean, host limitation may weaken suitability in wider areas. The greatest uncertainty is observed in transitional belts and areas with complex topography, reflecting differences between regional climate model members and microclimate buffering. In application, the ESI maps presented here identify the areas for monitoring and used in Integrated Pest Management, where the HSI and CSI overlap, earlier and more frequent feeding/damage windows can be predicted. This allows for targeted trapping, increased survey intensity, and monitoring of regulatory and commercial entry routes. The methodology can be expanded in a transparent manner by incorporating the water supply and soil moisture, managing heat stress extremes, and refining the photoperiod dependence of diapause/hibernation. This would result in a further increase in the decision support value.

CRediT authorship contribution statement

Katalin Somfalvi-Tóth: Writing – original draft, Visualization, Methodology, Data curation, Conceptualization. **Tamás Sipos:** Writing – review & editing, Visualization, Formal analysis.

Funding

The author(s) declare financial support was received for the research and/or publication of this article. Supported by the EKÖP-MATE/2024/25/K New National Excellence Program of the Ministry for Culture and Innovation from the source of The National Research, Development and Innovation Fund. This work was supported by the Flagship Research Groups Programme of the Hungarian University of Agriculture and Life Sciences.

Declaration of competing interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Acknowledgments

We thank the several independent reviewers for their insightful comments, which have made us re-think some of that we have said and have thus improved the paper. We hereby acknowledge the World Climate Research Programme's Working Group on Regional Climate, and the Working Group on Coupled Modelling, the former coordinating body of CORDEX and the responsible panel for CMIP5. We would also like to acknowledge the invaluable contribution of the climate modelling groups, whose efforts in producing and disseminating their model output are greatly appreciated. We also acknowledge the Earth System Grid Federation infrastructure, an international effort led by the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison, the European Network for Earth System Modelling, and other partners in the Global Organisation for Earth System Science Portals (GO-ESSP).

Data availability

Data will be made available on request.

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