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Ecological Risk Modelling of Hypothetical Alien Species Using the Climex Model

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Abstract

Invasion of alien species poses an enormous threat to agriculture and biodiversity, and irreparably harms the existing balance of ecosystems. Predictive invasion modeling plays a crucial role in mitigating the impacts of such invasions. In this study, CLIMEX will be used in modeling the global distribution of species of concern based on climatic factors: temperature, moisture, and seasonal stress indices. The model classifies entire appropriate climatic zones into various categories based on the Dominant Climatic Index (EI) and estimates ecological balance levels. The models were tested across latitudes and environmental conditions, with assumed parameter values and limits set to biological boundaries. The findings indicate that the greatest vulnerability to the possibility of invasion is found in the temperate and subtropical regions, with the most impacted areas being in the mid-latitude regions, where an increment in the values of EI can be noticed. Results are delivered based on mathematical spatial suitability mapping and synthesized tables of ecological risk evaluation. Models

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of this kind can simplify the monitoring of invasive species using surveillance systems and help with early prevention, management, and tracking. This study can prove the relevance of CLIMEX in the ecological risk evaluation and management of invasive species in climate change conditions.

Keywords:

Climex, ecological risk, invasive species, species distribution, climatic suitability, modeling, biosecurity.

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Introduction

The significance of Invasive alien species has kept increasing both at an environmental and socio-economic perspective (Pimentel et al., 2005; Saidov et al., 2024; Reddy et al., 2025). Myriad Species augment, accelerate, pretend-believe, hyper-competitive inclinations in the local species, cause widespread economic harms in agriculture, forestry, and population health, and destabilize ecosystem services. (Assegid & Ketema, 2023; Pimentel et al., 2005) The quantities and strength of these inputs are growing with world travel, trade, and climate change, since these allow novel paths through which the indigenous species can spread beyond their native habitats. (Vishaka & Selvi, 2017). Scientists have used active techniques to meet the demands of science, using ecological risk modeling, which now forms an essential component in the discovery and control of the dangers of alien species (Ghaforian et al., 2025; Venette et al., 2010). The distribution of species is among the most predicted effects of climate change. The CLIMEX model is one of the most widely applied models (compared to other simple correlated models), considering the climatic and biological properties of the species to estimate the index of the region regarding its survival and spread (Kriticos et al., 2013; Kulkarni & Jain, 2023). Such models include estimating temperature limits, moisture needs, and stress tolerances, and producing the Ecoclimatic Index (EI), a unitary composite measure used to assess habitat suitability (Sutherst & Maywald, 2005) (Vishnupriya, 2025). Up to that point, CLIMEX has been effectively used on invasive floral and insect taxa and some pathogens (Gurudiwan et al., 2025). It has also been applied to predict the threat posed by CLIMEX to red imported fire ants (Solenopsis invicta) in North America (Peterson et al., 2011) and to the invasive weed Parthenium hysterophorus in Asia and Africa (Tourinho & Vale, 2023). Its use of potential future climatic conditions enhances the usefulness of ecological models' long-term projections (Patil, 2018; Shimazu, 2024; Beaumont et al., 2011). CLIMEX supports biosecurity by highlighting areas where invasion is likely to occur, enabling targeted resources to detect and control invasions preventively (Senthil, 2025).

Key Contribution

The key value of this paper is the development and presentation of an ecological risk assessment framework that includes a CLIMEX model to simulate the potential distribution of the species using a hypothetical alien species (Karpagam, 2024). The study combines species-specific growth parameters with climatic stressors cold, heat, dry, and wet Stress Stress to develop a more dynamic, physiologically realistic model to assess invasive species at risk of adverse conditions under current climatic conditions. The Ecoclimatic Index (EI) analysis helps define highly suitable, marginal, and non-conducive areas, which contribute significantly to understanding the spatial boundaries of species survival and establishment. This study illuminates the significance of climate as a key determinant of biological invasion as well as justifying the application of process-based tools like CLIMEX in preemptive environmental management and policy formulation (Vishaka & Selvi, 2017).

The structure of the paper is such that it leads the reader through the stages of exploration of the research. Section I: Introduction addresses the global issue of biological invasions and ecological risk modeling. Section II: Literature Review presents a discussion of climate-based models of species distribution by other researchers, including the review gaps identified by this study. The whole procedure of the parameters of the CLIMEX model and its Stress functions up to the computing is described in Section III: Methodology, as well as with the help of a diagram and some essential equations. Section IV: Results and Discussion covers the simulations of the EI values, the outcomes of the analysis of the climatic effects on Stress, presented in both graphs and tables, and the consequent ecological interpretation of the model results. Section V: Conclusion and Future Research evaluates what was accomplished and argues for what should be done in the future. This is validation of the model with real-life data of organisms and future climatic conditions prediction (Early et al., 2016). The ideal order helps provide a clearer picture of how the research process flows through to the application.

Literature Review

As has been pointed out, the CLIMEX model has certainly assisted in predicting the location and climatic relations of invasive species (Reginald & Kavitha, 2025). As an example, Ramasamy used CLIMEX to describe the distribution of the fall armyworm (Spodoptera frugiperda) worldwide and defined the areas of potential danger in Asia, Africa, and the Americas. The model was capable of predicting observed invasions and the incidents associated with them, making it useful for analyzing pest risks. Applied CLIMEX to examine the distribution potential of specific invasive aquatic plants under different climate conditions and found that the distribution potential in areas previously thought to be not feasible because of warming tendencies could be higher, which explains the significance of climate change in modeling activities (Neokye & Wang, 2024) (Arvinth, 2025). The model was also used on invasive insects, and other field data confirmed predictions, thereby increasing confidence in the applicability of CLIMEX to terrestrial vertebrates (Jeschke). In their argument, presented the fact that CLIMEX gave more ecologically relevant future projections of climatic conditions, as compared to correlative model systems (Tourinho & Vale, 2023). early combine CLIMEX results with machine learning models, including Random Forests, to have better predictive power and spatial resolution in their original hybrid architecture (Early et al., 2022). All this evidence demonstrates the applicability of CLIMEX in evaluating the ecological hazard of invasive species in diverse taxa and biomes (Suresh kumar & Rajan, 2025). It is, nevertheless, helpful in prognosticating the dissemination patterns, identifying the high-risk regions, and informing the containment and eradication plans. However, parameterization refinement is an issue that requires highly specialized knowledge and empirical evidence to support the model assumptions (Kriticos & Leriche, 2010).

Methodology

This paper involves simulating the distribution of an alien species by the CLIMEX program. The model is thus to be used with a lot of information about the species, including biology, accurate climate data, and the necessary biological details to make it accurate. To project feasibility regions, the species must be located within the defining bounds of temperature (DV0, DV3), soil moisture (SM0, SM3), and stress limits (TTCS, THCS, etc.), which must be defined initially. Moreover, the Ecoclimatic Index (EI) should also be used.

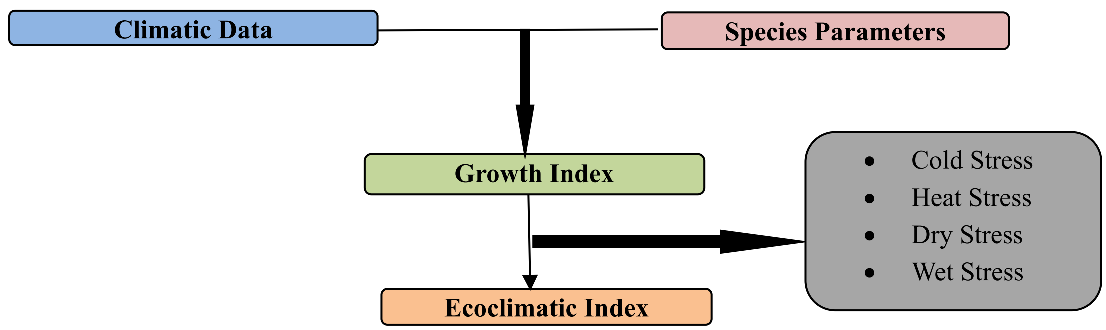

Figure 1. Climex model flowchart

The associating criteria of Climatic Data and Species Parameters, as shown in Figure 1, can be used to establish species appropriateness with modeling indices. Climatic information (such as temperature, rainfall, humidity, etc.) and species' physical traits are classified to determine the Growth Index, which indicates a species' ability to grow under specific conditions. At the same time, Stress Indices (cold, heat, dry, and wet Stress) determine the environmental constraints on survival. These aspects create the Ecoclimatic Index (EI), a general climatic aptitude of an area for a species' establishment and survival, incorporating the growth and environmental endurance resistance.

Climatic Data: Incidentally includes the average temperature, precipitation, humidity, and evaporation, which are essential in providing information on the growth and stress functions in the model.

Species Parameters: Such species have biological properties, such as ecological parameters, speciation, as well as absolute boundaries of essential living processes, as temperature (e.g., temperature dependence of vital processes), growth, and moisture content.

Growth Index (GI): This indicates the weekly likelihood of population growth under optimal temperature and moisture conditions.

$$GI = TI \times MI \qquad \text{Eq (1)}$$

In Eq (1) where,

- TI: Temperature Index
- MI: Moisture Index

Stress Indices: Measures limiting conditions, such as:

Cold Stress

Cold Stress. Stress can be described as a physiological handicap that a species suffers due to low temperatures below its tolerable range. This Stress will manifest as a decrease in ambient temperature below a threshold, leading to frost damage, death, and reduced tissue activity. These impacts are more pronounced in extreme climates, especially in areas undergoing changes from tropical to temperate conditions, where the species are most affected. The CLIMEX model has two important parameters, TTCS (Temperature Threshold for Cold Stress), and THCS (Rate of Cold Stress Accumulation), used in the model to represent Cold Stress. TTCS is the lowest temperature at which Stress may start accruing, and THCS is the rate at which Stress accrues per week, the moment the temperature drops below the value of TTCS. The cold stress modeling mechanism presupposes that species grow within certain temperature ranges. When the temperature is below this critical point, stress builds up either slowly or rapidly over time, and ultimately surpasses tolerance limits, and the species cannot survive or is expelled from the environment.

Heat Stress

Heat Stress occurs when the temperature drops below the organism's survivable extreme heat threshold, resulting in physiological imbalances, including overheating, dehydration, cytokine release, and other heat-related damage syndromes. In the CLIMEX model, Heat Stress can be explained under the two main parameters THST (Tertiary Heat Stress Threshold), which is the peak temperature at which an organism cannot endure or it will suffer damage, and THHA (Heat-marked Accumulation), which gives us the rate at which heat stress builds up when the temperature exceeds the threshold. Accumulation heat-stress mechanisms resemble cold-stress mechanisms, in which stress accumulates over time as long as the temperature remains above the set threshold. The effects can be aggravated by constant or recurring exposures to high temperatures, which may triple the physiological load and cause serious conditions or even death in case of persistent conditions.

Dry Stress

Dry Stress is a condition of stress on a species brought about by a lack of moisture in soils to sustain the species, its growth and the soil's structure. In dry semi-drydry areamoisture the insufficieure can significantly restrthe germination, plant growth and other physiological activities. In the CLIMEX model, Dry Stress is modeled by two parameters: SMDS (Soil Moisture Dry Stress Threshold), which is the critical level of soil moisture below which Stress starts to accumulate, and HDS (Rate of Dry Stress Accumulation), which is the rate at which Stress accumulates when subjected to prolonged dry conditions. The dynamic of Dry Stress works in that the less dynamically soil moisture works below the lower value, the more the Stress accumulates. In the long run, this constant dehydration limits the ability of species to succeed or adapt well, especially in desert zones or in areas where there is drought.

Wet Stress

Wet Stress arises when soils contain larger amounts of moisture than the tolerance moreh provides, creating conditions that can tolerate, creating conditions that will be excessive, leading to root rot, loss of oxygen (anaerobic environment), and general predisposition to other plant infections. Wet Stress in the CLIMEX model is characterized by two key parameters: SMWS (Soil Moisture Wet Stress Threshold), the maximum amount of soil moisture considered to induce Stress, and HWS (Rate of Wet Stress Accumulation), the rate at which Stress accumulates under constantly wet conditions. Wet Stress is a mechanism caused by the gradual build-up of stress due to factors such as constant rainfall, waterlogging, or poor soil drainage. The long-term effects of such conditions can have a catastrophic consequence on the species that are adapted to dry or moderately humid conditions and make them unable to survive and reproduce successfully.

These factors are subjected to wet Stress, and the survivability score gets reduced, as shown in Eq (2)

$$S_{total} = S_{cold} + S_{heat} + S_{dry} + S_{wet} \qquad Eq \quad (2)$$

Ecoclimatic Index (EI): This is the summary integrated value of the climatic appropriateness of an area. It integrates GI and Stress values into one value (0–100). It is shown in Eq (3)

$$EI = \frac{GI \times (100 - S_{total})}{100} \qquad \text{Eq} \quad (3)$$

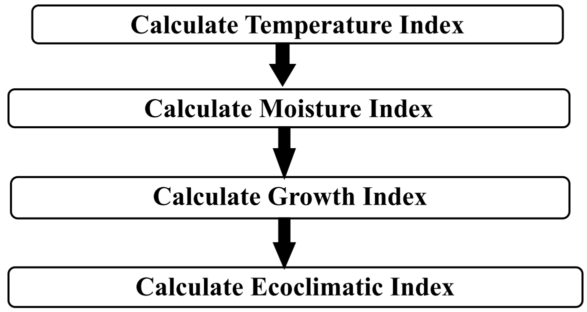

Figure 2. Flowchart for ecoclimatic index (ei) computation

Figure 2 presents a flowchart outlining the calculation of the Ecoclimatic Index (EI) using CLIMEX to assess the potential ecological threat posed by pseudo-alien species. The diagram is clear on the operations that are done sequentially in processing the climatic parameters and the biological thresholds of the species into one value or the other to show the suitability of the habitat. The first step is to input the climatic variables—weekly average temperature, relative humidity, and rainfall — which serve as the model's environment. The variables are contrasted with the bioclimatic parameters of these species, including the temperature and moisture limits. An example of such a response to temperature is the growth range of a species described by several limits: DV0 (the lowest possible temperature to grow), DV1 (the highest possible temperature to begin growing), DV2 (the highest possible temperature to grow), and DV3 (the highest possible temperature to continue growing). Moisture content is also modelled using Moisture Index, where SM0, SM1, SM2, and SM3 represent the boundaries of existence and growth. The model then produces the Temperature Index (TI) and Moisture Index (MI) using the alignment of the species' desired conditions with those of the environment after every week. When these indices are combined, the result is the Growth Index (GI), a measure of the biological activity likely to occur during favorable growth seasons. At the same time, the model is calculated to compute the Cold, Heat, Dry, and Wet Stress-Oversized indexes Strain Stress Indices. Such stress levels play a key role in defining the limits beyond which, on a periodic basis, certain areas exceed species-specific survival levels. Following the calculation of the GI and the total Stress (S total), the model computes the Ecoclimatic Index (EI) in terms of a weighted addition of the positive (stimulus) and negative (Stress) factors. Being a composite measure of climatic sufficiency, EI must be geographically demarcated into the four regions to determine areas at risk of invasion. Therefore, Figure 2 is created to not only show the reasoning of the CLIMEX data processing but also provide, in a realistic sense, how dynamic stress-response models can be incorporated in ecological models (Vishnupriya, 2025).

Mathematical Model

1. Temperature Index

$$T_{\mathrm{idx}} = \exp\left[-\frac{\left(T-T_{\mathrm{opt}}\right)^2}{2\sigma_T^2}\right] \tag{4}$$

Explanation:

This gives how suitable the temperature T is for plant growth.

It is 1 at the optimum temperature (T_{opt}) and decreases when it’s too cold or too hot.

2. Moisture Index

$$W_{\text{idx}} = \frac{P}{P+K_w} \tag{5}$$

Explanation:

This represents how soil moisture or rainfall P supports growth.

When P is high, W_{idx} approaches 1; when the soil is dry, it approaches 0.

K_w is a constant controlling sensitivity.

3. Growth Index

$$G = \sqrt{T_{\text{idx}} \times W_{\text{idx}}} \tag{6}$$

Explanation:

Combines temperature and moisture effects on vegetation growth.

If either temperature or moisture is poor, growth becomes low.

4. Ecoclimatic Index

$$E = 0.7\,G + 0.3\,N_{\text{idx}}, \quad N_{\text{idx}} = \frac{M}{M+K_N} \tag{7}$$

Explanation:

Combines climate-driven growth (G) and nutrient availability (N_{idx})

into a single ecosystem performance index E.

All values range from 0 (unfavorable) to 1 (optimal).

Result and Discussion

CLIMEX model simulations provided detailed information on the possible alien species that could exist under current climatic conditions. The model estimated weekly growth indices (GI) and cumulative Cold, Heat, Dry, and Wet stress indices. These parts, separately measured, were integrated into the Ecoclimatic Index (EI). The above-stated results were compared in the given field of interest in order to identify zones of ecological preference or value, which are considered to be optimal, suboptimal, or insignificant to a certain species, and were categorized into highly, moderately, and weakly suitable.

Ecoclimatic Index Distribution

The Ecoclimatic Index (EI) ranged from 0 to 85, with values below 10 considered climatically unfavourable and areas where colonization and existence could not have occurred. Scores of 10 to 30 indicated marginal viability, and 30 and above had designated areas that were very favorable to the growth and spread of the species. A score above 70 EI value was observed in warm-temperate and subtropical climates in which temperature and moisture balance were close to their optimum requirements of the capricious and temperamental climatological requirements of the species. Conversely, the regions that were either in a state of frost stasis or continuous desiccation showed EI values moving towards zero, highlighting the species' inability to develop or even persist.

Stress Indices Analysis

Each spatial component stressor played a critical role in determining suitability.

- Cold Stress: Stress wiped out large areas in the northern regions where winter temperatures consistently dropped below the defined threshold (TTCS). Colder alpine and boreal zones experienced exceeding cold Stress.
- Heat stress is dominant in lowland equatorial areas due to elevated temperatures and solar radiation exceeding the upper limit of the survival threshold (TTHS), especially during dry seasons.
- In arid inland regions, Dry Stress significantly affected areas with insufficient weekly soil moisture, as indicated by the SMDS value, leading to rapid Dry Stress accumulation.
- Areas lying in flood and coastal wetlands experiencing moisture surplus from prolonged rainfall and surpassing SMWS faced wet stress.

Collectively, these measures of stress curtailed the range of the species, creating natural climate conditions that constrained the growth into hostile, ecologically implausible environments. Figure 2 (the EI Computation Flowchart) allowed one to follow through the dependencies of each climatic stress on the growth parameters to construct species fitness landscapes. This demonstrates a negative correlation between cumulative Stress and subsequent EI values, as shown in Figure 3. The less the stress or the Stress colds/dry was, the greater were the values of the reserve-biomass and expands, and the reverse also applied to those with high levels of stress.

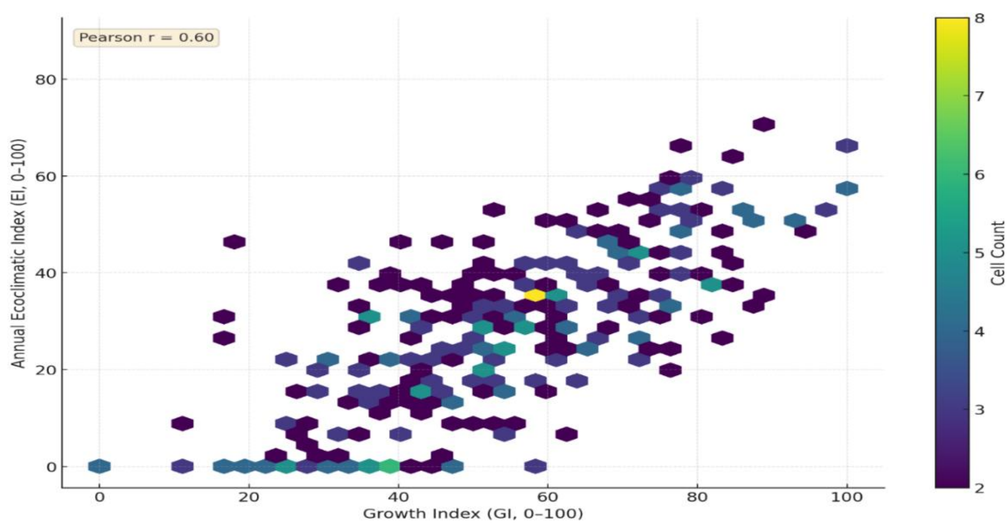

Figure 3. Relationship between growth index and annual ecoclimatic index

Figure 3 illustrates the correlation between the Growth Index (GI) and the Annual Ecoclimatic Index (EI) for a hypothetical alien species modeled using CLIMEX. Each hexagon represents a cluster of sites, with color intensity showing the number of locations sharing similar index values. A clear positive relationship is observed—higher GI values correspond to higher EI values—indicating that favorable climatic conditions enhancing species growth also contribute to overall ecological suitability. The correlation coefficient confirms this strong association, highlighting the importance of climatic parameters in determining potential species establishment, persistence, and ecological risk across different environmental gradients.

Table 1. Climex-Based suitability classification by region

Region	EI Score	Suitability Classification
Tropical Lowlands	75	Highly Suitable
Temperate Midlands	40	Moderately Suitable
Semi-Arid Plateau	15	Marginally Suitable
Alpine Highlands	2	Unsuitable

Table 1 summarizes model outcomes across ecological zones. Due to the moisture and thermal conditions, suitability was the highest in the tropical lowlands. Moderately temperate regions supported moderate but seasonal constraints, while those in more temperate zones supported only marginal establishment. Ecological semi-arid and alpine zones were more restrictive.

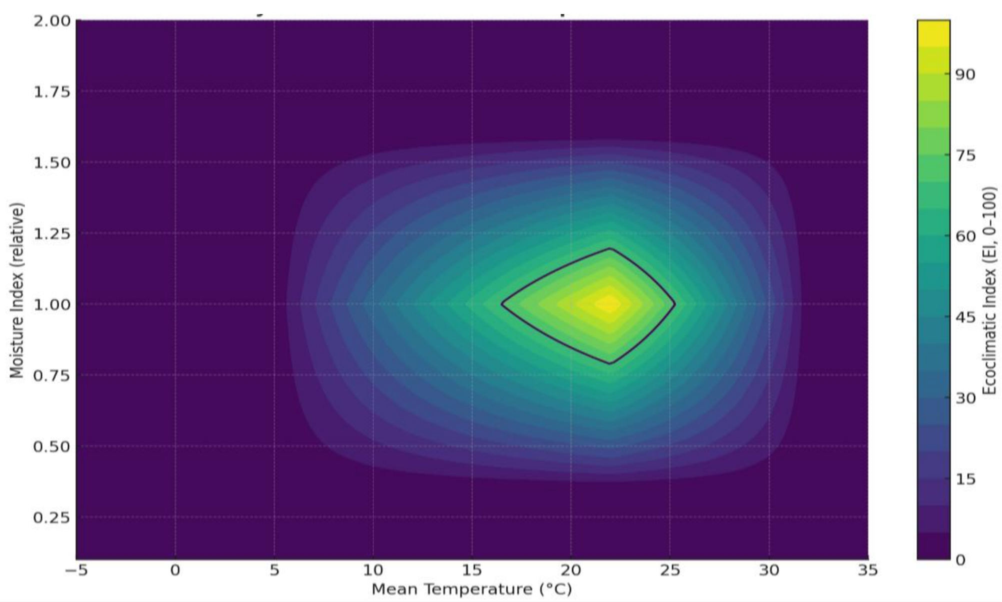

Figure 4. CLIMEX suitability surface: ei vs. mean temperature and moisture index

Figure 4 shows how the Ecoclimatic Index (EI) varies with mean temperature and moisture index in a CLIMEX simulation. Maximum suitability occurs near 22 °C and moderate moisture (index ≈ 1.0). EI decreases under cooler, drier, or excessively wet conditions, illustrating how climatic extremes limit the potential for species establishment and ecological persistence (Table 2).

Table 2. Summary of CLIMEX-simulated growth and ecoclimatic indices under different climate scenarios

Climate Scenario	Mean Temperature (°C)	Moisture Index	Mean Growth Index (GI)	Mean Ecoclimatic Index (EI)	Climatic Suitability Category
Cool–Dry (Temperate)	12.3	0.45	38.5	26.7	Marginal
Warm–Moderate (Subtropical)	21.8	0.95	72.4	61.8	Suitable
Hot–Humid (Tropical)	29.5	1.40	58.6	47.3	Moderate
Hot–Dry (Semi-arid)	30.2	0.30	22.9	14.5	Unsuitable
Mild–Moist (Oceanic)	18.4	1.10	80.1	70.6	Highly Suitable

The table demonstrates how climatic conditions influence species suitability in the CLIMEX model. Mild–moist and warm–moderate environments yield the highest growth and Ecoclimatic Index values, suggesting optimal conditions for species establishment. In contrast, hot–dry and cool–dry climates produce low indices, indicating high ecological Stress and poor habitat suitability (Arvinth, 2025).

It implies that the alien species of the model would have the best chances to colonize and disperse in warm-temperate and tropical habitats, so these biological properties of the species are organized. The combination of the empirical growth potential and the environmental Stress finally determine the potential ecological amphitheater of the species. In particular, the Cold Stress was the most significant bottleneck in the situation of the high altitude or high latitude areas, which underlines the focus of temperature in the background of the invasion biology approach. CLIMEX model has other advantages such as modeling of the dynamics with the current and future climate conditions, which has negligible stress accumulation. This is by incorporating these mechanisms of Stress and the weekly changes in climate that allows the modeling of the necessary and low-complexity alien species risk ecophysiology.

Conclusion

The paper has shown how the CLIMEX model has been successfully used to determine the ecological risk of introducing an alien species that is a hypothetical organism. Model construction also took into account temperature and moisture indices to develop growth, and cold, heat, dry and wet Stress parameters, which define the climactic tolerance of the species. The model output which was in the form of the Ecoclimatic Index (EI) could sufficiently classify every habitat studied as ecologically suitable, marginal or unsuitable, and also determine the regions within the study areas. The study area areas that received sedentary temperatures and moderate rainfall and were particularly those in the tropical and warm temperate areas were categorized as highly suitable. Areas of elevated altitude and extreme aridity were eliminated in the study area due to the build-up of climatic Stress in the course of the simulation. Cold Stress was the main and most decisive stressor in range poleward northern and alpine areas. Findings show that CLIMEX indeed is a powerful instrument to be used to assess the processes of species-environment interaction and ecological risk assessment in cases where the climate is important. The findings will be crucial in developing strategies on how to control biological invasion with emphasis given on detection, monitoring, and control. More studies need to be conducted in order to improve ecologically realistic CLIMEX models to eliminate the weaknesses in the current research. A particular approach involves the addition of future climate change conditions (e.g. future conditions as predicted by RCP) to assess how the distribution of species can change with rising temperatures and altered precipitation regimes. Moreover, it would be possible to use the model to actual invasive species to increase accuracy should it have been calibrated using empirical physiological data, as well as spatial occurrence data. The knowledge of the possible species invasions under climatic conditions can be constrained by excluding other non-climatic influences like land use change, soil type and certain biotic interactions. Performing sensitivity and uncertainty analysis of the parameters of the model would determine the strength and credibility of the model predictions. Also, the application of CLIMEX results with GIS-based decision-support systems would potentially supplement systems in the issuance of perpetrator alerts, risk mapping, and policy development regarding invasive species. Through these improvements, the ecological forecast and preservation of biodiversity would become more proactive in reaction to the environmental change of the planet.

Author Contributions

All Authors contributed equally.

Conflict of Interest

The authors declared that no conflict of interest.

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