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Modelling Current and Future Distribution of some Invasive Weeds at Local and Global Scales under Climatic Change

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Abstract

The global climate change, including increases in temperature and precipitation, may aggravate the invasion of weed species. In the present study, Ensemble modelling was performed to predict the distribution of three invasive weeds, namely *Atriplex lindleyi, Trianthema portulacastrum,* and *Xanthium strumarium*, worldwide and in Egypt under the current and future global climate changes. *T. portulacastrum* showed the highest suitability in Africa compare to other parts of the world and compare to other study species. Asia and Europe are more suitable for the potential presence of *X. strumarium*. For *A. lindleyi*, there was no clear change in the suitable habitat under the current and future climatic scenarios in Egypt. *T. portulacastrum* is predicted to have expansion under the climate change particularly in eastern desert of Egypt and Nile Delta. *X. strumarium* showed high expansion in Sinai compared to other regions under the highest climatic scenario 2090. *T. portulacastrum* presence increased gradually with the increase of the mean temperature of the wettest quarter (Bio8) and the driest quarter temperature (Bio9). This indicate that the global warming in the future will be in favour to increase the invasion risk of this species up to 40 ◦C. In contrast, the probability of presence of *X. strumarium* is gradually decreased with the increase of isothermality. Climatic models will predict the increase *T. portulacastrum* distribution both globally and locally. Therefore, long-term management plans are needed around the world and in Egypt to reduce the habitat expansion of *T. portulacastrum*.

Keywords: Climate change; Ensemble modelling; Habitat suitability; exotic weed species; Nile Delta.

Introduction

The definition of an invasive species is the movement of non-native species from their original habitat to a new location, where they colonize, spread, and endanger the local economy, environment, and ecosystem health (Christian, 2001; Falk-Petersen et al., 2006; Shackleton et al., 2020;Vitousek et al., 1996;). Invasive alien species have drawn attention in the field of ecology ever since Elton published the ecology of invasions by animals and plants

(Elton, 1958). By modifying the structure and functioning of ecosystems and obstructing crucial biological interactions, invasive species pose a danger to the sustainability of the world's biodiversity and social economy (Levine et al., 2003; Mitchell et al., 2006; Traveset and Richardson, 2006; Cook et al., 2007; Horvitz et al., 2014). These invasions have also been seen as a significant factor in recent extinctions and a key driver of environmental change on a global scale (Thomas et al., 2004). Recent years have seen a significant increase in ecologists' interest in the study of plant invasions, which are a key component of invasive alien species (Huang and Asner, 2009; Dostál et al., 2013; Hess et al., 2019; Weidlich et al., 2020). Additionally, the invasive plant species have been identified as a significant non-climatic driver of global change that can alter ecosystem metabolism and disturbance patterns (Evans and Brown, 2017).

The world's flora and fauna have been homogenized by bio-invasion, which has also impacted species composition, community organization, and biogeochemical cycles (Chakraborty, 2019). Moreover, ecosystems can be impacted by these biological invasions under a variety of bioclimatic situations. For the conservation of biodiversity over the long term, it is essential to comprehend how climate change affects species invasion (Hulme, 2017). The distribution of precipitation and solar radiation can be influenced by topographical factors, and the development of invasive plant roots and nutrient intake can be influenced by soil-related factors (Verlinden et al., 2014; Zhang et al., 2019). According to comprehensive studies of the dispersion distribution of invasive species, climatic conditions are the primary environmental drivers of species distribution at the macro-scale (Dyderski et al., 2018; Lamsal et al., 2018; Zhan et al., 2022). When determining the possible range of invasive alien species, other key elements still need to be taken into account, including terrain, soil type, changes in land use, plant cover, and human activities. Invasive plant colonization and dissemination are influenced by changes in land use/cover and anthropogenic causes, mostly through the disruption of their habitat (Pauchard and Alaback, 2004; Hobbs, 2000; Chytrý et al., 2008; Manzoor et al., 2021).

A recognized natural cause of the loss of global biodiversity and deteriorating ecosystem services is the size and fast expansion of invasive plant species. Due to these plants' detrimental effects on the environment, plant ecologists have recently been focusing on these invasive plant species (Amiri et al., 2022). Invasive plant species can hinder the establishment of native species, which in turn affects the structure and assembly of plant communities. In addition to this, the spread of invasive plant species is expected to be significantly influenced by global climate change. For example, an increase in temperature may lead to the emergence of new habitats that are suited for particular species, facilitating their spread and potential invasiveness (Bradley et al. 2009; Finch et al. 2021). On the other hand, the invasive plant species can affect various ecosystem features, including soil cover, nitrogen cycling, fire regimes, and hydrology, as well as the establishment and growth of native plants (Weidlich et al., 2020).

The early detection and quick reaction to these invasive species in newly invaded places can be aided by understanding the distribution dynamics of invasive species (Zhang et al., 2022). Therefore, it is crucial to incorporate the use of computational methods into estimating the effects of climate change on the availability of suitable habitats for a certain species in order to comprehend the current and future direction of population changes.

There are different prediction models such as future species distributions (FSDs), species distribution models (SDMs) and generalized linear models (GLMs) are widely used. FSDs increasingly predicted using tools like bioclimatic modelling. Moreover, the use of species distribution models (SDMs) in early detection is efficient in locating ecologically vulnerable areas, monitoring invasive species, and taking swift action (Srivastava et al., 2019). SDMs have made a huge contribution to vegetation mapping at many scales and presented amazing opportunities (Oldeland et al., 2010; Amiri et al., 2022; Moshobane and Esser, 2022). SDMs depend on an organism's connection to a certain geographic area, and more recently have also included additional elements like different forms of land use (Villemant et al. 2011; Shi et al. 2021). SDMs are beneficial for making conservation decisions in addition to projecting the suitability of the habitat for the present and the future (Pereira et al. 2010). SDMs have recently been

utilized extensively in studies to forecast the future distribution of invasive alien species (Urbina - Cardona et al. 2019).

A. lindleyi, popularly known as Lindley's saltbush, is a member of the Amaranthaceae family. This Australian native plant is particularly common in arid regions. Additionally, California in United States, is well-known for having invasive species (Milton et al., 1999). Another invasive plant is *T. portulacastum*, which is primarily found in farms and wide desert plains and also named by Horse purslane. *T. portulacastrum* is a member of Aizoaceae family and is indigenous to South Africa. It has also been documented to exist in India, Pakistan, Tropical America, West Asia, Sri Lanka, and Africa (Macdonald, 1989; Thomas et al., 2016; Kaur and Aggarwal, 2017). *X. strumarium* is invasive plant species belongs to Asteraceae family (Everitt et al., 2007) that has several names such as rough cocklebur, clotbur, common cocklebur, huge cocklebur, and woolgarie bur. It is native to North America, and is currently one of China's invasive alien species (IAS) (Iqbal et al., 2020).

In this study, we hypothesized that under future climate change, the semi arid or humid areas become more drier and hence might be suitable for invasive species. For example, an increase in the precipitation will be favor to invasive species particularly in the newly invaded areas and hence the competition is expected to be high and affects the resident natural flora. Therefore, our objectives were to:

1. Explore the potential distribution and invasion risk of target species at global and local scale (Egypt) under current climate scenario,
2. Explore the invasion risk of the three studied species under climate change scenarios (shared socioeconomic pathways, ssp126 low scenario, and ssp585 high scenario) in the near future (2021-2040) and far future (2081-2100),
3. Determine the key factors or drivers explaining the potential distribution (invasion risk) for each species, and
4. Identify the priority conservation areas or regions with high risk of invasion.

Methods

Species occurrence data

We obtained 6210, 3920, and 29169 occurrence records for the three target species *A. lindleyi*, *T. portulacastrum*, and *X. strumarium* respectively from the GBIF database using '*rgbif*' package (Chamberlain et al., 2017) in R 4.2.0; then we cleaned and verified the data using '*Coordinate Cleaner*' package (Zizka et al., 2019).

Bioclimatic predictors and multicollinearity

We obtained the nineteen bioclimatic predictors from WorldClim at resolution of 2.5 arc-minutes (Fick and Hijmans, 2017). To assess the impact of climate change scenarios, we selected two global general circulation models (GCMs): BCC-CSM2-MR and IPSL-CM6A-LR. We used the ensemble average of their outputs for the near future (2021-2040; later called 2030) and far future (2081-2100; later called 2090) for two shared socioeconomic scenarios pathways (low scenario: SSP126 and high scenario: SSP585). We extracted values for multicollinearity to avoid model overfitting; then, we used the '*usdm*' package (Naimi, 2015) to apply the variance inflation factor (VIF) to exclude the correlated variables with VIF > 5 and a correlation threshold of 0.75 (Guisan et al., 2017).

The response curves show how environmental variables affect the prediction of habitat suitability. The curves show how the predicted probability of presence changes as each environmental variable is changed, keeping all the other environmental variables at their average values (Phillips et al., 2011).

Ensemble modelling and potential habitat suitability

We used '*sdm*' package in R 4.2.0 (Naimi and Araújo, 2016) to apply ensemble modelling of the three common species distribution models (SDMs): generalized linear model (GLM), Boosting Regression Trees (BRT), and random forests (RF), which are characterized by high stability and transferability compared to other models (Thuiller et al., 2019). We used 70% as training data and 30% as testing data. We used the True Skill Statistic (TSS) to weigh the ensemble models, and the threshold of maximum training sensitivity plus specificity (MTSS) (Liu et al., 2016). We calculated the area under the receiver-operating characteristic curve (AUC) and TSS to evaluate the model accuracy (Guisan et al., 2017).

We transformed continuous maps of

the current and future habitat suitability into binary maps using the MTSS threshold to visualize the changes in habitat.

Results

Model performance, predictors importance, and response curves

The cleaning of occurrence data resulted in 3917, 2715, 23049 verified records for *A. lindleyi, T. portulacastrum, and X. strumarium* respectively (**Figure 1**). The results from the multicollinearity test (with VIF < 5) indicated seven uncorrelated variables for *A. lindleyi,* ten for *T. portulacastrum,* and eight for *X. strumarium.* The ensemble model showed excellent accuracy or performance (>= 0.81) for the three invasive species using AUC as model accuracy measure. Moreover, the TSS measure of model performance for *A. lindleyi* showed excellent performance, *T. portulacastrum* showed very good, while *X. strumarium* showed good performance with TSS of 0.55 (**Table 1**).

Table 1. Variance inflation factor (VIF) of the selected bioclimatic variables. True skill statistic (TSS) and the area under the receiver-operating characteristic curve (AUC) indicate the model performance or accuracy. MTSS threshold is the maximum training sensitivity plus specificity.

Variable*	A. lindleyi	T. portulacastrum	X. strumarium
Bio2	1.77	2.11	2.33
Bio3	1.55	2.35	3.55
Bio8	-	1.92	3.45
Bio9	1.51	2.85	4.02
Bio10	-	3.63	3.89
Bio11	3.00	-	-
Bio13	-	4.96	1.68
Bio14	-	2.28	1.85
Bio15	2.61	2.31	-
Bio18	1.48	4.43	-
Bio19	2.29	2.04	2.10
AUC	0.98	0.90	0.81
TSS	0.89	0.69	0.55
MTSS Threshold	0.61	0.46	0.45

* Bio2-mean diurnal range (℃); Bio3-isothermality (℃); Bio8-mean temperatures of wettest quarter (℃); Bio9-Mean temperature of driest quarter (℃); Bio10-Mean temperature of warmest quarter; Bio11-Mean temperature of coldest quarter (℃); Bio13-

precipitation of wettest month (mm), Bio14-precipitation of Driest Month (mm); Bio15-precipitation seasonality (C of V); Bio18-precipitation of warmest quarter (mm) and Bio19-precipitation of coldest quarter (mm).
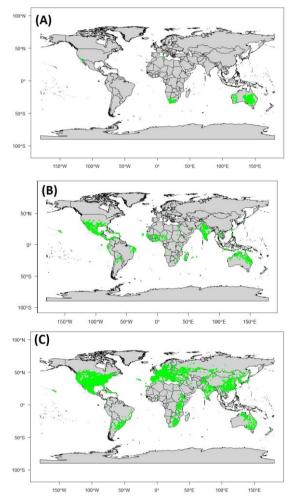

Figure 1. Global distribution of the target invasive three species. Green points indicate the occurrence records of invasive species: (A) *A. lindleyi*; (B) *T. portulacastrum*; (C) *X. strumarium*

The precipitation seasonality (Bio15) and the mean temperature of coldest quarter (Bio11) were the most important variables explaining the potential distribution of *A. lindleyi* with relative importance higher than 20% (**Figure 2**). For *T. portulacastrum,* mean temperature of the wettest quarter (Bio8) and the driest quarter (Bio9) were the most important bioclimatic variables determining its potential distribution with contribution % > 30. Moreover, isothermality (Bio3) and the mean temperature of the driest quarter (Bio9) explained the potential distribution of *X. strumarium* with relative importance higher than 10% and 30% respectively.
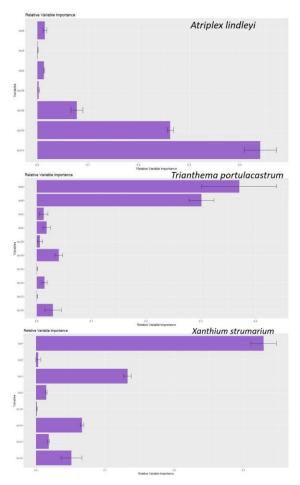
Figure 2. Relative importance of the climatic predictors explaining the potential distribution of the target three invasive species. Abbreviations of the bioclimatic variables are described in table 1.

The probability of the presence of *A. lindleyi* decreased in response to precipitation seasonality (Bio15), up to a variation of 13% (**Figure 3**). The likelihood of *T. portulacastrum* presence increased gradually with the increase of the mean temperature of the wettest quarter (Bio8) and the driest quarter temperature (Bio9). This indicate that the global warming (increase of temperature) in the future will be in favour to increase the invasion risk (i.e. this species will be predicted to have a suitable habitat) up to 40 ˚C. In contrast, the probability of presence of *X. strumarium* is gradually decreased with the increase of isothermality (Bio3, smaller level of temperature variability within an average month relative to the year) while the increase in bio9 would be predicted to increase the probability of its presence.
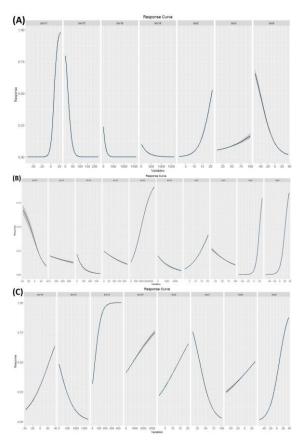

Figure 3. Response curves of the bioclimatic predictor variables explaining the potential distribution of invasive species: (A) *A. lindleyi*; (B) *T. portulacastrum*; (C) *X. strumarium*

Global potential suitability under current climate and future climate scenarios

However, the potential habitat suitability of *A. lindleyi* under the current climate was less than that of the other two species (*T. portulacastrum and X. strumarium),* the habitat suitability was high in North Africa including Egypt (**Figure 4**). Africa is highly suitable for the invasion risk of the three species particularly *T. portulacastrum* which showed the highest suitability in Africa compare to other parts of the world and compare to other study species. Asia and Europe are more suitable for the potential presence of *X. strumarium* and *T. portulacastrum* than *A. lindleyi.* North America showed high suitability for the potential distribution of *X. strumarium* than the other two species; while South America showed higher suitability for *T. portulacastrum* than the other two species. Australia showed high suitability to all species compared to other continents of the world.
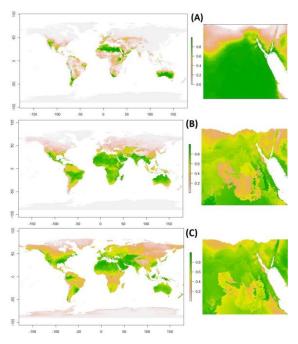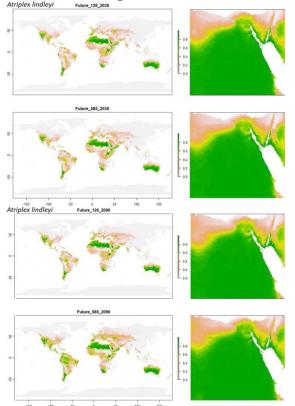
Figure 4. Global potential habitat suitability under the current climate of the study invasive species: (A) *A. lindleyi*; (B) *T. portulacastrum*; (C) *X. strumarium*

Regarding habitat suitability under the future climate scenarios, for *A. lindleyi,* it was similar to that under current climate except under the highest scenario (SSP585_2090) which showed high invasion risk particularly in South America (**Figure 5**).
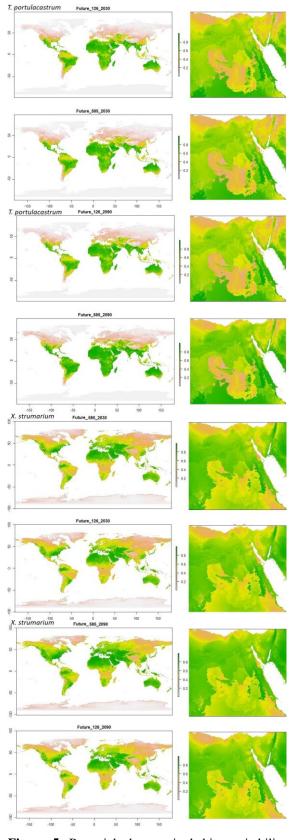

Figure 5. Potential changes in habitat suitability using the threshold MTSS under the four future climate scenarios (ssp126 and ssp585) for the periods 2030 and 2090

The potential predicted invasion risk of *T. portulacastrum,* increased gradually under the climate change scenarios with its highest expansion under the scenario SSP585_2090. The predicted habitat suitability of the invasive species *X. strumarium* increased under climate change scenarios SSP585_2030 and SPP585_2090 showing high expansion particularly in Europe (**Figure 5**).

National potential suitability under current climate and future climate scenarios

For *A. lindleyi,* there was no clear change in the suitable habitat under the current and future climatic scenarios in Egypt (**Figure 4** and **Figure 5**).
T. portulacastrum is predicted to have expansion under the climate change scenario SSP585_2090 particularly in eastern desert and Nile Delta (**Figure 4 and Figure 5**).
X. strumarium showed high expansion in Sinai and Eastern desert of Egypt compared to other regions under the highest climatic senario SSP585_2090.
The less variation between the low scenario and high scenario indicate the worst effect of the invasion of these species in the near or far future under global warming.

Discussion

The resilience of local ecosystems and socioeconomic development will be put in jeopardy by the invasion of plants species. Because early avoidance of alien plants is believed to be a more effective economic strategy than control and removal after the outbreak, early warning of alien invasive plants is required (Zhang et al., 2022). From the collected data of the present study, it was found that, the global distribution of the invasive species *A. lindleyi* was highly found at Tunisia, South Africa, (California, USA) and Australia. Elizabeth and Zacharias (2013) stated that, *A. lindleyi* is native plant species in Australia and considered as invasive species in California State. Moreover, the collected data of this study showed that, *T. portulacastrum* was commonly found in North and South America, Africa, Middle East, Australia and Asia. Whereas, Kaur and Aggarwal (2017) mentioned that, *T. portulacastrum* is native species to eastern and tropical Africa, Madagascar, western Asia, the Indian Sub-continent, China, Taiwan, south-eastern Asia, eastern and southern USA, Mexico, Central America, the Caribbean and South America. It well known that Mexico is a highland country with mountains, with an average annual temperature of 17 to 27℃ and 750 to 2000 mm of precipitation. The other country of origin, such as Costa Rica, experiences annual precipitation of 2540 mm and temperatures ranging from 16 to 25℃ on average (Lu and Ma., 2004).

On the other hand, the data of this study presented that, the global distribution of *X. strumarium* was found in Europe, America, Africa, Asia and Australia. In addition, Van Staden and Lall (2018) assumed that, *X. strumarium* is originated in Central and South America but is currently originate in the subtropical and Mediterranean parts of Asia and Africa.

It was discovered that temperature was the most significant bioclimatic variable that affected the worldwide distribution of the invasive species. This was in relation to the selected bioclimatic variables and the effect of temperature on the distribution of the invasive species (Howse, 2020; Yoon and Lee, 2021). The findings of the present work indicated that, both the wettest and driest seasons may have an impact on *T. portulacastrum* distribution. In another study, the *T. portulacastrum*'s growth was inhibited by summer's high temperatures While, the seeds production capacity of the *T. portulacastrum* were positively influenced by increasing temperature and negatively influenced by the moisture availability (Mandal et al., 2017). This was confirmed by Poorter and Navas (2003) and Trumble (2013), who found that when the availability of a resource changes in the environment, weeds respond better to growth and reproduction than crops in terms of genetic variety and adaptation. Furthermore, the findings indicated that the driest quarter was the best time of year for *X. strumarium* distribution. Under anticipated levels of climate warming, the species geographic spread would expand. Under future climate scenarios, some areas of unsuitable habitat would change to be suitable, leading to the local growth of that habitat (Hansen et al., 2001; Hulme, 2005; Valle et al., 2014; Valladares et al., 2014). The results of present study showed that, the elevation of temperature in the future as a result of global warming will be in favor to increase the

invasion risk for the invasive plant species. In contrast, the probability of presence of *X. strumarium* is gradually decreased with the temperature increasing. This finding may be return to found that, in many scenarios, various species may respond to climate change differently at local and regional scales Amiri et al. (2022).

According to the findings, the three species are more liable to invade the African continent (*A. lindleyi, X. strumarium* and *T. portulacastrum*). In Africa, *T. portulacastrum* was regarded as the main invasive species. The reason for this may have something to do with the fact that, Africa has suitable temperature and humidity to survive the invasive species (Sutherst and Bourne, 2009; Cornelissen et al., 2019; Msweli et al., 2020). Moreover, Some African nations are used as model source regions for invasions globally because they are major exporters of plant species to other regions of the world due to the enormous global demand for indigenous flora from this biodiversity hotspot (Thuiller et al., 2005).

The results of the current study proved that, Asia and Europe are more suitable for the potential presence of *X. strumarium* and *T. portulacastrum* than *A. lindleyi*. While, North America showed high suitability for the potential distribution of *X. strumarium* than the other two species; furthermore, South America showed higher suitability for *T. portulacastrum* than the other two species. This finding is supported by several research works (McMillan, 1974; McMillan et al, 1975; Kathiresan, 2006; Javaid et al., 2018; Iqbal et al., 2020; Patzelt and Lupton, 2021; Ullah et al., 2022).

According to the present study, there was no difference between the current climate and future climate scenarios in the adaptability of *A. lindleyi's* habitat. South America will have a significant invasion risk for *A. lindleyi* under the worst case scenario. Additionally, For *A. lindleyi,* there was no clear change in the suitable habitat under the current and future climatic scenarios in Egypt. The core niche is yet unclear, and the effects of ambient and climatic factors cannot be distinguished from the effects of vegetation interactions (Poggiato et al., 2021).

According to the findings of the current study, *A. lindleyi's* suitable habitat in Egypt did not significantly alter under the existing and projected climatic conditions. It is commonly known that *A. lindleyi* is widely distributed in Egypt, particularly in arid regions (El Souda et al., 2015).

In Egypt, *T. portulacastrum* can be found in both the southern Nile Delta and the northern Nile Valley (Hosny, 2000). Recent studies have documented the distribution of this target species throughout Egypt, including in agricultural areas of the Nile Delta, and the Faiyum region, (Al-Sherif and Gharieb, 2011; Fahmy et al., 2019). According to the study's findings, *T. portulacastrum* will likely grow in the future as a result of climate change, especially in the eastern desert and the Nile Delta. *T. portulacastrum* species, which was native to the Gebel Elba district in Egypt, is widely distributed, indicating that it has a high invasion potential depending on the impacts of various temperatures, pH, salinity, dryness, and sowing depth (Tanveer et al ., 2013; Fahmy et al., 2019). On the other hand, El-Gawad et al. (2019) mentioned that, *X. strumarium* is widely distributed in Egypt. According to the prediction models utilized in the current study, *X. strumarium* shown high expansion in Sinai and the Eastern Desert of Egypt compared to other regions under the highest climatic conditions in the far future.

Conclusion

For early monitoring of the local ecological environment and biodiversity preservation, it is essential to predict the distribution area of invasive plant species under climate change. Under several climate scenarios, we anticipated the geographical and temporal distribution patterns and dispersal regions of *A. lindleyi, T. portulacastrum*, and *X. strumarium*. While *T. portulacastrum* was widely spread in North and South America, Africa, Europe, Asia, and Australia, *A. lindleyi* has invaded Tunisia, South Africa, and California under the current climate scenario. Regarding, *X. strumarium* was widely dispersed throughout Australia, Africa, Asia, and North and South America. In comparison to other continents, Australia demonstrated great compatibility to the three invading species. According to projected changes in climate, *A. lindleyi* will become a serious pest in South America. However, *T. portulacastrum* is steadily spreading around the planet under extreme climate change scenarios. According to predictions for the near (2030) and

far (2090) futures, *X. strumarium* will be able to invade Europe. In order to stop the spread of these invasive species, we should increase the management of human activities while also monitoring and regulating these potential distribution areas. Finally, our work helps to predict the future invasion area of invasive plants by offering vital knowledge for the early prediction and prompt response to foreign invasive species in a new ecosystem.

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الملخص العربي

عنوان البحث: نمذجة التوزيع الحالي والمستقبلي لبعض أنواع الحشائش الغازية الضارة محليا وعالميا في ظل ظروف التغيرات المناخية

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يؤدي تغير المناخ العالمي، بما في ذلك ارتفاع درجات الحرارة وهطول الأمطار، إلى زيادة غزو أنواع الأعشاب الضارة. في هذه الدراسة، تم إجراء نمذجة حسابية للتنبؤ بتوزيع Atriplex lindleyi و Trianthema portulacastrum و Xanthium strumarium في جميع أنحاء العالم وفي مصر في ظل التغيرات المناخية العالمية الحالية والمستقبلية بما في ذلك الزيادات في درجات الحرارة وهطول الأمطار.

أظهر نبات T. portulacastrum أعلى ملاءمة في إفريقيا مقارنة بأجزاء أخرى من العالم ومقارنتها بأنواع الدراسات الأخرى. تعد آسيا وأوروبا أكثر ملاءمة للوجود المحتمل لنبات X. strumarium . في ظل السيناريوهات المناخية الحالية والمستقبلية في مصر، لم يكن هناك تغيير واضح في الموطن المناسب لنبات A. lindleyi . من المتوقع أن يتوسع T. portulacastrum في ظل تغير المناخ خاصة في الصحراء الشرقية لمصر ودلتا النيل. أظهر X. strumarium توسعا كبيرا في سيناء مقارنة بالمناطق الأخرى تحت أعلى سيناريو مناخي ٢٠٩٠.

تنبأت الدراسة بزيادة توزيع نبات T. portulacastrum تدريجياً مع زيادة متوسط درجة الحرارة في الربع الأكثر أمطاراً (Bio8) ودرجة الحرارة الأكثر جفافاً في الربع (Bio9)، وهذا يشير إلى أن الاحتباس الحراري في المستقبل سيكون لصالح زيادة خطر

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غزو هذا النوع حتى ٤٠ درجة مئوية. وفي المقابل ، تقل احتمالية وجود X. strumarium تدريجيًا مع زيادة درجة الحرارة. تشير نتائج الدراسة أن تغير المناخ في المستقبل سيزيد من توزيع T. portulacastrum على الصعيدين العالمي والمحلي. لذلك، هناك حاجة إلى خطط إدارة طويلة الأجل في جميع أنحاء العالم وفي مصر للحد من التوسع في بيئات T. portulacastrum.