Global invasion reconstructed and spatio-temporal distribution pattern dynamics of Sorghum halepense under climate and land-use change

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Research Article

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Abstract

Context

Sorghum halepense competes with crops and grass species in cropland, grassland, and urban, increasing invasion risk. However, invasive historical dynamics and distribution patterns of *S. halepense* associated with current and future climate change and land-use change (LUC) remain unknown.

Objectives

We first analyzed invasive historical dynamics of *S. halepense* to explore its invasion status and expansion trends. We then used species distribution model to examine whether future climate change and LUC will facilitate the invasion of *S. halepense*.

Methods

We reconstructed invasive historical countries of *S. halepense* based on databases with detailed recorded countries and occurrences. We run biomod2 based on climate data and land-use data at 5’ resolution, assessing the significance of environmental variables and LUC.

Results

Sorghum halepense was widely distributed worldwide through grain trade and forage introduction, except in Africa. Future global cropland and urban areas were expected to increase, yet grassland areas decreased. Europe and North America provided more the PGSH of *S. halepense* in cropland, grassland, and urban, covering 48.69%, 20.79%, and 84.82%, respectively. The future PGSH of *S. halepense* increased continuously in Northern Hemisphere, transferring to higher latitudes. Environmental variables were more significant than LUC in predicting the PGSH of *S. halepense*.

Conclusions

We constructed species distribution models associated with the near current and future environmental variables and LUC. Future PGSH of *S. halepense* was expected to increase, increasing invasion risk on agricultural LUC. These results are basic for the early warning and prevention of *S. halepense* worldwide.

1 Introduction

Global changes, including international trade, climate change, and land-use change (LUC), are direct drivers of biological invasion (Walther et al. 2009; Pyšek et al. 2020). The continuous increase in invasive alien plants (IAPs) is closely related to the globalization of trade in which landscape gardening and long-distance carriage of grass are introduced in grassland and agriculture (Wilson et al. 2009; Ribeiro et al. 2022; Wu et al. 2023). More than 500 species of IAPs are traded daily worldwide (Humair et al. 2015). In the United States, 61% of the 1285 IAPs, including half of the state-regulated IAPs, are available via plant trade (Beaury et al. 2021). Therefore, analyzing the invasive historical dynamics of IAPs is beneficial for understanding their invasion status and expansion trends. With global warming, IAPs possibly create new habitats at high elevations because of the suitable thermal conditions of climate change (Freeman et al. 2018). In addition, individuals first settle at low elevations and subsequently transfer to higher-elevation regions, causing LUC changes in plant communities, and increasing the possibility of IAPs (Nogués-Bravo et al. 2008; Elsen et al. 2020). Meanwhile, IAPs at low elevations are more possibly affected by LUC (Freeman et al. 2018). These factors have a profound influence on native ecological communities, species interactions, and

suitable ranges based on the ecology of invasive species (Pecl et al. 2017). The emergence and expansion of IAP are notably increasing with climate warming and are expected to become more pronounced in association with LUC (MacDonald et al. 2020; Taheri et al. 2021). Therefore, to decrease the impact of IAP, predicting the spatial dynamics of invasive species through an invasive risk assessment with species distribution models is beneficial for management to formulate relative policies and measures on IAPs.

Sorghum halepense (Fabaceae) is among the ten most noxious and destructive global annual weeds (Klein and Smith 2020). Its exact native range originates in western Asia, the Mediterranean, and North Africa (PIER 2019; USDA-ARS 2023). However, wide distributions worldwide have recently been introduced as a contaminant of crop seeds and forage cultivation, increasing invasion risk and threatening agriculture, economic development, and human health (CABI 2023). The high density of *S. halepense* resulting from faster seed germination leads to floral bimoss loss, drastically affecting cotton, soybean, and wheat production in Asia and North America (Williams and Hayes 1984; Bridges and Chandler 1987; Nouri et al. 2012). *Sorghum halepense* seedlings, which have significant similarities with annual grains, mixed with sorghum and maize plants, decrease fresh weight and crop yield losses in North America (Mitskas et al. 2003; Nouri et al. 2012). Mature *S. halepense* with a higher leaf area is a host of numerous pests, nematodes, and fungal pathogens for annual crops, including the sorghum midge (*Contarinia sorghicola*), *Meloidogyne incognita*, and leaf spot diseases (*Cercospora sorghi*) (Holm et al. 1977; Warwick and Black 1983). In addition, it can develop wider subterranean root systems that produce secondary metabolites, threatening medical plant development in Africa, such as *Plantago ovate* and *Ocimum basilicum* (Asgharipour 2010). Furthermore, the pollen of *S. halepense* probably contributes to hay fever in North America, impacting human health (Wodehouse 1971). Furthermore, *S. halepense* seeds are easily established in rangeland and agricultural fields where they grow superior to C_4 prairie plants, reducing native flora diversity (Klein and Smith 2020). *Sorghum halepense* extension dramatically affects soil nutrition, changing soil temperature and water content, leading to C_3 species decrease as well as a C_4 group biomass increase (Klein and Smith 2020). Therefore, predicting the potential global suitable habitats (PGSH) of *S. halepense* in ecological systems associated with future climate change and LUC has considerable practical value for agriculture and livelihoods.

Species distribution models (SDMs) are typically used to forecast the impacts of climate change on the potential spatial distribution of invasive species in ecology and biogeography (Guillera-Arroita et al. 2015). SDMs combine species presence-absence occurrence data and related environmental conditions for distribution prediction, including generalized linear models (GLM), maximum entropy (MaxEnt), random forest (RF), and CLIMEX (Guisan and Thuiller 2005; Kriticos et al. 2015; Lopatin et al. 2016; Favretti 2018). Biomod2 is the most popular and well-constructed platform of the SDMs community, composed of ten single models that GLM, gradient boosting models (GBM), RF, artificial neural network (ANN), generalized additive models (GAM), flexible discriminant analysis (FDA), MaxEnt, classification tree analysis (CTA), surface range envelope (SRE), and multivariate adaptive regression splines (MARS), can randomly choose to ensemble models (EM) (Thuiller 2003; Hao et al. 2019). With high prediction accuracy achieved by minimizing the disadvantages of each single model, EM is more robust than single models in the risk assessment of IAPs (Stohlgren et al. 2010). For instance, the potential distribution prediction of *Ambrosia* L. worldwide and the predicted suitable areas of *Ageratum houstonianum*, *Chromolaena odorata*, *Hyptis suaveolens*, *Lantana camara*, *Mikania micrantha*, and *Parthenium hysterophorus* in Nepal are widely used in biomod2 (Shrestha et al. 2018; Xian et al. 2023).

In the present study, we (a) reconstructed the invasive historical countries, analyzing the movement means and dispersal dynamics of *S. halepense* by collecting geographical information that detailed the longitude, latitude, and invasive countries as time clapsed; (b) predicted the PGSH of *S. halepense* under climate change and LUC in the

2030s and 2050s, mainly extracting three land-use types in cropland, grassland, and urban areas; (c) analyzed the suitable probability of *S. halepense* in three land-use types; and finally (d) screened the significant environmental variables for the PGSH of *S. halepense.*

2 Methods

2.1 Occurrence data and reconstruct invasive historical countries

Global occurrences of *S. halepense* were collected from Global Biodiversity Information Facility (GBIF), Barcode of Life Data Systems (BOLD), Southwest Environmental Information Network (SNIet), Ministry of Agriculture and Rural Affairs of the People's Republic of China, some published literature on Web of Science (WOS), and field sampling in China. A total of 32972 occurrences of *S. halepense* were found in 124 countries (including regions, stated below) (Supplementary Excel). To avoid sampling bias in constructing the species distribution model, retained occurrences of *S. halepense* were filtered using ENMTools, retaining only one occurrence in a 10 × 10 km raster (Warren et al. 2021). The finally occurrence data comprised 21443 occurrences of *S. halepense* (Fig. S1).

To reconstruct invasive historical countries of *S. halepense*, we first removed 21 countries, including 18 countries that had no detailed geographical information on occurrence of *S. halepense* and three countries without recorded databases and literature, compared with recorded countries in Centre for Agriculture and Biosciences International (CABI) and European and Mediterranean Plant Protection Organization (EPPO) based on GBIF and WOS. The earliest recorded time for field sampling and the literature review was assumed to be the invasion time in each country. We confirmed 18 countries native to *S. halepense* based on CABI and EPPO. The invasive countries recorded before 1900 were regarded as one category, and other invasive countries from 1900 to 2022 with an interval of 20 years were used to reconstruct the global spatio-temporal dynamics of *S. halepense* invasion. In addition, we calculated the variation dynamics of the number of invasive countries over time and analyzed the invasive trends of *S. halepense*. Geographical observations were set to the World Geodetic System 1984 geographic coordinate system and imported to ArcGIS 10.8 (ArcGIS ESRI 1999). We presented the capital of each invasive country for *S. halepense* in ArcGIS.

2.2 Land-use harmonization data

Land-use harmonization data were used to examine how changes in the PGSH of *S. halepense* may be affected by LUC. The annual datasets for 2015–2100 with a 1-km resolution estimated the fractional land-use patterns, underlying land-use transitions, and key agricultural management information (Chen et al. 2022). In addition, we obtained historical reconstructions of land-use in the annual fraction state layers in 2015 to consist of near-current climate data. The future harmonized land-use dataset covered 2040 and 2060 to match future periods of the baseline, including SSP1-2.6, built with IMAGE; SSP2-4.5, built with MESSAGE-GLOBIOM; and SSP5-8.5, built with REMIND-MAGPIE (Stehfest et al. 2014). The harmonized land classifications considered were mainly cropland, grassland, urban, and others, which may be transferred from one land-use type to another (Fig. S2).

We predicted the potentially suitable and unsuitable habitats for *S. halepense* during the near current and future periods, quantifying the proportion of land-use for each classification in every grid cell. In addition, the predicted PGSH of *S. halepense* under the near current and future climate scenarios were mainly around three land-use types: cropland, grassland, and urban. Therefore, by analyzing the decrease, increase, or unchanged PGSH for *S. halepense* towards the mid-century, we could examine the response to climate change and LUC from the near current climate to future scenarios.

2.3 Climate data

We downloaded 19 historical environmental variables from 1970 to 2000 and the future period (2021–2040 and 2041–2060) at a 5 min spatial resolution from WorldClim v2.1 (Fick and Hijmans 2017). Future data were based on BCC-CSM2-MR global climate models (GCMs) for four shared socio-economic pathways (SSPs): SSP1-2.6, SSP2-4.5, and SSP5-8.5. SSP1-2.6 is regarded as the future ideal scenario in that 1.5 ℃ global warming is avoided, while extreme scenarios SSP5-8.5 are more likely to occur (Schwalm et al. 2020; Lee and J. Mutemi 2021). Hence, climate change and LUC analyses mainly focused on the emission scenarios SSP2-4.5 and SSP5-8.5 to estimate the spatial dynamics and PGSH of *S. halepense*. In addition, strong correlations between environmental variables can lead to multicollinearity (Dormann et al. 2013). We used ENMTools to examine the variable correlations ($|r| \geq 0.8$) and removed variables that were strongly correlated (Fig. S3). Finally, we retained seven significant environmental variables for *S. halepense* (Table 1).

Table 1
Screened significant environmental variables and contribution importance

Variable	Description	Unit	Importance
bio2	Mean diurnal range (Mean of monthly (max temp-min temp)	℃	0.078
bio5	Max temperature of warmest month	℃	0.067
bio6	Min temperature of coldest month	℃	0.091
bio12	Annual precipitation	mm	0.085
bio15	Precipitation seasonality (coefficient of variation×1	-	0.048
bio17	Precipitation of driest quarter	mm	0.108
bio19	Precipitation of coldest quarter	mm	0.317
LUC	Land-use change		0.019

2.4 Model construction and evaluation

We predicted the PGSH of *S. halepense* in the near current climate and future scenarios based on occurrence records and environmental variables that included climate data and harmonized land-use data using eight single models, including GLM, GBM, RF, Maxnet, CTA, ANN, FDA, and MARS in biomod2 4.2.3 package in Rstudio (Thuiller et al. 2023). The training data randomly used 75% of the occurrence data, and the remaining 25% was selected as the testing dataset, with five model replicates. Global 10000 pseudoabsence points selected were randomly replicated once to run the models. Finally, 40 models were reconstructed, and their performances were evaluated using the test dataset. In the present study, we selected a single model in which the true skill statistic (TSS) is higher than 0.8 and the area under receiver operating characteristic (ROC) curve (AUC) was higher than 0.9 from 40 models to construct an EM predicting the PGSH of *S. halepense* in the near current climate and future period.

TSS, AUC, and KAPPA were used to estimate the model performance (Fielding and Bell 1997). TSS is an independent threshold calculated as sensitivity and specificity-1 ranging from − 1 to + 1 (Allouche et al. 2006). A value closer to + 1 indicates excellent performance, and zero or less indicates worse performance than random (Allouche et al. 2006). The AUC is a metric that varies in true positive and negative rates and ranges from 0 to 1, with values closer to 1 indicating more perfect discrimination. KAPPA ranges from − 1 to + 1, and values closer to + 1 indicate perfect performance (Allouche et al. 2006). The probability (P) of the presence of *S. halepense* was generated in the ASCII raster and ranged from 0 to 1 in the model results. We classified the PGSH of *S. halepense* into two categories based on the maximum KAPPA value: unsuitable habitats ($0 < p \leq 0.37$) and suitable habitats ($0.37 < p \leq 1$).

3 Results

3.1 Reconstruct invasive historical countries

The native regions of *S. halepense* were mainly distributed in southern Asia, eastern Africa, and southern Europe, following CABI and WOS (Fig. 1; Supplementary Excel). In Asia, the earliest introduction of Napel in 1805 was subsequently transferred from the native region of southern Asia to eastern Asia. As a result, it is widely distributed in western, southern, and eastern Asia. In 1900, *S. halepense* was introduced into the Mediterranean Sea in Europe and transferred to western Europe in 1880. *Sorghum halepense* tended to reach northern Europe in the subsequent two decades and is now distributed throughout almost all of Europe. In the 1800s, *S. halepense* was discovered in the United States and spread to southern North America between 1900 and 2022. However, in South America, although it was first discovered in Argentina in the 1800s, newly introduced countries spread from southern North America until the 1980s. In Africa, it spread to northeastern and northern Africa between the 1900s and 2022. It has been widely distributed throughout Oceania since *S. halepense* was introduced to Australia in 1871. In summary, *S. halepense* is now widespread in most countries worldwide, except Africa, which has a potential invasive risk.

3.2 Model performance and significant environmental variables

We calculated the model accuracy of ANN, CTA, FDA, GBM, GLM, MARS, MaxEnt, RF, and EM using ROC, TSS, and KAPPA values (Fig. S4). The mean ROC of the eight models were 0.885, 0.943, 0.948, 0.960, 0.947, 0.952, 0.951, and 0.983, respectively (Table S2). The mean TSS of eight single models were 0.666, 0.818, 0.773, 0.809, 0.775, 0.778, 0.785, and 0.880, respectively. The mean KAPPA of eight single models were 0.685, 0.810, 0.768, 0.808, 0.777, 0.782, 0.778, and 0.880, respectively. The mean ROC, TSS, and KAPPA of the EM were 0.984, 0.851, and 0.856, respectively, which were higher than those of single models, indicating that the EM predicted PGSH of *S. halepense* was reliable.

We analyzed the significant environmental variables to predict the PGSH of *S. halepense* using EM, and the mean contributions are listed in Table 1. Precipitation of coldest quarter (bio19, 0.317) was the most significant environmental variables, followed by precipitation of driest quarter (bio17, 0.108), min temperature of coldest month (bio6, 0.091), annual precipitation (bio12, 0.085), mean diurnal range (mean of monthly (max temp-min temp) (bio2, 0.078), max temperature of warmest month (bio5, 0.067), precipitation seasonality (coefficient of variation) (bio15, 0.048), and LUC (0.019). The response curves of significant variables are shown in Fig. S7. When the suitability probability achieved the maximum values, the survival probability of *S. halepense* was more reliable. Bio19 and bio17 were the most significant environmental variables for the predicted PGSH of *S. halepense* in the three land-use types, achieving approximately the maximum values at 200 mm and from 140 mm, respectively.

3.3 The PGSH of *S. halepense* under the current and future climate scenarios

The PGSH of *S. halepense* extracted from the three land-use types was mainly distributed in eastern, southeastern, central, and western Asia; western Europe; southern North America; southeastern South America; east-central, southwestern, and northern Africa; and southeastern and southwestern Oceania projected in the near current climate and future scenarios (Figs. 2 and 3). Compared with the near current climate, the predicted global total cropland and urban areas would increase under future scenarios, yet the predicted total grassland area would decrease to a certain extent (Table 2). As a result, the PGSH of *S. halepense* notably increases in the three land-use types, achieving a maximum under SSP5-8.5 in the 2030s and the 2050s.

In cropland, the PGSH of *S. halepense* was located in eastern Asia (eastern Japan, South Korea), southeastern Asia (southern and eastern China), central Asia (southern and northern India, northeastern Pakistan, Afghanistan, southeastern Uzbekistan, western Tajikistan, and southern Kazakhstan), and western Asia (Iran, northern Iraq, northern Syria, and Turkey,), near total western countries in Europe, southern North America (central and western United States, Mexico, Cuba, and the Dominican Republic), southeastern South America (southern and eastern Brazil, center Bolivia, Paraguay, eastern Argentina, and Chile), northern Africa (northern Morocco, northern Algeria, northern Tunisia), east-central Africa (Ethiopia, Kenya), southwestern Africa (Uganda, Malawi, Mozambique, Zimbabwe, and South Africa), southeastern and southwestern Oceania (southeastern and southwestern Australia).

In grassland, the PGSH of *S. halepense* was mainly located in central Asia (Pakistan, Afghanistan, Tajikistan, Uzbekistan, and Kazakhstan), western Asia (Turkey), western Europe (northern Mediterranean Sea and western coastal), southern North America (the United States and Mexico), southeastern South America (central Bolivia, eastern and southwestern Brazil, Paraguay, Uruguay, and northeastern Argentina), southern Africa (Ethiopia, eastern Mozambique, Lesotho, southern Madagascar, and South Africa), southeastern and southwestern Oceania (Australia and New Zealand). However, in urban areas, the PGSH of *S. halepense* was widely distributed worldwide.

Table 2
Potential global suitable habitats (PGSH) of *Sorghum halepense* in three land-use types between the near current climate and different future scenarios

Land-use	cropland			grassland			urban		
($\times 10^4$ km)	suitable area	total area		suitable area	total area		suitable area	total area	
Near current	921.99	2177.42	42.34%	280.41	1675.80	16.73%	50.42	61.89	81.47%
2030s,SSP1-2.6	1026.27	2150.03	47.73%	297.00	1555.53	19.09%	75.24	89.92	83.67%
2030s,SSP2-4.5	1073.00	2279.08	47.08%	317.87	1638.99	19.39%	72.92	87.09	83.73%
2030s,SSP5-8.5	1079.24	2340.77	46.11%	315.38	1613.94	19.54%	78.81	93.78	84.04%
2050s,SSP1-2.6	1060.59	2178.33	48.69%	281.28	1448.65	19.42%	85.00	101.57	83.69%
2050s,SSP2-4.5	1091.27	2345.28	46.53%	315.51	1577.10	20.01%	82.24	99.20	82.90%
2050s,SSP5-8.5	1113.91	2377.42	46.85%	334.58	1609.21	20.79%	95.63	112.74	84.82%

The suitable areas of *S. halepense* in cropland were mainly located in Europe under the near current climate, approximately 311.95 × 10^4 km, accounting for 33.83% of the PGSH of *S. halepense*, followed by Asia (228.21 × 10^4, 24.75%), South America (127.91 × 10^4, 13.87%), North America (117.19 × 10^4, 12.71%), Africa (79.29 × 10^4, 8.60%) and Oceania (54.21 × 10^4, 5.88%). In the 2030s, future suitable cropland areas achieved the maximum under SSP2-4.5 in Europe, approximately 379.84 × 10^4 km, accounting for 33.83% of the PGSH of *S. halepense*, followed by Asia (249.93 × 10^4, 24.35%), South America (151.74 × 10^4, 14.38%), North America (147.60 × 10^4, 14.38%), Africa (85.07 × 10^4, 8.29%) and Oceania (55.69 × 10^4, 5.43%). In the 2050s, future cropland areas of *S. halepense* were mainly distributed in Europe, approximately 407.34 × 10^4 km, accounting for 36.57% of the PGSH of *S. halepense*, followed

by Asia (254.32 × 10^4, 22.83%), North America (160.65 × 10^4, 14.42%), South America (148.04 × 10^4, 13.29%), Africa (87.94 × 10^4, 7.89%), and Oceania (52.28 × 10^4, 4.69%).

Suitable areas of *S. halepense* in grassland were mainly located in North America under the near current climate, approximately 95.63 × 10^4 km, accounting for 34.10% of the PGSH of *S. halepense* followed by Europe (55.47 × 10^4, 19.78%), South America (46.70 × 10^4, 16.65%), Oceania (43.16 × 10^4, 15.39%), Africa (19.51 × 10^4, 6.96%) and Asia (18.2 × 10^4, 6.49%). In the 2030s, future suitable grassland areas achieved the maximum under SSP5-8.5 in North America, approximately 116.18 × 10^4 km, accounting for 36.84% of the PGSH of *S. halepense* followed by Europe (66.83 × 10^4, 21.19%), South America (43.55 × 10^4, 13.81%), Oceania (39.18 × 10^4, 12.42%), Asia (25.53 × 10^4, 8.09%) and Africa (22.30 × 10^4, 7.07%). In the 2050s, future grassland areas of *S. halepense* were mainly distributed in North America, approximately 131.39 × 10^4 km, accounting for 39.27% of the PGSH of *S. halepense*, followed by Europe (81.90 × 10^4, 24.48%), South America (39.69 × 10^4, 11.86%), Oceania (33.83 × 10^4, 10.11%), Asia (26.96 × 10^4, 8.06%), and Africa (18.82 × 10^4, 5.62%).

Suitable areas of *S. halepense* in urban were mainly located in Europe under the near current climate, approximately 14.98 × 10^4 km, accounting for 29.71% of the PGSH of *S. halepense*, followed by North America (14.18 × 10^4, 28.12%), Asia (13.00 × 10^4, 25.78%), South America (3.02 × 10^4, 5.99%), Africa (2.50 × 10^4, 4.96%) and Oceania (1.24 × 10^4, 2.46%). In the 2030s, future suitable urban areas achieved the maximum under SSP5-8.5 in North America, approximately 25.01 × 10^4 km, accounting for 31.73% of the PGSH of *S. halepense* followed by Europe (20.47 × 10^4, 25.97%), Asia (20.05 × 10^4, 25.44%), Africa (4.81 × 10^4, 6.10%), South America (4.06 × 10^4, 5.15%) and Oceania (2.46 × 10^4, 3.12%). In the 2050s, future urban areas of *S. halepense* were mainly distributed in North America, approximately 34.10 × 10^4 km, accounting for 35.62% of the PGSH of *S. halepense*, followed by Europe (24.43 × 10^4, 25.52%), Asia (21.42 × 10^4, 22.37%), Africa (5.65 × 10^4, 5.90%), South America (4.17 × 10^4, 4.36%), and Oceania (3.67 × 10^4, 3.83%).

3.4 Changes in PGSH of *S. halepense*

Future increased cropland habitats were virtually distributed in the North Hemisphere, including eastern, central, and western Asia (China, Iran, Kazakhstan, and Turkey); southwestern Europe (Russia and Byelarus); and central North America (Canada and the United States); and partly in South America (Brazil) and Africa (Cote d' Ivoire) (Fig. 4). The suitable area achieved its maximum under SSP5-8.5 in the 2050s, approximately 172.09 × 10^4 km^2. Future decreased cropland habitat was mainly distributed in central Asia (Pakistan and India), sporadically in southern North America (Mexico), central South America (Argentina, Bolivia, Brazil, and Paraguay), and eastern and central Africa (Ethiopia, Congo, and Zimbabwe). The suitable area achieved the minimum under SSP5-8.5 in the 2050s, approximately 29.21 × 10^4 km^2.

Future increased grassland habitats were virtually distributed in the Northern Hemisphere, including central and western Asia (Afghanistan, Kyrgyzstan, Tajikistan, and Turkey); southern and southwestern Europe (Austria, Norway, Russia, San Marino, Slovenia, Switzerland, and the United Kingdom); central North America (the United States), and partly in southern Africa (Namibia and South Africa) (Fig. S5). The suitable area achieved the maximum under SSP5-8.5 in the 2050s, approximately 72.58 × 10^4 km^2. Future decreased grassland habitat was virtually distributed in eastern, central, and western Oceania (Australia). The suitable area achieved the minimum under SSP5-8.5 in the 2050s, approximately 12.64 × 10^4 km^2.

There was no decrease in suitable urban habitats in the future scenarios, which were distributed in the Northern Hemisphere, including eastern Asia (China); southern Europe (Russia); and central North America (United States) (Fig. S6). The suitable area achieved the maximum under SSP5-8.5 in the 2050s, approximately 3.62×10^4 km^2.

3.5 Trend of suitable probability of *S. halepense* with latitudinal gradients

Compared with the near current climate, the PGSH of *S. halepense* in croplands tended to have high latitudinal gradients with a higher suitability probability under SSP1-2.6, SSP2-4.5, and SSP5-8.5, in the 2030s and the 2050s (Fig. 5). In the Northern Hemisphere, the suitable probability of *S. halepense* in croplands was positioned at 28°N–39°N under a near current climate, while it increased at 31°N–42°N, 35°N–50°N, and 58°N–61°N under future scenarios. In the Southern Hemisphere, a suitable probability of *S. halepense* in croplands was positioned at 22°S–43°S under a near current climate, while remaining firm at 22°S–42°S in future scenarios.

The global suitability probability of *S. halepense* in grasslands increased slightly in higher latitudinal gradients under SSP1-2.6, SSP2-4.5, and SSP5-8.5 in the 2030s and the 2050s compared with the near current climate (Fig. 6). In the Northern Hemisphere, the suitable probability of *S. halepense* in grasslands was positioned at 20°N under the near current climate, while it increased at 20°N–26°N under future scenarios. In the Southern Hemisphere, the suitable probability of *S. halepense* in grasslands was positioned at 30°S–41°S under the near current climate, while it increased at 31°S–46°S under future scenarios.

The global suitability probability of *S. halepense* in urban areas increased dramatically in higher latitudinal gradients under SSP1-2.6, SSP2-4.5, and SSP5-8.5 in the 2030s and the 2050s compared with the near current climate (Fig. 7). In the Northern Hemisphere, the suitable probability of *S. halepense* in urban areas was positioned at 20°N–52°N under a near current climate, while it increased at 19°N–61°N under future scenarios. In the Southern Hemisphere, a suitable probability of *S. halepense* in urban areas was positioned at 22°S–33°S under the near current climate, while it increased at 26°S–41°S under future scenarios.

4 Discussion

Sorghum halepense, with its high reproduction and quick dispersal, is a well-known IAP worldwide that has a negative influence on crops, such as cotton, soybean, and wheat, in croplands and grasslands (Williams and Hayes 1984; Bridges and Chandler 1987; Nouri et al. 2012). This study analyzed, the dispersal modes and distribution dynamics of *S. halepense* using reconstructed global historical invasive countries of *S. halepense* mixed crop seeds and introduced them as forage based on CABI, GBIF, and WOS (Wilson et al. 2009). The expansion of IAPs is driven by climate change and possibly associated with LUC (Taheri et al. 2021). The impacts of climate change, LUC, or their interactions on the habitat suitability of IAPs have been broadly investigated, however, few studies have examined how future LUC associated future climate change might affect IAPs (Murray et al. 2012; Puchalka et al. 2021). This is the first study to explore the joint effect of LUC and climate change on the PGSH of *S. halepense* under the near current climate and future climate scenarios using biomod2 model, which could be a vital premise for the management and prevention of IAPs.

4.1 Invasive historical reconstruct

Globalization of trade facilitates the invasion of IAPs by intentionally moving away from their native range for commercial purposes or accidentally introducing them into new environments (Gottfried et al. 2012). The future

dynamics of IAPs remain unclear and are associated with socioeconomic changes and increased human populations that are more difficult to predict (Bonnamour et al. 2021). *Sorghum halepense*, either introduced as a potential fodder or imported and exported mixed with grains, are vital factors for rapid invasion via global trade (Ikeda et al. 2022). Early in the 1800s, as a potential fodder plant and pasture grass, it was probably introduced from Turkey to South Carolina and Argentina and subsequently introduced to Australia and the southeastern United States, California, and New Mexico by farmers in the middle of the 1800s (Gottfried et al. 2012). Our results showed that the expansion countries of *S. halepense* were widely distributed in most countries worldwide, except for central Asia (Myanmar and Mongolia), northern Europe (Byelarus, Latvia, Lithuania, and Estonia), northern North America (Greenland), northern South America (Venezuela, Guyana, and Surname), central, western, and northern Africa (Chad, Mali, and Libya). Furthermore, global crop reproduction and pasturing livestock, which are vulnerable to population growth and climate change, are likely to affect the invasion of *S. halepense* (Godber and Wall 2014). How socioeconomic drivers impact the future distribution of IAPs is unknown, but the influence of socioeconomic dynamics facilitates the invasion and establishment of IAPs in new environments restrained by climate change and LUC (Bonnamour et al. 2021).

4.2 Impact of climate change and LUC on suitable habitats

The combined effects of climate change and LUC on IAPs have shown that the impact of LUC on suitable ranges of invasive plants is weaker than that of climate change (Gong et al. 2020). Our results showed that the contribution values of LUC in predicting the distribution of *S. halepense* were smaller than those of climate change (Table 1). Climate change plays an important role in the distribution of IAPs at larger scales, whereas LUC has a stronger influence on variables at smaller scales (Sirami et al. 2017). Considering the invasion of *S. halepense* in croplands and grasslands, we explored the combined effects of climate change and LUC on the distribution of invasive plants at the global scale. With future rising temperatures and elevated CO_2 emissions, the PGSH of *S. halepense* will increase in future scenarios and transfer to higher altitudes in cropland, grassland, and urban areas. Climate change may facilitate plant transfer along elevational gradients. IAPs respond faster to climate change than native plants (Lenoir et al. 2008; Liu et al. 2017). Warming occurs in mid-high latitude regions, therefore more adaptable plants are expected to exhibit elevated shifts (Gottfried et al. 2012).

Climate change may expand the range of IAPs by changing their traits, such as greater high-temperature tolerance, better adaptable growth with elevated CO_2 emissions, and latitude dependence (Molina-Montenegro and Naya 2012; Bongaarts 2019). Temperature is a vital factor that restricts plant growth and reproduction and is closely correlated with latitude (Walther et al. 2009). Therefore, IAPs are expected to be transferred to higher latitudes with climate warming (Walther et al. 2002). Our results showed that the future PGSH of *S. halepense* in the three land-use types transferred to higher latitudes in future scenarios. In contrast, future changes in precipitation are more variable than those in temperature under elevated emissions scenarios (Finch et al. 2021). *Sorghum halepense*, with high adaptability in new environments, could tolerate the maximum temperature of 35℃ and decline to -26℃ at the coldest each year (Coiner et al. 2018; CABI 2022). In addition, the wide range of mean annual precipitation that fits *S. halepense* growth is from 300 to 2000 mm (CABI 2022). The odds of fitting the future climate change that causes extreme climates are significantly increasing. Our results showed that the future PGSH of *S. halepense* is expected to increase in the Northern Hemisphere, achieving the maximum under SSP5-8.5 in the 2050s (Table 2). This is similar to other IAPs, which change their potentially suitable habitats in response to climate change. For instance, suitable global habitats of three ragweeds (*Ambrosia artemisiifolia, A. psilostachya*, and *A. trifida*) are expected to increase by the 2050s (Xian et al. 2023).

With future climate warming, many regions will become increasingly hot, leading to frequent droughts that cause physiological stress and mortality in invasive and native plants, which is expected to cause grassland degradation (Ravi et al. 2022). However, IAPs' responses to temperature, precipitation, and landscape changes outcompete those of native plants, therefore invasive plants become dominant (Yu et al. 2016). Previous studies have shown that *S. halepense* has a climate suitability of 50–90% in plains and grasslands in the United States, which poses a potential risk of transforming native grasslands into invaded prairies (Barney and DiTomaso 2011). Our results showed that the global grassland area projected for future LUC scenarios decreased to some extent, yet the invasive area of *S. halepense* progressively increased (Table 2; Fig. 3). In addition, cropland expansion has been gradually increasing in tropical areas since 2000 and is closely correlated with urban expansion (Grassini et al. 2013). To satisfy the housing demands of an increasing urban population, urban land is expected to increase dramatically in the future. More than 60% of global croplands are distributed near urban land, therefore urban expansion is expected to be transferred from croplands (Thebo et al. 2014; Bren d'Amour et al. 2017). Therefore, future PGSH of *S. halepense* in cropland and urban areas increases northward and more suitable areas are located in eastern China, western Europe, and northern North America under future climate scenarios (Table 2; Fig. 3). Similarly, future increase in the PGSH of *S. halepense* in grasslands is located in western Europe and northern North America.

4.3 Prevention and control

The unintentional introduction of the global grain trade mixed with *S. halepense* and its intentional introduction as a forage crop is the key to *S. halepense* spread (Wilson et al. 2009). Our results showed that future increased the PGSH of *S. halepense* in the three land-use types was mainly located in eastern China, Turkey, Iran, Afghanistan, Tajikistan, and southern Kazakhstan in Asia; Austria, Norway, San Marino, Slovenia, Switzerland, United Kingdom, western Russia, and Byelarus in Europe; northern United States and southern Canada in North America; southern Brazil in South America; and southern Cote d' Ivoire, South Africa, Ghana, and Ethiopia in Africa. For newly expanding countries such as San Marino, Byelarus, Cote d' Ivoire, and Ghana, assessing the early warming of *S. halepense* through risk assessment is important. However, for the new expansion region, customs quarantine controls in each country play a crucial role in resisting the expansion and spread of *S. halepense*. Furthermore, for the invasion and establishment of *S. halepense*, there are a few measures to control population outbreaks, such as chemical control and integrated pest management (IPM). Selective herbicides may be effective against *S. halepense*, including quizalofop, nicosulfuron, and glyphosate, achieving 88–97% effectiveness (Johnson et al. 2003). In addition, pre-sowing soybean and sorghum with glyphosate, Merlin, and Stromp is a vital method for controlling *S. halepense* (Defelice et al. 1987; Brown et al. 1988; Tóth and Lehoczky 2007).

5 Conclusions

Our study was the first time to reconstruct the historical invasive countries of *S. halepense* and explore how climate change and LUC influence the PGSH of *S. halepense* in the three land-use types (croplands, grasslands, and urban). *Sorghum halepense* is widely found worldwide except in Africa through the import and export trade and the introduction of fodder grass species. Our results found that environmental variables were more significant than LUC in predicting the PGSH of *S. halepense*. In addition, future croplands and urban areas were expected to increase continuously, while grassland area was expected to decrease. The future increased PGSH of *S. halepense* in the three land-use types is expected to increase continuously in the Northern Hemisphere and transfer to higher latitudes with climate warming. Furthermore, new expansion countries, such as San Marino, Byelarus, Cote d'Ivoire, and Ghana, need risk assessment of *S. halepense* to prevent its introduction. For increased regions in six continents need to increase plant quarantine at customs facilities of each country. The reconstructed historical invasive countries of *S. halepense* and the predicted PGSH of *S. halepense* are favorable for providing a more reliable risk assessment.

Declarations

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Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Author Contributions

The study conception and design were performed by Ming Yang and Haoxiang Zhao. Data acquisition was performed by Haoxiang Zhao. Data analysis was performed by Ming Yang and Yuhan Qi. The first draft of the manuscript was written by Ming Yang. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Data Availability

Global occurrences of *S. halepense* generated during and/or analysed during the current study are available in the GBIF (https://www.gbif.org/, accessed December 19, 2022), BOLD (http://boldsystems.org/, accessed December 19, 2022), SNIet (http://swbiodiversity.org, accessed November 6, 2022), Ministry of Agriculture and Rural Affairs of the People's Republic of China (http://www.moa.gov.cn/, accessed December 7, 2022). CABI generated during and/or analysed during the current study are available at https://www.cabi.org/. EPPO generated during and/or analysed during the current study are available at https://www.cabi.org/.Land-use harmonization data generated during and/or analysed during the current study are available at http://www.geosimulation.cn/Global-SSP-RCP-LUCC-Product.html. Climate data generated during and/or analysed during the current study are available in WorldClim v2.1 (https://worldclim.org/). Biomod2 4.2.3 package generated during and/or analysed during the current study are available at https://github.com/biomodhub/biomod2.

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Figures

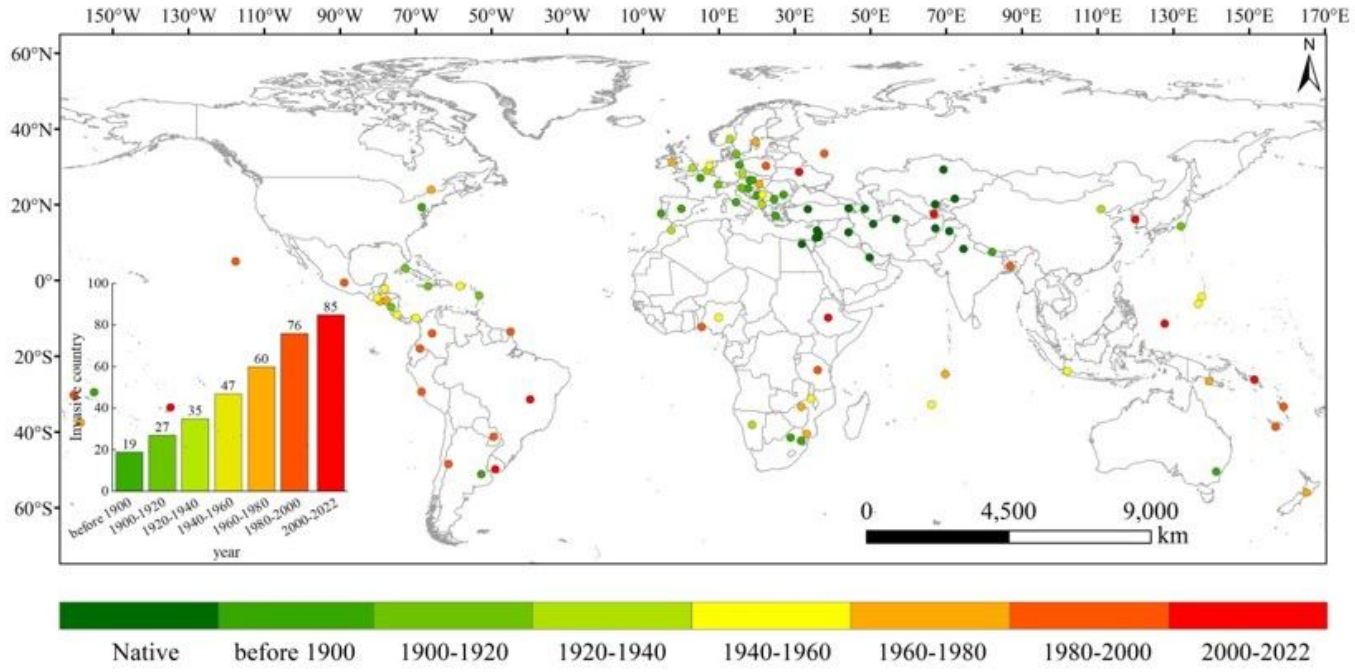

Figure 1

Reconstruct global invasive countries of *Sorghum halepense*. Eight-time intervals are shown until 2022 from green to red, except for native countries. Temporal accumulation histograms of invasive countries are displayed in the bottom left corner

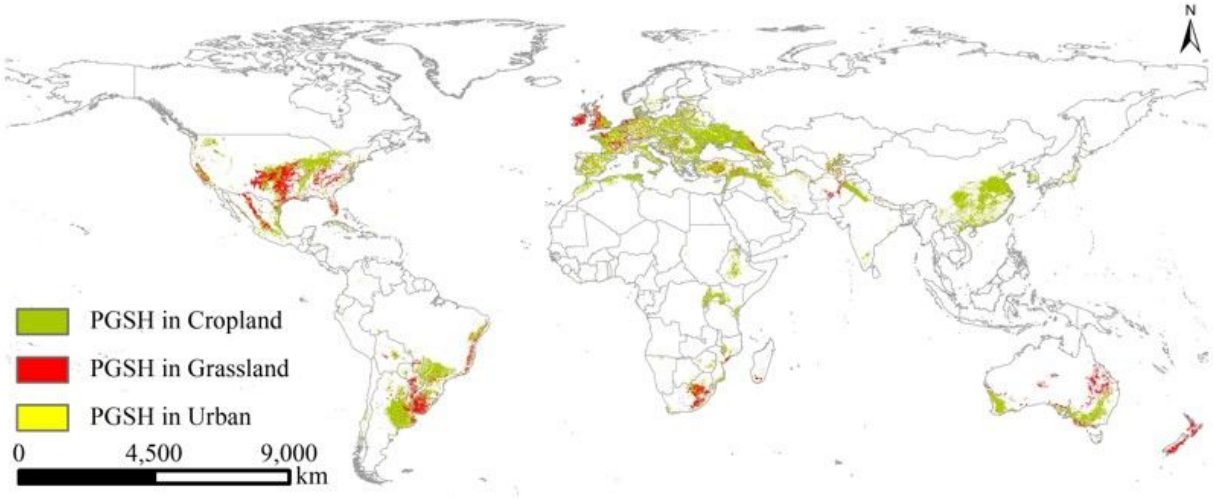

Figure 2

Potential global suitable habitats (PGSH) of *Sorghum halepense* in three land-use types under the near current climate

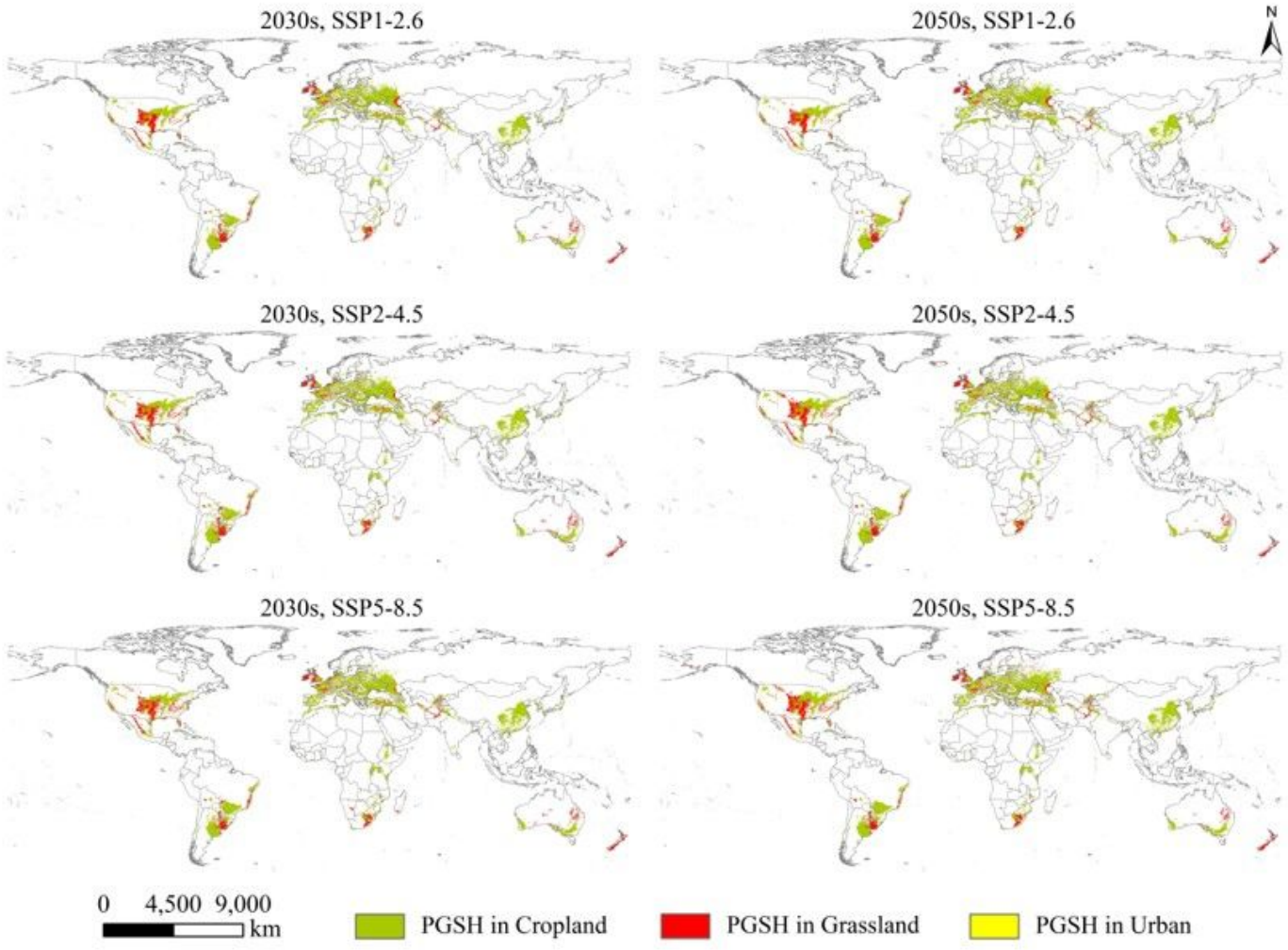

Figure 3

Potential global suitable habitats (PGSH) of *Sorghum halepense* in three land-use types under different future scenarios

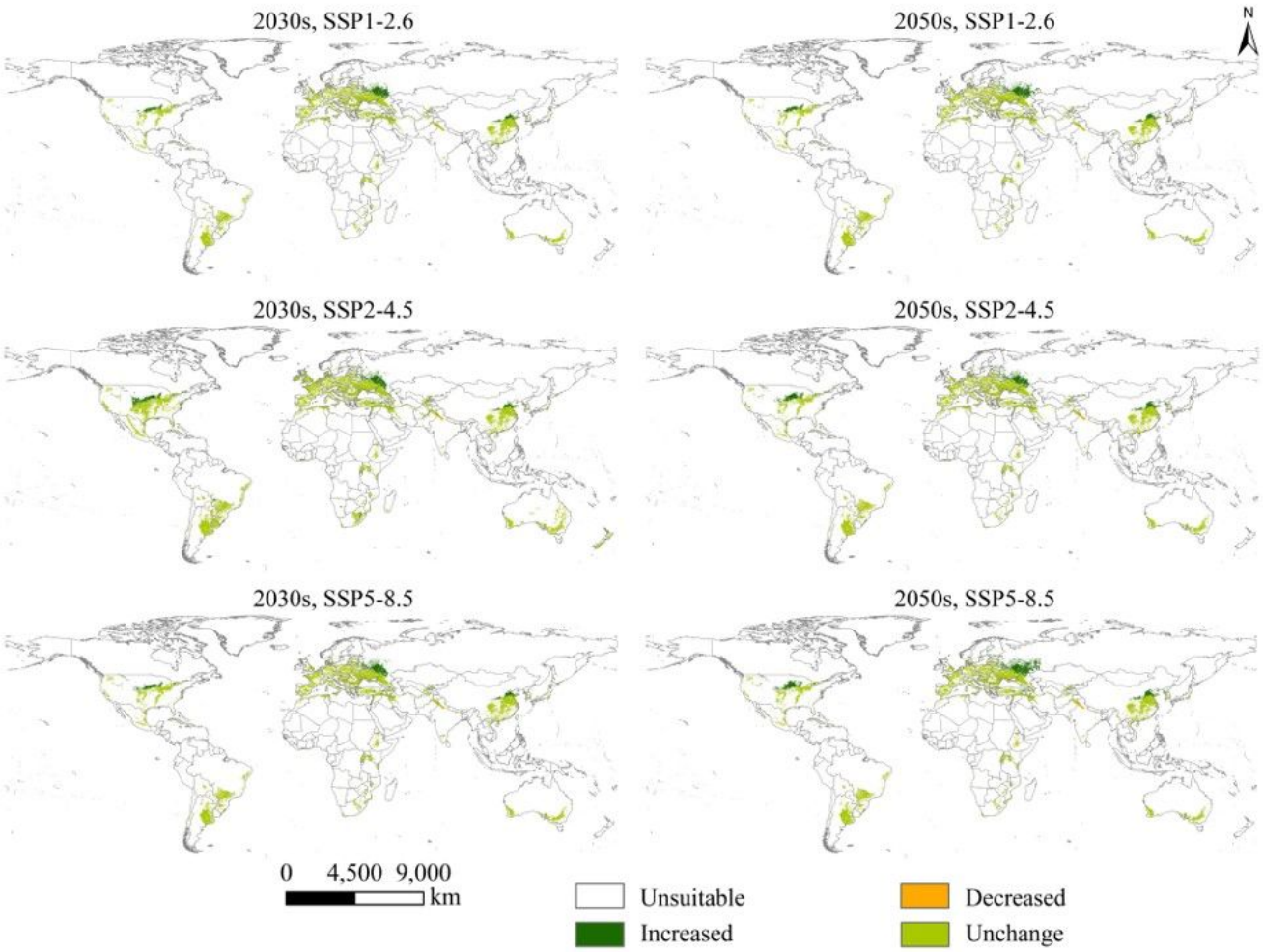

Figure 4

Changes in suitable cropland area for *Sorghum halepense* from different future scenarios to the near current climate

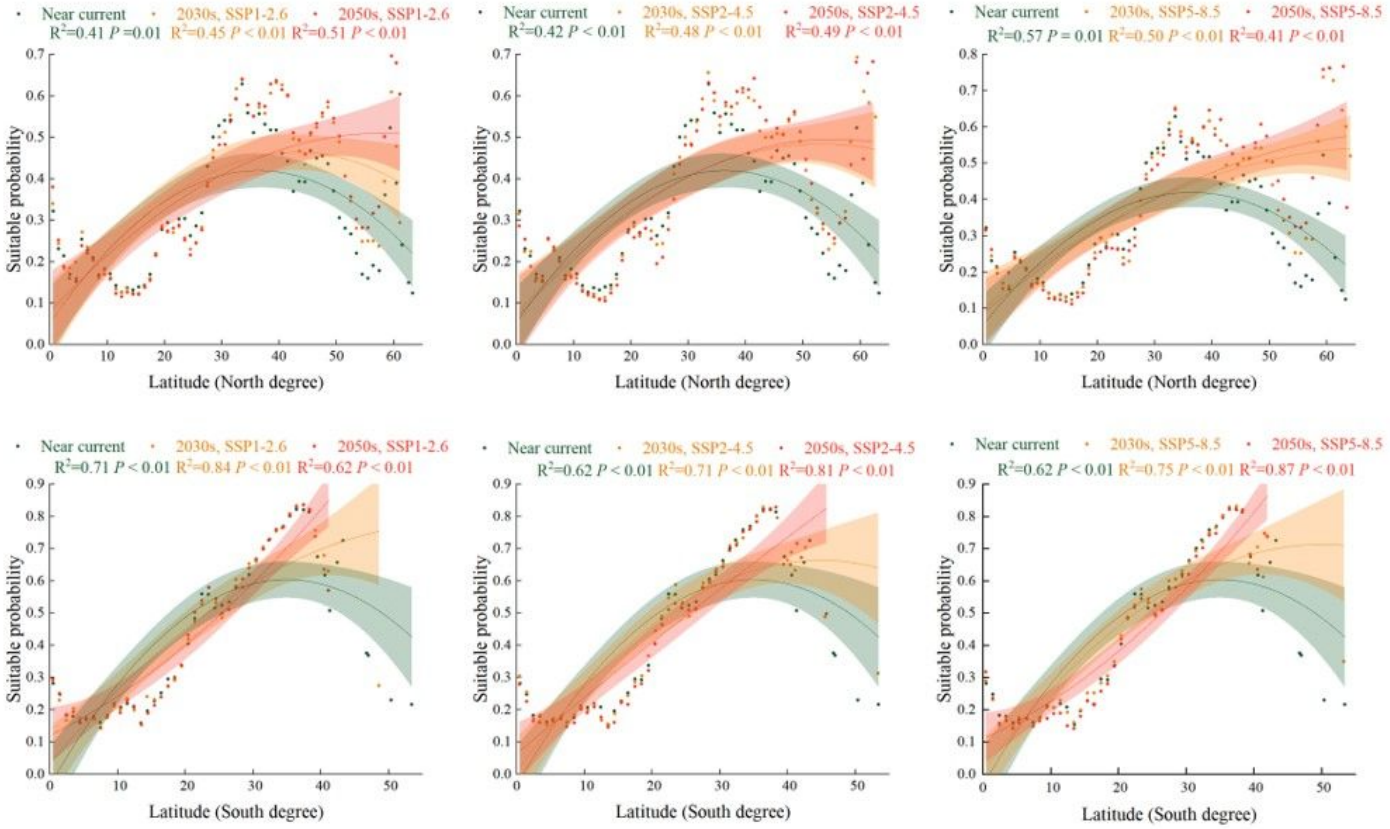

Figure 5

The PGSH of *Sorghum halepense* in cropland for the Southern and Northern Hemispheres in the near current climate and different future scenarios. For each group, we added 95% confidence bands via binomial fitting

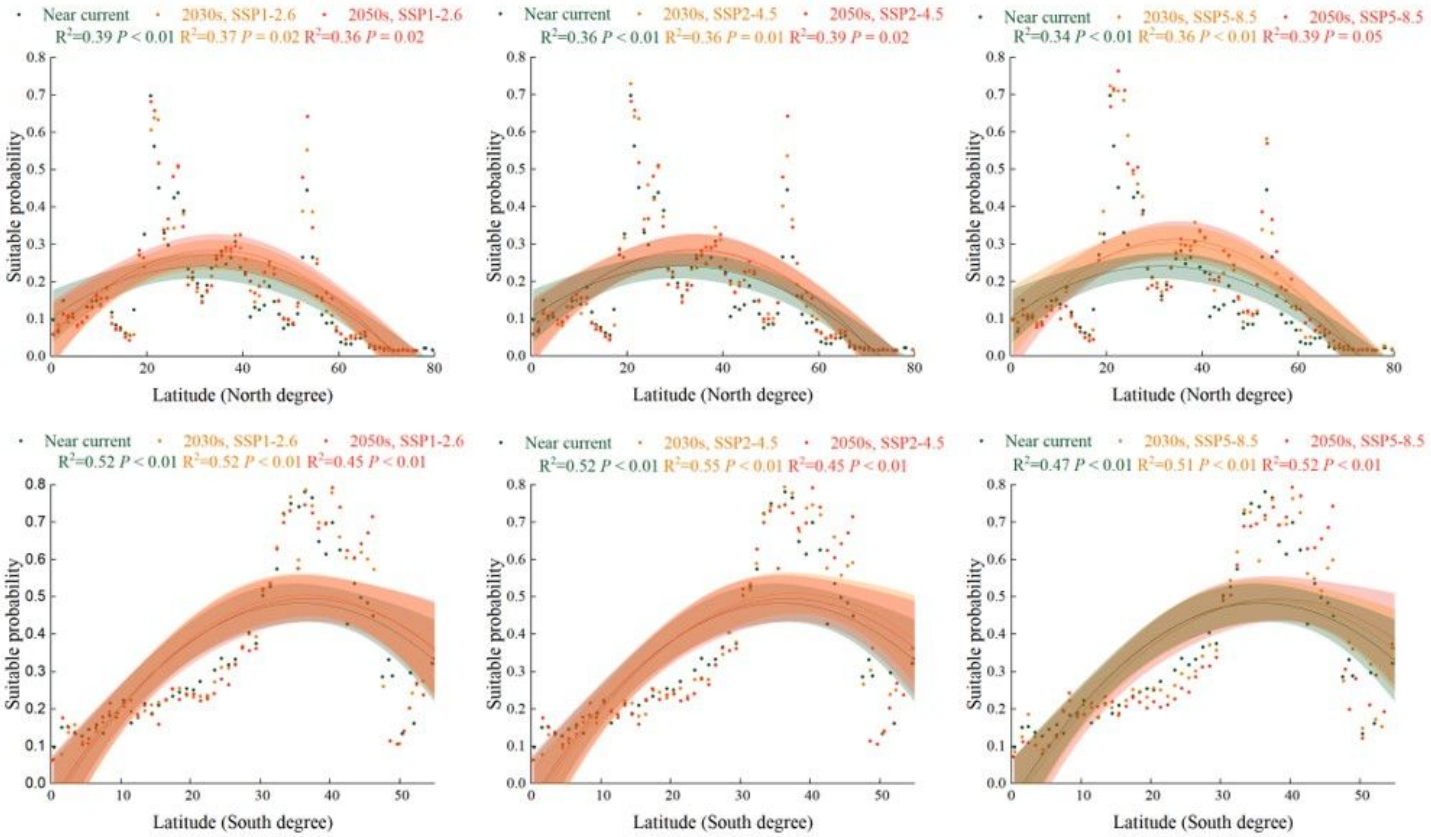

Figure 6

The PGSH of *Sorghum halepense* in grassland for the Southern and Northern Hemispheres in the near current climate and different future scenarios. For each group, we added 95% confidence bands via binomial fitting

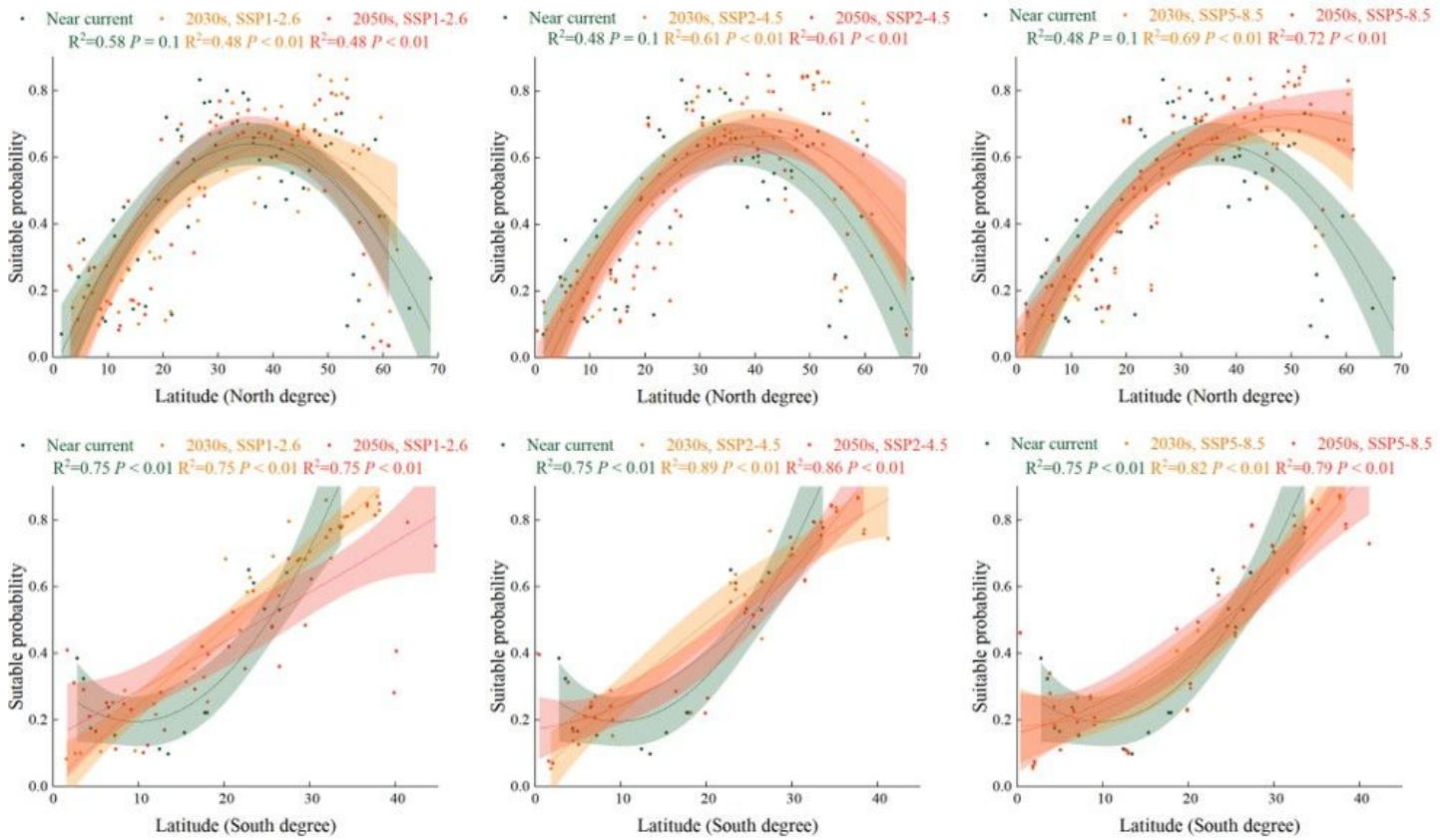

Figure 7

The PGSH of *Sorghum halepense* in urban for the Southern and Northern Hemispheres in the near current climate and different future scenarios. For each group, we added 95% confidence bands via binomial fitting

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SupplementalExcel.xlsx
- SupplementalInformation.docx