CLIMATE CHANGE AND AGRICULTURE RESEARCH PAPER

Predicting global geographical distribution of Lolium rigidum (rigid ryegrass) under climate change

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SUMMARY

Lolium rigidum L. (rigid ryegrass) is one of the most extensive and harmful weeds in winter cereal crops. A bioclimatic model for this species was developed using CLIMEX. The model was validated with records from North America and Oceania and used to assess the global potential distribution of L. rigidum under the current climate and under two climate change scenarios. Both scenarios represent contrasting temporal patterns of economic development and carbon dioxide (CO₂) emissions. The projections under current climatic conditions indicated that L. rigidum does not occupy the full extent of the climatically suitable area available to it. Under future climate scenarios, the suitable potential area increases by 3.79% in the low-emission CO₂ scenario and by 5.06% under the most extreme scenario. The model’s projection showed an increase in potentially suitable areas in North America, Europe, South America and Asia; while in Africa and Oceania it indicated regression. These results provide the necessary knowledge for identifying and highlighting the potential invasion risk areas and for establishing the grounds on which to base the planning and management measures required.

INTRODUCTION

Global climate change is one of the greatest threats to the sustainability of ecosystems (Bellard et al. 2012) with multiple consequences from a reduction in biodiversity to irreversible soil erosion of land (Perarnaud et al. 2005). Therefore, there will be important alterations in agrosystems, in which some predictions indicate a reduction of around 10–20% in crop production (IPCC 2007). Weed flora would be especially affected, both negatively and positively, with alterations in the competitive interactions between weeds and crops (Gonzalez-Andujar 1995; Ziska et al. 2011) and in the geographic distributions of weeds (Walck et al. 2011; Bourdöt et al. 2013). Estimating weed species’ climate matches under projected climate change is a priority to predict future climatically suitable areas for species occupation. Recently, process-based niche models such as CLIMEX have been widely used to project the potential geographic distribution of plants under current and future climate change scenarios (Chejara et al. 2010; Kriticos et al. 2010; Clements & Ditommaso 2011; Castellanos-Frias et al. 2014).

Lolium rigidum Gaud. is one of the most widespread and harmful grass weeds in winter cereal crops in Mediterranean environments (Monaghan 1980; Recasens et al. 1997; Steadman et al. 2004). Its origin is located in the Middle East (Recasens et al. 1997) and from there it spread throughout the Mediterranean. Later, it was introduced or spread to North and South America, South Africa and Australia. The biology of L. rigidum in these cropping systems is characterized by high germination rates from the soil seedbank and high adult fertility, with low natural mortality of seedlings and adults (Recasens et al. 1997; Taberner 2001), which favours high population densities of this weed in the absence of control measures. The consequences of heavy infestations of rigid ryegrass on winter cereal crops bring about negative impacts on agricultural productivity and economic losses.
crops can significantly affect the profitability of the crop, with yield losses of up to 83% seen in barley when densities reached 1240 plants/m² in central Spain (Izquierdo et al. 2003). In Australia, densities of 300 plants/m² produced 42 and 55% losses in wheat and barley, respectively (Lemerle et al. 1995).

The emergence of *L. rigidum* is highly dependent on temperature and rainfall (Izquierdo et al. 2013). Therefore, it is highly likely that *L. rigidum* might be affected by climate change with a resulting modification of its current geographic distribution. Despite the large economic losses that *L. rigidum* can cause in cereal crops, there is no information about the geographic range over which this species could potentially spread under the current and future climate change scenarios. Information describing this range would offer considerable insight into the areas vulnerable to the invasion of this weed, allowing farmers to prioritize control programmes. In the present study a process-based niche model was developed and used to (i) estimate the current global potential distribution of *L. rigidum* and (ii) predict the potentially global suitable area under future climate scenarios. Ultimately the current work should help prioritize management efforts against *L. rigidum* by identifying locations that might be suitable for this species.

**MATERIAL AND METHODS**

The software program CLIMEX (Hearne Scientific Software, Sutherst et al. 2007) was used to develop the bioclimatic niche model for *L. rigidum*. It is a dynamical model that provides a measure of potential distribution based on the climatic requirements of a species. It uses various growth- and stress-related indices to describe the potential of population growth under favourable and unfavourable conditions. The growth and stress indices combine to provide the ecoclimatic index (EI), which gives an overall estimate of the suitability of a given location for the species in question (Sutherst et al. 2007). It ranges from 0 to 100, where 0 = area not suitable for species persistence and 100 = area wholly suitable for persistence. In the present study, EI was divided into four classes of suitability for species growth for further analysis: 0, unsuitable; 1–10, marginal; 10–20, suitable; and >20, optimal (Sutherst & Maywald 2005; Sutherst et al. 2007). The EI data generated by CLIMEX were interpolated using the inverse distance weighted method, and represented in ArcGIS 10 to quantify suitable areas. The resulting grid cells were then reclassified according to the three EI classes and the total area in each class was determined. The current global distribution was derived from the literature and various databases (Terrell 1968; Cocks & Donald 1973; Gramshaw 1976; Tutin et al. 1980; Recasens et al. 1997; Fernández-Quintanilla et al. 2000; Chen et al. 2006; Kirkby et al. 2011; EUROMED 2014; CABI 2014; GBIF 2014; Missouri Botanical Garden 2014; USDA 2014; CHAH 2014) (Supplementary Material: go to http://journals.cambridge.org/AGS).

Parameter values were obtained mainly from the literature and, when necessary, were calibrated iteratively based on the current distribution of ryegrass in Europe (Sutherst et al. 2007; Kriticos et al. 2010). Lower optimal temperature (DV1) and upper optimal temperature (DV2) were obtained from seed germination and seedling emergence studies (Recasens et al. 1997; Taberner 2001; Izquierdo et al. 2013) and were set at 7·4 and 30 °C, respectively (Table 1). The lower temperature threshold (DV0) and the limiting high temperature (DV3) were defined from minimum and maximum temperatures recorded in the area where the species is currently distributed (Recasens et al. 1997; Taberner 2001) (Table 1). The heat stress temperature threshold (THS) was established at 35 °C because it was reported that *L. rigidum* is able to persist up to this temperature in Spain (Recasens et al. 1997; Taberner 2001) with an accumulation rate (THHS) of 0·00001/week (Table 1). Moisture indices and dry stress were established iteratively based on geographic distribution records for the species (Table 1). The cold stress threshold (TTCS) and accumulation rate (THCS) were set at 0 °C and 0·0015/week, respectively, because the plant is susceptible to frost damage. These parameters were adjusted iteratively to allow it to barely persist in some areas of northern Spain where the minimum winter temperature regularly goes well below 0 °C (Table 1). The parameters degree-days threshold (DTCS) and cold stress accumulation rate (DHCS) (Table 1) evaluate whether thermal accumulation is enough to explain the presence of this species. As shown by Kriticos et al. (2010) and McConnachie et al. (2011) in their studies with weeds, it is advisable to include these indices in order to obtain a better fit of the geographic distribution, otherwise the presence of *L. rigidum* in Northern Europe and North America would be overestimated.

*Lolium rigidum* is well suited to Mediterranean conditions (Recasens et al. 1997), where the moisture level is low and, thus, a wet excess could be negative...
The wet stress threshold (SMWS) was set at 1.4 and the accumulation rate (HWS) was adjusted to 0.001/week (Table 1) (Sutherst et al. 2007) in order to prevent *L. rigidum* from growing in very wet locations.

The hot-wet stress index is recommended to separate Mediterranean species from tropical ones. It was defined according to Sutherst et al. (2007) and fine-tuned with the results of the model. The temperature threshold for hot-wet stress (TTHW) was set at 24 °C, with a moisture threshold (MTHW) of 0.3 and a stress accumulation rate (PHW) of 0.099/week.

Geographic distribution of species is also determined by the thermal accumulation required to reach a minimum amount of development to complete the life-cycle (Sutherst et al. 2007; Kriticos et al. 2010). Thermal accumulation (PDD) was collected from the literature (Recasens et al. 1997) and set at 2032 degree-days (Table 1).

The Dormancy induction day length (DPD0) was taken from Sutherst et al. (2007) for Mediterranean areas. Seed dormancy induction temperature (DPT0) and seed dormancy termination temperature (DPT1) were iteratively calibrated.

The minimum number of days necessary to terminate seed dormancy (DPD) was set at 120 days (Table 1) based on the literature on the life-cycle of *L. rigidum*, reporting seed dormancy between June and October (Recasens et al. 1997; Taberner 2001).

**Model validation**

The model was validated with records from North America and Oceania (Sutherst & Maywald 2005). A
quantitative assessment of the agreement between known and predicted distribution of *L. rigidum* was made through the calculation of the area under the curve (AUC) of the receiver operating characteristic (ROC). The ROC curve is obtained by plotting the species’ true positive (correspondence between real presence and simulated data) rate and the false positive (no correspondence between real presence and simulated data) rate and describes the compromise that a model attains between including known presences and excluding absences. The AUC provides an objective measure of accuracy (Elith et al. 2006), varying from 0·5 for randomness to 1·0 for a perfect fit. This AUC is commonly applied in the assessment of the accuracy of species distribution models (Ni et al. 2012).

Meteorological database

The climate database was taken from the CliMond website (Kriticos et al. 2012) as it provides the variables required by CLIMEX. The historical meteorological data are centred on the year 1975, representing the reference period 1961–90. These data consist of a global 30′ regular grid with 67 419 points distributed over the land worldwide, corresponding to approximately 50 × 50 km of resolution. The climate database was included in the rigid rye-grass model to infer its climate requirements, and thus to establish its geographic distribution.

Climate change scenarios

The effect of climate change on the potential global distribution of *L. rigidum* was assessed through the CSIRO-MK3 (CSIRO, Australia) global climate model (GCM). This model represents the climate at a regional scale relatively well, and provides the data required by CLIMEX (Kriticos et al. 2012). The target year was set at 2100 using different greenhouse gas emission scenarios. The GCM was subjected to the conditions of medium (A1B) and high (A2) emission scenarios (IPCC 2007; Rahmstorf et al. 2007) (Table 2). These two scenarios include contrasting temporal patterns of economic development and carbon dioxide (CO2) emissions. The A2 scenario describes a world with a great regional inequality based on a continuous increase in global population, economic growth and technological change, fragmented and medium-high CO2 emissions. The A1B scenario contemplates a rapid economic growth with a maximum value of global population in mid-century, declining thereafter, and a rapid and more efficient introduction of new technologies based on a balanced use across all sources of energy (Table 2).

### RESULTS

Validation analysis shows a good agreement with the known distribution of *L. rigidum* in North America (AUC = 0·98) and Oceania (AUC = 0·96). Any AUC values >0·75 are indicative of high prediction accuracy and >0·9 models are considered to be excellent (Elith et al. 2006). These results reveal a good model performance for predicting with high accuracy the geographic distribution of *L. rigidum*.

Potential distribution under the current climate

Model prediction of the current global geographic distribution of *L. rigidum* corresponded well to their known distribution (Fig. 1). The AUC value of 0·97 indicates that the model has great discrimination ability. The current potential global distribution of rye-grass was estimated at 7·9 × 10^6 km^2, of which 47% (3·7 × 10^6 km^2) are optimal locations, 19% (1·5 × 10^6 km^2) are suitable ones and 34% (2·7 × 10^6 km^2) are marginal locations (Table 3). The optimal areas were located mainly in Mediterranean climate areas (Fig. 1). Europe and Oceania have the largest suitable areas with 22% and 16% of their territory, respectively (Fig. 1). In Europe, the territory appropriate for *L. rigidum* is almost continuous, covering 2·19 × 10^6 km^2 and including the Mediterranean countries, central Europe, low altitude regions of northern Europe, and also a small area in the southeast (Fig. 1;
Table 4). The area of potential distribution of ryegrass in Oceania reaches 1·39 × 10^6 km², much of southern Australia and northern New Zealand (Fig. 1; Table 4). In North America, the most suitable areas (0·61 × 10^6 km²) are concentrated on the West Coast, in Mediterranean-type environments (Fig. 1; Table 4), while in South America, distribution (0·46 × 10^6 km²) affects Chile and Argentina (Fig. 1; Table 4). The distribution in Africa (0·88 × 10^6 km²; Fig. 1; Table 4) fitted the existing records for the north of the continent very well (a narrow strip along the Mediterranean basin), and in South Africa (Fig. 1). In Asia, ryegrass can potentially infest 2·37 × 10^6 km², affecting countries adjacent to the Mediterranean sea, the Black and Caspian seas and central latitudes of the continent (Fig. 1; Table 4).

Future geographic distribution under climate change

Under future climate change scenarios, areas climatically suitable to L. rigidum are projected to increase globally, by up to 3·79 and 5·06% of the earth’s land surface under both the low-carbon emission scenario (A1B) and the most extreme scenario (A2), respectively (Table 3; Figs 2 and 3). Nevertheless, the optimal areas for the weed species are potentially reduced by 16·2% (A1B) and 10·8% (A2). In contrast, suitable and marginal distribution areas show a sharp increase. The suitable areas increase by 26·7% under both A1B and A2 scenarios, whereas marginal areas experience a potential increase of 18·5 and 14·8% under A1B and A2 scenarios, respectively (Table 3; Figs 2 and 3).

Europe, Asia, North and South America show a potential increase in suitable areas for rigid ryegrass, indicating considerable scope for further invasion of L. rigidum. The most pronounced expansion of this weed might happen in North America and Europe. In North America, an increment of 109·7 and 175·6% in distribution area is projected under A1B and A2 scenarios, respectively (Table 4; Figs 2 and 3).
mainly concentrated in coastal areas of western United States and Canada and central areas of the USA (Figs 2 and 3). Suitable areas are also projected to increase substantially in Europe, by 108·7 and 167·3% under A1B and A2 scenarios, respectively (Table 4; Figs 2 and 3), with suitable territories shifting towards northern (Ireland, Denmark, Sweden or Norway) and eastern countries (Latvia, Estonia, Moldova, Ukraine or Russia) (Figs 2 and 3). Minor increments in distribution areas are projected for South America and Asia (Figs 2 and 3; Table 4). Africa and Oceania presented a marked reduction under the two climate change scenarios (Table 4; Figs 2 and 3).

DISCUSSION

The ultimate value of the results is subject to the validity of the model, which is supported by a high degree of congruence between known distribution and predicted geographic distribution and the high AUC values. The present results clearly suggest that, under the current climate, this weed species is capable of occupying a greater range globally than it covers at present. Continents with the most potential for expanding in its native range are Europe, Asia, North America and South America.

Under future climate conditions the potential geographic distribution of L. rigidum may change following a poleward trend, occupying areas that are currently too cold for its survival. The potential area climatically suitable is projected to increase by 3·79% (0·3 × 10^6 km^2) under the A1B scenario and by 5·06% under scenario A2 (0·4 × 10^6 km^2). Both scenarios produced a similar available area for the growth of ryegrass.

The largest increases in infestation area, under both climate change scenarios, would happen in North America and Europe. In North America, the potential increment in distribution area could reach 175·6% (1·67 × 10^6 km^2) under the worst-case scenario (A2). According to the potential distribution projected for rigid ryegrass, the US states mostly affected could be California, Oregon, Washington, Idaho, Montana, Nevada, Utah, Wyoming, Colorado, Nebraska, Kansas, Oklahoma, Texas and Michigan, all of which have important extensions of cereal crops (NASS-USDA 2014). Therefore, the potential spread of L. rigidum throughout these states may involve a significant impact in terms of crop yield losses.

In the same vein, Europe also shows a significant potential increase in the rigid ryegrass distribution area of 167·3% under the worst-case scenario (A2). The general trend of L. rigidum is a north-eastern movement. Regions with the highest potential for invasion are located in the centre of the continent, the northern regions (Ireland, north of the UK and the Scandinavian countries) and the eastern countries (Ukraine and Russia).

Table 3. Projected land area climatically suitable (EI ≥ 1) for L. rigidum under current climate, expressed as an area and as a percentage of increment/decrement on total infested land area under climate change scenarios (A1B and A2) for 2100

<table>
<thead>
<tr>
<th></th>
<th>Total Area (km^2)</th>
<th>%</th>
<th>Marginal Area (km^2)</th>
<th>%</th>
<th>Suitable Area (km^2)</th>
<th>%</th>
<th>Optimal Area (km^2)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current climate</td>
<td>7.9 × 10^6</td>
<td></td>
<td>2.7 × 10^6</td>
<td>3.79</td>
<td>1.5 × 10^6</td>
<td>18.51</td>
<td>3.7 × 10^6</td>
<td></td>
</tr>
<tr>
<td>CSIRO A1B</td>
<td>8.2 × 10^6</td>
<td></td>
<td>3.2 × 10^6</td>
<td>18.51</td>
<td>1.9 × 10^6</td>
<td>26.66</td>
<td>3.1 × 10^6</td>
<td>-16.21</td>
</tr>
<tr>
<td>CSIRO A2</td>
<td>8.3 × 10^6</td>
<td></td>
<td>3.1 × 10^6</td>
<td>14.81</td>
<td>1.9 × 10^6</td>
<td>26.66</td>
<td>3.3 × 10^6</td>
<td>-10.81</td>
</tr>
</tbody>
</table>

Table 4. Percentage change, by continent, of the potential distribution of L. rigidum under climate change (A1B and A2), with respect to the current surface

<table>
<thead>
<tr>
<th></th>
<th>Africa</th>
<th>Asia</th>
<th>Europe</th>
<th>North America</th>
<th>Oceania</th>
<th>South America</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current (×10^6 km^2)</td>
<td>0.88</td>
<td>2.37</td>
<td>2.19</td>
<td>0.61</td>
<td>1.39</td>
<td>0.46</td>
</tr>
<tr>
<td>CSIRO A1B (%)</td>
<td>-46.1</td>
<td>17.5</td>
<td>108.7</td>
<td>-48.0</td>
<td>20.8</td>
<td></td>
</tr>
<tr>
<td>CSIRO A2 (%)</td>
<td>-66.8</td>
<td>22.3</td>
<td>167.3</td>
<td>-59.5</td>
<td>17.9</td>
<td></td>
</tr>
</tbody>
</table>
In South America and Asia, the model’s results show the same trend of displacement towards the poles described for Europe or North America. The increasing area of *L. rigidum* over Asia poses a potential risk for countries like Turkey, Kazakhstan, Pakistan, Iran or Uzbekistan, important producers of wheat globally (FAOSTAT 2014). Meanwhile, China and India infestation areas might be reduced.

Conversely, the climate change scenarios project a reduction of up to 66-8% in the total suitable area for *L. rigidum* in Africa and Oceania.

In the present study, two contrasting scenarios have been analysed. Both scenarios project increases in the potential suitable area of ryegrass. However, the variation does not always appear to be significant, depending on which climate model is used (Table 3),

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**Fig. 2.** The potential global geographical distribution of *L. rigidum* under climate change scenario CSIRO A1B projected for 2100, based on the EI using CLIMEX model: □ unsuitable; □ marginal; □ suitable and □ optimal.

**Fig. 3.** The potential global geographical distribution of *L. rigidum* under climate change scenario CSIRO A2 projected for 2100, based on the EI using CLIMEX model: □ unsuitable; □ marginal; □ suitable and □ optimal.
Chemical control of this weed is currently the main viable option. However, herbicide resistance (Gill & Holmes 1997) in *L. rigidum* has been detected globally (Heap 2014). The likely global expansion of *L. rigidum* throughout Europe and North America could lead to an expansion of herbicide-resistant populations in these territories and, conversely, a decrease in Australia where rigid ryegrass resistance to herbicides is currently a problem (Owen et al. 2014).

Knowledge of shifts in the geographic distribution of *L. rigidum* under climate change is essential for identifying and highlighting potential invasion areas. This is a prerequisite on which to base preventive planning and management measures. The spread rate at which a weed occupies its potential range is dependent on its dispersal ability. In assessing the potential of *L. rigidum* invasion at a regional scale, the major factor that determines *L. rigidum* seed dispersal is human action (Baker et al. 2000). Special emphasis should be given to controlling global commerce of crop seeds in order to ensure that seed lots are weed-free (Michael et al. 2010), since otherwise they may favour the spread of *L. rigidum* over new potentially suitable areas.

The model developed in the present study provides some measure of confidence in the direction of the expected changes in the global distribution of *L. rigidum* under climate change. However, if anthropogenic emissions of greenhouse gases can be significantly reduced and/or there are significant changes in agricultural policies (e.g. changes in the amount of land used for cereal cultivation), then the changes in the geographic range of *L. rigidum* may be substantially different from those projected under the scenarios analysed in the current paper.

In summary, the present study has developed global distribution maps that identify areas in which *L. rigidum* could extend its range and countries that are at risk of invasion based on their climatic suitability. It also provides an indication of the likely changes in its geographic distribution under climate change. As climate conditions become extreme, it is expected that this weed will substantially increase its range, posing a serious threat to the economic and environmental sustainability of winter cereal crops. Therefore, this model could prove useful for identifying and highlighting the potential invasion risk areas and for establishing the grounds on which to base the planning and management measures required.

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**SUPPLEMENTARY MATERIAL**

The Supplementary Material for this paper can be found at: http://journals.cambridge.org/AGS

**REFERENCES**


