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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 (CO_2) 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 CO_2 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; Bourdôt *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-Frías *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

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crops can significantly affect the profitability of the crop, with yield losses of up to 83% seen in barley when densities reached 1240 plants/m^2 in central Spain (Izquierdo *et al*. 2003). In Australia, densities of 300 plants/m^2 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 (TTHS) 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 the 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

Table 1. *Parameters used in the CLIMEX model for* L. rigidum

Index	Parameter		Value
Temperature	DV0	Lower temperature threshold	1·8 °C
	DV1	Lower optimum temperature	7·4 °C
	DV2	Upper optimum temperature	30 °C
	DV3	Upper temperature threshold	35 °C
Moisture	SM0	Lower soil moisture threshold	0·24*
	SM1	Lower optimal soil moisture	0·3*
	SM2	Upper optimal soil moisture	1*
	SM3	Upper soil moisture threshold	1·4*
Cold stress	TTCS	Cold stress temperature threshold	0 °C
	THCS	Cold stress accumulation rate	−0·0015/week
	DTCS	Degree-days threshold	13 degree-days
	DHCS	Cold stress accumulation rate	−0·00004/week
Heat stress	TTHS	Heat stress temperature threshold	35 °C
	THHS	Heat stress accumulation rate	0·00001/week
Dry stress	SMDS	Soil moisture dry stress threshold	0·01*
	HDS	Dry stress accumulation rate	−0·006/week
Wet stress	SMWS	Soil moisture wet stress threshold	1·4*
	HWS	Wet stress accumulation rate	0·001/week
Hot-wet stress	TTHW	Temperature threshold	24 °C
	MTHW	Hot-wet moisture threshold	0·3*
	PHW	Hot-wet stress accumulation rate	0·099/week
Thermal accumulation	PDD	Number of degree-days above DV0 necessary to complete one generation	2032 degree-days
Dormancy	DPD0	Dormancy induction daylength	13·9 h
	DPT0	Dormancy induction temperature	12 °C
	DPT1	Dormancy termination temperature	20 °C
	DPD	Dormancy development days	120 days
	DPSW	Dormancy summer indicator	1*

* Dimensionless value.

for this species. 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

Table 2. *Climate change scenarios in the world by the year 2100*

Emissions scenario		Global population (billion)	CO_2 concentration (ppm)	Global ΔT (°C)	Likely range (°C)
2100	A1B	7·1	711	2·9	1·7–4·4
	A2	15·1	857	3·8	2·0–5·4

Source: IPCC (2007).

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 ryegrass 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 (CO_2) 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 CO_2 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 ryegrass was estimated at $7{\cdot}9 \times 10^6$ km^2, of which 47% ($3{\cdot}7 \times 10^6$ km^2) are optimal locations, 19% ($1{\cdot}5 \times 10^6$ km^2), are suitable ones and 34% ($2{\cdot}7 \times 10^6$ 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 $2{\cdot}19 \times 10^6$ 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;

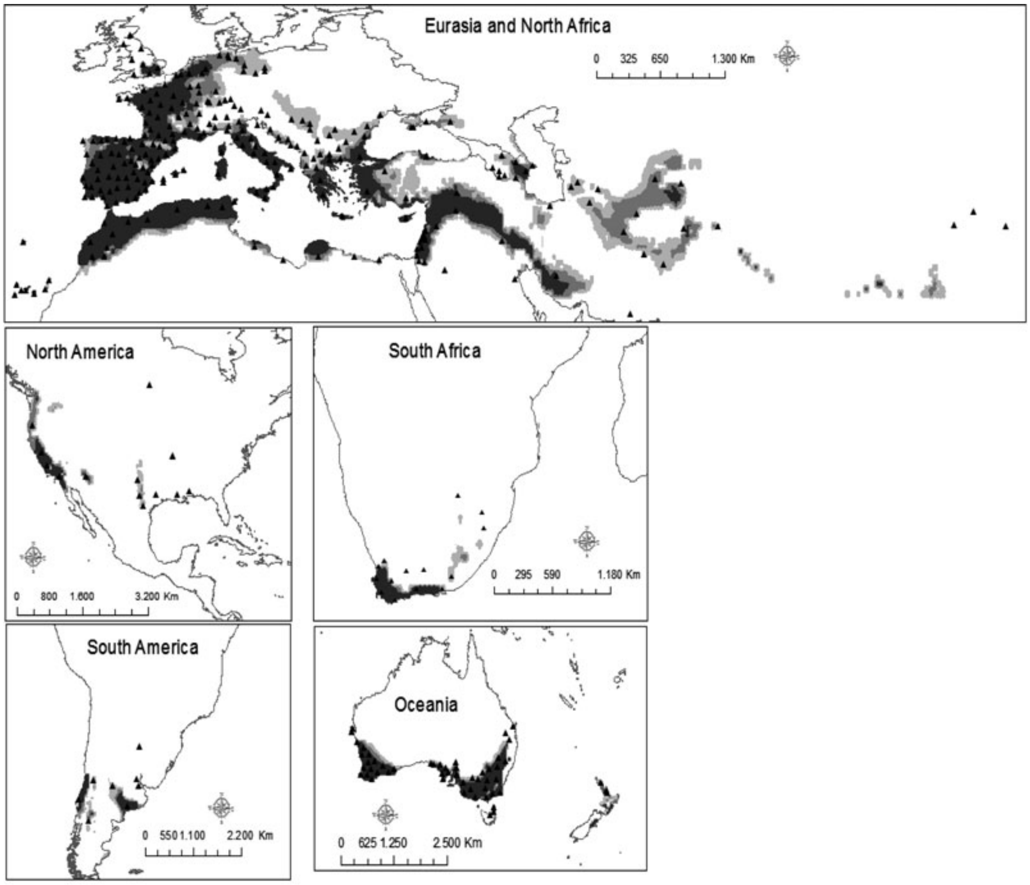

Fig. 1. Current projected global geographical distribution of *L. rigidum* according to the EI using CLIMEX model: □ unsuitable; ▩ marginal; ▩ suitable and ■ optimal. Known distribution of *L. rigidum* (triangles). Field occurrences were obtained from published records and databases.

Table 4). The area of potential distribution of ryegrass in Oceania reaches $1{\cdot}39 \times 10^6$ km^2, much of southern Australia and northern New Zealand (Fig. 1; Table 4). In North America, the most suitable areas ($0{\cdot}61 \times 10^6$ km^2) are concentrated on the West Coast, in Mediterranean-type environments (Fig. 1; Table 4), while in South America, distribution ($0{\cdot}46 \times 10^6$ km^2) affects Chile and Argentina (Fig. 1; Table 4). The distribution in Africa ($0{\cdot}88 \times 10^6$ km^2; 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 $2{\cdot}37 \times 10^6$ km^2, 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),

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*

	Total		Marginal		Suitable		Optimal	
	Area (km^2)	%	Area (km^2)	%	Area (km^2)	%	Area (km^2)	%
Current climate	$7{\cdot}9 \times 10^6$		$2{\cdot}7 \times 10^6$		$1{\cdot}5 \times 10^6$		$3{\cdot}7 \times 10^6$	
CSIRO A1B	$8{\cdot}2 \times 10^6$	3·79	$3{\cdot}2 \times 10^6$	18·51	$1{\cdot}9 \times 10^6$	26·66	$3{\cdot}1 \times 10^6$	−16·21
CSIRO A2	$8{\cdot}3 \times 10^6$	5·06	$3{\cdot}1 \times 10^6$	14·81	$1{\cdot}9 \times 10^6$	26·66	$3{\cdot}3 \times 10^6$	−10·81

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*

	Africa	Asia	Europe	North America	Oceania	South America
Current (×10^6 km^2)	0·88	2·37	2·19	0·61	1·39	0·46
CSIRO A1B (%)	−46·1	17·5	108·7	109·7	−48·0	20·8
CSIRO A2 (%)	−66·8	22·3	167·3	175·6	−59·5	17·9

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% ($0{\cdot}3 \times 10^6$ km^2) under the A1B scenario and by 5·06% under scenario A2 ($0{\cdot}4 \times 10^6$ 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% ($1{\cdot}67 \times 10^6$ 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).

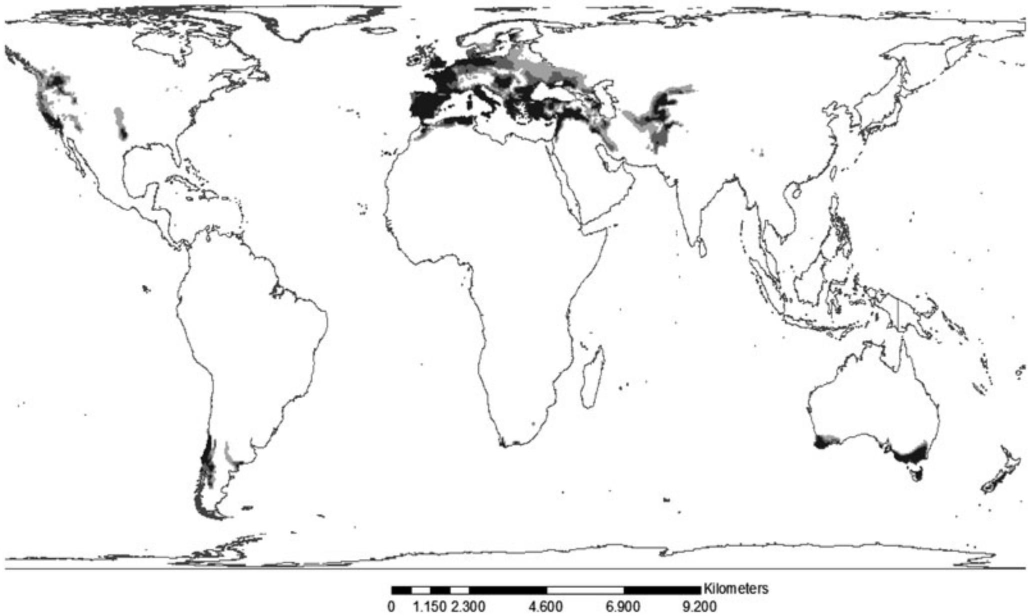

Fig. 2. The potential global geographical distribution of *L. rigidum* under climate change scenario CSIRO A1B projected for 2100, based on the EI using CLIMEX model: □ unsuitable; ▪ marginal; ▪ suitable and ■ optimal.

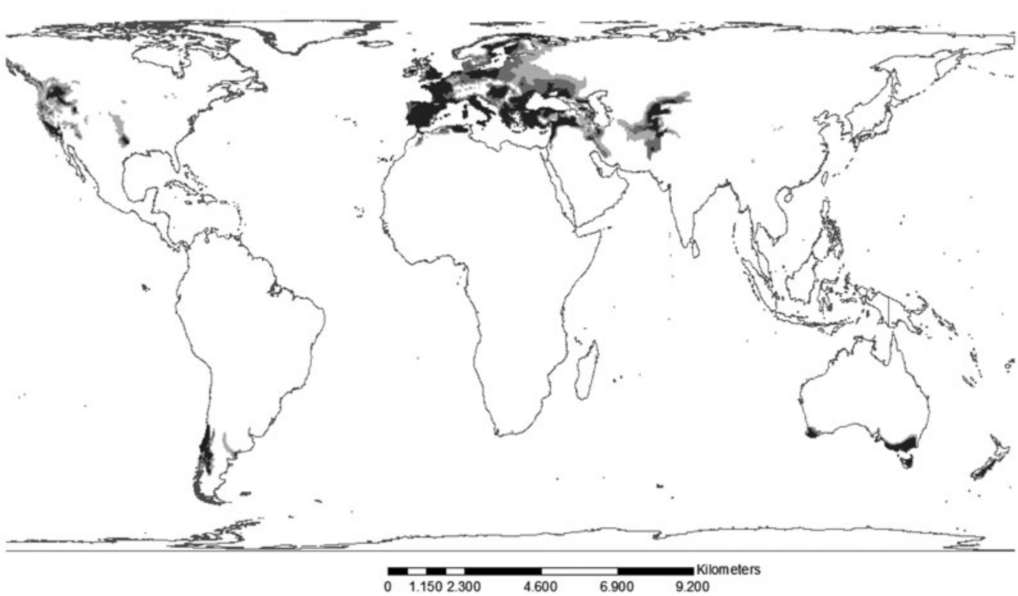

Fig. 3. The potential global geographical distribution of *L. rigidum* under climate change scenario CSIRO A2 projected for 2100, based on the EI using CLIMEX model: □ unsuitable; ▪ marginal; ▪ suitable and ■ optimal.

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), 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

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