Downscaling Pest Risk Analyses: Identifying Current and Future Potentially Suitable Habitats for *Parthenium hysterophorus* with Particular Reference to Europe and North Africa

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Abstract

Pest Risk Assessments (PRAs) routinely employ climatic niche models to identify endangered areas. Typically, these models consider only climatic factors, ignoring the ‘Swiss Cheese’ nature of species ranges due to the interplay of climatic and habitat factors. As part of a PRA conducted for the European and Mediterranean Plant Protection Organization, we developed a climatic niche model for *Parthenium hysterophorus*, explicitly including the effects of irrigation where it was known to be practiced. We then downscaled the climatic risk model using two different methods to identify the suitable habitat types: expert opinion (following the EPPO PRA guidelines) and inferred from the global spatial distribution. The PRA revealed a substantial risk to the EPPO region and Central and Western Africa, highlighting the desirability of avoiding an invasion by *P. hysterophorus*. We also consider the effects of climate change on the modelled risks. The climate change scenario indicated the risk of substantial further spread of *P. hysterophorus* in temperate northern hemisphere regions (North America, Europe and the northern Middle East), and also high elevation equatorial regions (Western Brazil, Central Africa, and South East Asia) if minimum temperatures increase substantially. Downscaling the climate model using habitat factors resulted in substantial (approximately 22–53%) reductions in the areas estimated to be endangered. Applying expert assessments as to suitable habitat classes resulted in the greatest reduction in the estimated endangered area, whereas inferring suitable habitats factors from distribution data identified more land use classes and a larger endangered area. Despite some scaling issues with using a globally conformal Land Use Systems dataset, the inferential downscaling method shows promise as a routine addition to the PRA toolkit, as either a
Introduction

Whilst the roots of pest risk modelling extend back to early in the 20th Century [1], modern computer-based pest risk modelling has only been practised for some 30 years [2,3]. In that time, there has been a progressive refinement of the spatial distributions of the modelled risks. In the earliest maps, risks were portrayed wherever climate stations were situated [2]. Following the development of climatic splining techniques [4], spatially interpolated results were presented e.g., [5,6]. Increased computing power, and a thirst for more detailed risk maps saw the development of finer-scaled gridded climate datasets [7,8,9], and their application to pest risk modelling problems e.g., [10,11,12].

Under the International Standards for Phytosanitary Measures (ISPM’s), Pest Risk Assessments (PRAs) need to identify the endangered area, "an area where ecological factors favour the establishment of a pest whose presence in the area will result in economically important loss" [13]. Whilst the standards define the area as “...an officially defined country, part of a country, or all or part of several countries”, the Decision-support scheme for quarantine pests of the European and Mediterranean Plant Protection Organisation [14] encourages the risk assessor to define the endangered area at a very fine ecological and geographical scale. In order to achieve this, it is not sufficient to use even finer resolution climate datasets. Ecological theory indicates that we need to consider the effects of non-climatic factors as we investigate species niches at finer geographical scales [15].

Considering the non-climatic factors affecting a species potential distribution can be a challenging prospect. Many factors could affect the potential habitat suitability for a species, and the importance and effect of these factors may often, themselves, depend on climatic factors [1,16,17]. For example, topographic features that concentrate overland flow of water may improve the suitability of habitat at the dry end of the species’ potential range, helping it to avoid drought stress; conversely, at the wet end of the range, this same factor may decrease habitat suitability due to waterlogging. Whilst it is theoretically possible for correlative species distribution models to uncover such relationships, the inclusion of these variables in models may add further to the notorious problems of model over-fitting. This will have the effect of diminishing model transferability; consequently reducing even further the value of such models for pre-border pest risk applications.

Until ecological niche modelling methods improve to the point where these non-climatic factors can be better understood and incorporated into modelling frameworks appropriately, there is a need for a practical risk analysis method that can refine a climatic analysis. Baker et al. [18] is amongst the earliest attempts to incorporate non-climatic information into a PRA, combining a CLIMEX model of climate suitability with a crop host distribution map for Diabrotica virgifera virgifera. In order to assess the pest risks from invasive alien species more precisely, one prospect is to extend the method of Baker et al. [18], combining the semi-mechanistic climate modelling methods with spatial land use. In the present study, we use Parthenium hysterophorus (Asteraceae) as a case study.

Parthenium hysterophorus is an annual or short-lived perennial plant native to the subtropics of North and South America. It is a notorious invasive species which has spread to Australia, Africa, Asia, Oceania, and the Middle-east, where it has become a serious agricultural and
rangeland weed affecting crop production and animal husbandry, as well as human health and biodiversity [19,20].

Within the European and Mediterranean Plant Protection Organization region, *P. hysterophorus* is presently officially recorded only in Israel [21]. It is recorded as naturalised in Egypt [22] and it has also been observed as casual in Belgium [23] and Poland [24]. It is thought to have been introduced in Israel in 1980, probably through the import of contaminated grains from the USA for use as fish food in ponds [25]. The species was also introduced in India and Ethiopia, possibly as a contaminant of grain from the USA. In addition, there are records of its introduction as a contaminant of pasture seed and food aid [26], and through the movement of animals and seed attached to used vehicles (harvesters, military machinery, and other vehicles) [27].

*Parthenium hysterophorus* reproduces by seeds and is known to be highly prolific, as a single plant may produce on average 40 000 seeds [28]. These seeds are dispersed locally by wind and water and as a contaminant of hay, seed, harvested material, soil, vehicles, machinery, or animals. *Parthenium hysterophorus* seeds exhibit dormancy mechanisms and can form persistent seed banks, especially where the seeds are incorporated into soil at moderate depths [29]. The species tolerates a wide variety of soils and is a pioneer that can colonise a wide range of habitats: grazing land, summer crops, disturbed and cultivated areas, roadsides, recreation areas, as well as riverbanks and floodplains. *Parthenium hysterophorus* matures very quickly, with flowering commencing 4–6 weeks after germination; given suitable temperatures it can establish in areas receiving very low rainfall [30].

*Parthenium hysterophorus* causes major negative impacts on pastures and crops. In India, it has been observed that *P. hysterophorus* can cause yield losses of up to 40% in several dryland crops [31] cited in [32]. In Ethiopia, the yield of *Sorghum bicolor* grain was reduced by between 40 and 97% when *P. hysterophorus* was left uncontrolled throughout the growing season [33]. In Queensland (Australia), it has invaded 170 000 km² of high quality grazing areas and losses to the cattle industry have been estimated to be AUD$22 million per year in control costs and loss of pasture [34]. Infestations of *P. hysterophorus* can also degrade natural ecosystems, and outcompete native plant species [35,36]. Because *P. hysterophorus* contains sesquiterpenes and phenolics, it is toxic to cattle, horses and other animals [30]. In addition, meat and milk produced from livestock that has eaten the plant can develop an undesirable flavour [37]. Frequent contact with *P. hysterophorus* or its pollen can produce serious allergic reactions such as dermatitis, hay fever and asthma in humans and livestock, especially horses [38].

The impacts of *P. hysterophorus* and reports of its presence in Israel and Belgium sparked concern within the EPPO region and a desire for a PRA to gauge the extent of the threat it posed [39]. A critical component of pest risk is an understanding of the potential distribution of the pest within the PRA area. McConnachie *et al.* [40] presents a CLIMEX model of *P. hysterophorus* based on its then known distribution and experimental observations drawn from the scientific literature. In the light of the present known distribution of *P. hysterophorus*, the CLIMEX model of McConnachie *et al.* appears somewhat conservative, especially with respect to the cold tolerance limits of this species.

In this paper we refit the CLIMEX model of *P. hysterophorus* developed by McConnachie *et al.* [40], and apply irrigation and climate change scenarios to inform global pest risks. We extend the methods of Baker *et al.* [18] using readily available habitat data, comparing two methods for downscaling the risk map, globally, and for Europe. The first method uses the standard EPPO PRA procedure involving expert assessment of the habitat types that are suitable for invasion, while the second uses an objective inferential method.
Materials and Methods

Modelling outline

The modelling scheme is presented in Fig 1. The distribution data and ecophysiological knowledge for *P. hysterophorus* were used to develop a CLIMEX model under natural rainfall conditions. Because some distribution records for *P. hysterophorus* appear to represent populations that are able to persist only due to the presence of supplementary soil moisture, the CLIMEX model is used to run a natural rainfall and an irrigation scenario. These model outputs are combined on a cell-by-cell basis using a map of the distribution of irrigation areas [41] to create composite climate risk models for transient and established populations. The suitable habitat types are used to refine the climate suitability map for establishment to create the endangered area map for the risk assessment. A climate change scenario based on a Global Climate Model is then used to create a future composite climate risk scenario as a means of better understanding the sensitivity of any policy responses to the risks posed by *P. hysterophorus*.

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Fig 1. Modelling scheme for assessing pest risks for *Parthenium hysterophorus* in the EPPO region using the EPPO Decision-support scheme for quarantine pests. Green boxes are inputs, blue boxes are models, grey is an intermediate product, and orange boxes are outputs.

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Distribution data

The known distribution of *P. hysterophorus* was assembled from the Global Biodiversity Information Facility ([www.gbif.org](http://www.gbif.org)), Clark & Lotter [42], Dhileepan [43], Department of Natural Resources [44], Kilian *et al.* [45], and Shabbir *et al.* [46] (Fig 2). Administrative regions that had been reported as being infested by *P. hysterophorus*, but had no point location records were added to the distribution map as polygons, and shaded lightly to reinforce the lack of spatial precision of these reports. The 2 536 point distribution records were transformed into shapefiles and imported into CLIMEX for overlaying results during model fitting. During model fitting for the natural rainfall scenario, records were checked to consider whether the populations were likely to be able to persist in the absence of irrigation, and whether they represented *Established* or *Transient* populations (*sensu* FAO [13]).

CLIMEX modelling

CLIMEX V3 [2,47] was used to refit the model of McConnachie *et al.* [40] for *P. hysterophorus*. CLIMEX calculates a weekly Growth Index (GI<sub>W</sub>) that describes the species population response to temperature and soil moisture through the Temperature (TI) and Soil Moisture (MI) indices respectively. GI<sub>W</sub> is integrated annually to calculate the Annual Growth Index (GI<sub>A</sub>). Stress indices (hot, cold, wet, dry) are factors that limit a species’ ability to persist at a particular location. Individual stress values are combined to create the total Stress Index (SI), and when combined with the Annual Growth Index (GI<sub>A</sub>) CLIMEX calculates the Ecoclimatic index (EI). The EI is a measure of the overall suitability of a location for species persistence.
We classified the invasion risk as **Endangered** if the model indicated that *P. hysterophorus* was likely to be able to persist year-round (EI > 0). At locations where it could grow during a favourable season, but is unlikely to persist year-round due to an inability to complete a generation, due either to stresses or an insufficient heat sum to complete reproductive development (EI = 0, GIA > 0), we classified it as **Transient** (which is synonymous with casual populations *sensu* Richardson *et al.*[48]).

The model-fitting strategy involved fitting the stresses to the distribution data in the native range in South America, and the introduced range in Africa, India, and North America. Distribution data in Australia and Eastern Asia were reserved for model validation. In fitting the stress and growth functions, consideration was given to any reported experimental data or theoretical expectations. This practice, combined with the structure of the CLIMEX Compare Locations model helps guard against over-fitting [49]. All CLIMEX model parameters for *P. hysterophorus* are provided in Table 1, and their derivation is detailed below.

**Temperature index.** Williams and Groves [50] found an optimal temperature regime for *P. hysterophorus* of 25°C night/30°C day. The Temperature Index parameter values remain unchanged from McConnachie *et al.* [40].

**Cold stress.** The cold stress threshold and rate parameters of McConnachie *et al.* [40] were relaxed to allow *P. hysterophorus* to persist in the known, northern locations in the USA and northern India. In doing so, the extreme cold records in China and northern Pakistan and India also became suitable. Williams and Groves [50] (p. 50) noted that plants that were frosted at -6°C suffered “...leaf damage, leading to complete senescence and lateral floret development

### Table 1. CLIMEX model parameters for *Parthenium hysterophorus*. Parameter mnemonics follow Sutherst *et al.* [47].

| Parameter     | Description                        | Values | Units |
|---------------|------------------------------------|--------|-------|
| **Moisture**  |                                    |        |       |
| SM0           | Lower soil moisture threshold       | 0.1    |       |
| SM1           | Lower optimal soil moisture         | 0.3    |       |
| SM2           | Upper optimal soil moisture         | 0.8    |       |
| SM3           | Upper soil moisture threshold       | 1.5    |       |
| **Temperature** |                                  |        |       |
| DV0           | Lower temperature threshold         | 6      | °C    |
| DV1           | Lower optimal temperature           | 22     | °C    |
| DV2           | Upper optimal temperature           | 32     | °C    |
| DV3           | Upper temperature threshold         | 39     | °C    |
| **Cold stress** |                                 |        |       |
| TTCs          | Cold stress temperature threshold   | -7.5   | °C    |
| THCS          | Cold stress accumulation rate       | -0.01  | Week⁻¹|
| **Heat stress** |                                |        |       |
| TTHS          | Heat stress temperature threshold   | 40     | °C    |
| THHS          | Heat stress accumulation rate       | 0.001  | Week⁻¹|
| **Dry stress** |                                |        |       |
| SMMD          | Soil moisture dry stress threshold  | 0.10   |       |
| HDS           | Dry stress accumulation rate        | -0.015 | Week⁻¹|
| **Threshold Annual Heat Sum** |                |        |       |
| PDD           | Annual heat sum threshold           | 2 000  | °C days|

†Units without symbols are a dimensionless index of available soil moisture, scaled from 0 (oven dry), with 1 representing field capacity. Values in bold face type have been changed from values included in McConnachie *et al.* [40].

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ceased”. Using -7.5°C as a damaging cold stress threshold (TTCS), the stress accumulation rate of -0.01 week⁻¹ fitted all but two of the coldest locality records in the northern hemisphere. The outlying records in the Himalayas are found in a region of extremely dissected topography, and the altitude and temperature are so extremely different to the next closest location records that this is likely to be a case of mismatch in either geocoding precision or the climate data. In Argentina, a number of location records for P. hysterophorus in the GBIF database referred to locations that were apparently too cold or too dry for persistence, and for the dry records, did not appear to fall in irrigation areas defined in the irrigation areas database of Siebert et al. [41]. Searching Google Earth using the locality description of these records revealed that they were incorrectly geocoded, and actually referred to wetter locations found at lower elevations.

**Dry stress.** In the CLIMEX framework, dry stress may not be a factor that affects annual plants directly, because these plants may be able to survive extended periods of drought in the seed life stage. In this case, Dry Stress (in concert with the GIA) acts in such a manner as to ensure that there is a sufficient period within which the soil moisture is sufficient to complete the life cycle. The dry stress accumulation rate was increased to make the westernmost record in Queensland, Australia barely climatically unsuitable. This had the consequence of making some of the records in Pakistan and Western Argentina unsuitable in the absence of irrigation, which was practised there according to the GMIA database of Portmann et al. [51]. In a small number of cases, location records in Argentina (17), Australia (1), India (1) and Pakistan (2) fell in areas that, according to the climate database were extremely xeric and which were not associated with widespread crop irrigation, at least as portrayed in the global irrigated area database we used (see Composite Risk Mapping below). Examining these locations in Google Earth revealed that these records were not able to be related logically to a long-term climatology. The Argentinian records fell in towns or roadsides where there was irrigation or a concentration of rainfall respectively within areas that were extremely sparsely vegetated. The Australian record was within a braided river channel that floods very infrequently due to rain mostly falling further up the catchment. The Indian record fell in Bikaner, a moderately large town that is in the middle of a desert. Bikaner and its surrounding cropping plots are sustained by the Ganges and Indira Ghandi Canals. The Pakistani records were located along a road through an area between the Indus and Chenab Rivers. This area is a desert, which is covered in extremely sparse vegetation, except for some scattered cropping plots.

**Wet stress.** In the native range of P. hysterophorus in South America, there is an extremely large area around the Amazon Basin where the CLIMEX model indicates potential for growth and persistence, but where there are no location records. Whilst this may be due to a lack of surveying and reporting effort, we explored the possibility that P. hysterophorus is unable to persist there due to excessive cloudiness associated with high rainfall (the species is reportedly sensitive to shading [50]). It was possible to make this wet habitat unsuitable using wet stress, improving the model specificity in this area. However, when this level of wet stress was applied, all of Bangladesh, North-eastern India and parts of Central Kenya also became unsuitable; but these areas are covered in location records for P. hysterophorus (see [52] for detailed maps of P. hysterophorus in East Africa. This paradox can perhaps be explained by the fact that whilst the natural vegetation of Bangladesh, North-eastern India, and Central Kenya are similar in structure to that of the Amazon Basin, most of the vegetation in these introduced range locations has been disturbed by intensive agriculture [53]. In the absence of agricultural or pastoral disturbance regimes, we might expect that P. hysterophorus would tend to be outcompeted by the natural vegetation.

**Annual heat sum threshold.** The annual heat sum threshold (PDD) of McConnachie et al. [40] was retained at 2 000°C days above 6°C (DV0), barely allowing P. hysterophorus to persist at the coldest known locations of P. hysterophorus in the Himalaya Mountains.
Climate data

The model was fitted initially using the 30' CliMond CM30_1975H_WO_V1.1 dataset, and subsequently refined with the CM10_1975H_WO_V1.1 [9]. The CliMond 10' results for 2070 of the A2 SRES climate change scenario run on the CSIRO Mk 3 GCM (CM10_2070_CS_A2_WO_V1.1) was chosen because it represented a reasonably extreme scenario that would highlight the sensitivity of the invasion potential for *P. hysterophorus*.

Irrigation

An irrigation scenario of 2.5 mm day\(^{-1}\) was applied as a top-up to natural rainfall. Under this scenario, in any week in which average daily precipitation did not meet this threshold, the difference was assumed to be added to the rainfall inputs to the soil moisture model. Actual irrigation rates depend on a variety of factors, including the crops, their stage of growth and climatic factors such as wind flux, temperature, and humidity. The selected rate accords with indicative low-end rates [54]. The irrigation scenario was run on the global CM10_1975H_WO_V1.1 dataset.

Composite soil moisture risk mapping

The irrigation area map from Siebert *et al.* [41] was used to select within each climate cell, which of the natural and irrigated CLIMEX model results to use in a composite risk map. For each 10' cell, if the irrigation area was greater than 0, the irrigation scenario results were included. Otherwise the natural rainfall scenario value was used.

Habitat factors

We compared two methods for identifying habitat types that are suitable for invasion by *P. hysterophorus*. The first, loosely termed an expert assessment, reflects the current standard practice within the EPPO pest risk assessment framework, while the second is an objective inferential method.

In the expert assessment, the habitat types listed in the CORINE database [55] were considered by the EPPO Expert Working Group while performing the PRA for *P. hysterophorus*, and classified as either suitable or unsuitable for *P. hysterophorus* based upon consideration of the habitat types where it has been reported in the literature, and where the panel members had observed it in the field. The CORINE database was selected because it is preferred by the EPPO due to its fine spatial resolution. Notably, the spatial coverage of the CORINE database is limited to Europe. The assessors used a consensus method to decide on suitable land use factors, drawing upon published descriptions and personal observations of *P. hysterophorus* occupying different habitat types.

In the inferential method, the distribution points in *Fig 2* were spatially intersected with a global habitat dataset; habitat types with one or more point records were listed. This list was used to identify the subset of habitat types in Europe that was considered suitable. Because the geographical coverage of the CORINE database is limited to Europe, the FAO Land Use Systems of the World version 1.1 [www.fao.org/nr/lada/] was used to identify suitable habitat types. This database has a moderately coarse spatial resolution (5 arc minutes) which is equivalent to a map scale of approximately 1:10 000 000. This is coarser than the CORINE database, which summarises the spatial data at a scale of 1:100 000 (equivalent to a raster resolution of approximately 50 m). The attraction of the FAO dataset is that it has a global coverage, enabling risks to be projected globally.
For both the CORINE and FAO datasets, the suitable habitat classes were spatially intersected with the CLIMEX model of climate suitability to create composite climate and land use/habitat risk maps and statistics.

**Results**

The modelled potential distribution of *P. hysterophorus* is very extensive, stretching from equatorial areas, through to warm temperate and Mediterranean climates (Fig 3). The effect of irrigation in extending the potential range into xeric regions is obvious in the scattered pockets of suitable locations in the western deserts of the USA (Fig 3A) and the Sahara Desert, where the Nile Valley is a particularly prominent feature (Fig 3B). The model also identifies that there is an additional, extremely large area in the northern hemisphere in which *P. hysterophorus* could pose a transient biosecurity risk (Fig 4). This accords with its observation in Belgium and Poland, where it was thought to be a transient. In its native range in the Americas, its modelled potential range extends into wet tropical areas, from which there are no recorded observations. Its modelled potential range for establishment in the USA is supported by a few northern location records. Extensive records in Asia in similarly cool conditions further support the conclusion that the plant can likely tolerate such cold conditions. In the wet tropics, consistent excessive soil moisture appears to prevent modelled population growth. In South America, the modelled potential range extends into colder regions than the recorded distribution (compare Figs 2 and 3).

In Eastern Asia and Australasia, the areas reserved for model validation, the model agreed perfectly with the known distribution (a model sensitivity score of 1.0). Model specificity was also good, with relatively few areas of range underlap. However, in China in particular, there appears to be considerable opportunity for in-filling invasion within the climatically suitable range.

Within the EPPO region, the countries at risk are Albania, Algeria, Azerbaijan, Bosnia & Herzegovina, Bulgaria, Cyprus, Croatia, Former Republic of Macedonia, France, Greece, Hungary, Israel, Italy, Jordan, Kazakhstan, Kyrgyzstan, Malta, Moldova, Morocco, Portugal, Romania, Russia, Serbia, Slovakia, Slovenia, Spain, Tunisia, Turkey, Ukraine and Uzbekistan. The modelled climate suitability pattern is consistent with the reported transient nature of the plant populations in Belgium and Poland (Fig 4) [23,24]. Under the historical (current) climate scenario, more than 2 million ha of the EPPO region is apparently climatically suitable for establishment by *P. hysterophorus* (Table 2, Fig 5). Of this total area, less than half (approximately 946 000 ha) consists of habitat types considered suitable under the expert model (Table 2). The habitat classes considered at greatest risk (by area) are disturbed (urban, cropping and pastures). Perhaps also of cultural and economic significance is the threat to olive groves (100% of the plantations are at risk), vineyards (90%) and fruit and berry plantations (77%) may be threatened.

Under the inferential FAO habitat model 29 land use classes were identified as being at risk in Europe, including cropping and pasture areas (Table 3, Fig 6). However, grazed forests and shrublands were also identified as being at risk (Table 3). The total area of suitable habitat in Europe modelled as at risk using the FAO dataset and the inferred habitat suitability classes was 1.6 million ha, nearly twice that from the CORINE dataset based on the expert opinion.

The global risk patterns based on the inferential FAO model are similar to those for the expert-based system applied to Europe (Table 4, Fig 7B). However, there are some interesting differences: there was a significant number of records collected from areas classed as open water or wetlands. The likely causes are discussed below.
Fig 3. Climate suitability for *Parthenium hysterophorus* establishment modelled using CLIMEX with the CliMond CM10_1975H_WO_V1.1 climate dataset [9], including the effect of irrigation [41]. (A) Global and (B) Europe and North Africa.

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Fig 4. Combined establishment and transient invasion risks posed by *Parthenium hysterophorus* modelled using CLIMEX with the CliMond CM10_1975H_WO_V1.1 climate dataset [9], including the effect of irrigation [41]. (A) Global and (B) Europe and North Africa.

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Climate change impacts on pest risk

Under the climate change scenario explored here, in the Northern Hemisphere, the modelled pest risks from *P. hysterophorus* extend further poleward compared with the current climate risks (Fig 8A, see Table 5 for legend description). The USA, continental Europe and northern Middle East are particularly sensitive to this scenario, with the risks changing from transient to endangered over huge areas. There is also a marked band along the equator where decreasing rainfall conditions could allow highland areas of western South America, Central Africa and South East Asia to become endangered by *P. hysterophorus* (Fig 8A).

Table 2. Areal summary of composite invasion risk to Europe from *Parthenium hysterophorus* by habitat class according to the CORINE environmental database, considering climate with irrigation scenarios applied according to the GMIAV5 database [41]. Habitat classes are listed in descending order of area at risk under the current climate scenario. Land use is assumed to remain static under the future climate scenario.

| CORINE Code | CORINE Name                      | Suitable | Area (km²) | Change in Area at risk (km²) | Percentage increase‡ |
|------------|----------------------------------|----------|------------|-----------------------------|----------------------|
|            |                                  | Corine   |            |                             |                      |
|            |                                  | Code     | Total      | EI ≥ 1                      | Percentage of total area | EI ≥ 1               | Percentage of total area |
| 1975H      |                                  |          |            |                             |                      |
| 2080       |                                  |          |            |                             |                      |
| 211        | Non irrigated arable land        | Y        | 1 212      | 536 661                     | 44                   | 1 029                | 382                    | 492 721 | 92          |
| 321        | Natural grasslands               | Y        | 206 952    | 82 510                      | 40                   | 135 763              | 66                     | 53 253  | 65          |
| 231        | Pastures                         | Y        | 392 670    | 79 759                      | 20                   | 228 264              | 58                     | 148 505 | 186         |
| 212        | Permanently irrigated arable land| Y        | 81 519     | 71 185                      | 87                   | 80 877               | 99                     | 9 692   | 14          |
| 333        | Sparsely vegetated areas         | Y        | 236 279    | 61 732                      | 26                   | 116 978              | 50                     | 55 246  | 89          |
| 223        | Olive groves                     | Y        | 37 560     | 37 445                      | 100                  | 37 557               | 100                    | 112     | 0           |
| 221        | Vineyards                        | Y        | 40 182     | 36 195                      | 90                   | 39 982               | 100                    | 3 788   | 10          |
| 222        | Fruit trees and berry plantations| Y        | 28 596     | 21 969                      | 77                   | 27 965               | 98                     | 5 996   | 27          |
| 241        | Annual crops associated with permanent crops | Y | 9 458 | 9 281 | 98 | 9 439 | 100 | 158 | 2 |
| 511        | Water courses                    | Y        | 13 115     | 6 283                       | 48                   | 9 758                | 74                     | 3 474   | 55          |
| 133        | Construction site                | Y        | 1 862      | 1 258                       | 68                   | 1 634                | 88                     | 375     | 30          |
| 122        | Roads and rail networks and associated land | Y | 2 546 | 1 037 | 41 | 2 130 | 84 | 1 093 | 105 |
| 141        | Green urban areas                | Y        | 3 046      | 688                         | 23                   | 2 159                | 71                     | 1 471   | 214         |
| 132        | Dump sites                       | Y        | 1 114      | 277                         | 25                   | 781                  | 70                     | 504     | 182         |
| 522        | Estuaries                        | Y        | 540        | 149                         | 28                   | 295                  | 55                     | 147     | 99          |
| 000        | Not classified                    | Y        | 3 405      | 1 060                       | 31                   | 1 939                | 57                     | 878 621 | 83          |
| Total (suitable habitats only) |                           |          | 2 267      | 946 429                     | 42                   | 1 722                | 76                     | 776 536 | 82          |
| Total (Climatically suitable) |                           |          | 5 673      | 2 007                       | 35                   | 3 662                | 65                     | 1 655 157 82    |

† The cells where the Ecoclimatic Index is positive, indicating potential for persistent populations to establish.
‡ Compared with the baseline area at risk under historical climate.

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Within the EPPO region, many countries that appear presently to face only transient risks from *P. hysterophorus* may become endangered in the future, due primarily to rising temperatures (Austria, Belarus, Belgium, Czech Republic, Germany, Estonia, Latvia, Lithuania, the Netherlands, Poland, Slovenia, the United Kingdom, as well as larger parts of Bosnia and Herzegovina, Hungary, Kazakhstan, Moldova, Russia, Slovakia, Switzerland, Turkey, Ukraine, the southern coast of Sweden) (Fig 8B). The modelled change in climate suitability represents a near doubling of the endangered area (Fig 8B, Table 4).

**Discussion**

Despite its extensive present known distribution (Fig 2), the modelled global potential distribution of *P. hysterophorus* greatly exceeds this, particularly in Africa, Asia, Australia, and Europe. Within its native range, the climate in the Amazon basin appears suitable for *P. hysterophorus*, but possibly only in the presence of frequent disturbance that reduces competition from other vegetation. If human disturbance patterns are extended into this region, we may find that *P. hysterophorus* also extends its range there.

Whilst *P. hysterophorus* is present in Israel within the EPPO region, it is thought to be absent from Europe *per se*. There is clearly an opportunity to prevent, or at least slow the spread of *P. hysterophorus* into Europe through vigilant phytosanitary measures. The requirement for free trade pathways between member states means that Israeli exports to Europe may pose a significant threat to the other EPPO member states, and special phytosanitary measures may be worth considering. The movement of people and material from Africa and the Middle East are also dispersal pathways that should be of concern to European biosecurity managers.
Table 3. Areal summary of composite invasion risk to Europe from *Parthenium hysterophorus* by land use system class according to the FAO Land Use Systems of the World database, considering climate with irrigation scenarios applied according to the GMIAV5 database [41]. Habitat classes are listed in descending order of area at risk under the historical (1975H) climate scenario.

| LUS Code | LUS Name | Suitable (expert assessment) | Area (km²) Total | 1975H | 2080 | Change in Area at risk (km²) | Percentage increase |
|----------|----------|------------------------------|-------------------|-------|------|---------------------------|-------------------|
|          |          |                              |                   |       |      | EI ≥ 1                    | Percentage of total area | EI ≥ 1  | Percentage of total area | Percentage of total area |
| 21       | Crops and high livestock density | Y | 767 150 | 683 276 | 89 | 413 993 | 154 |
| 04       | Forest—with moderate or higher livestock density | Y | 839 138 | 596 854 | 71 | 352 409 | 144 |
| 20       | Crops and modest intensive livestock density | Y | 559 709 | 514 881 | 92 | 173 303 | 51 |
| 25       | Urban land |                              | 614 847 | 460 600 | 75 | 198 164 | 76 |
| 19       | Rainfed crops (Subsistence/Commercial) | Y | 441 245 | 333 289 | 76 | 113 928 | 52 |
| 03       | Forest—with agricultural activities |                              | 670 509 | 179 390 | 27 | 79 677 | 80 |
| 17       | Shrub—high livestock density | Y | 202 972 | 167 145 | 82 | 78 321 | 88 |
| 22       | Crops, large-scale irrig., mod. or higher livestock dens. | Y | 146 219 | 140 798 | 96 | 16 853 | 14 |
| 11       | Grasslands—high livestock density | Y | 215 631 | 105 041 | 49 | 78 361 | 294 |
| 16       | Shrub—moderate livestock density | Y | 101 199 | 90 508 | 89 | 12 795 | 16 |
| 33       | Sparsely vegetated areas—mod.or high livestock dens. | Y | 64 079 | 57 269 | 89 | 15 958 | 39 |
| 23       | Agriculture—large scale Irrigation | Y | 49 789 | 49 161 | 99 | 2 946 | 6 |
| 15       | Shrub—low livestock density | Y | 57 545 | 46 321 | 80 | 6 411 | 16 |
| 02       | Forest—protected |                              | 84 952 | 31 277 | 37 | 13 829 | 79 |
| 10       | Grasslands—moderate livestock density | Y | 40 424 | 30 915 | 76 | 17 570 | 132 |
| 40       | Open Water—inland Fisheries |                              | 94 259 | 22 994 | 24 | 10 922 | 90 |
| 24       | Agriculture—protected |                              | 34 909 | 22 892 | 66 | 8 588 | 60 |
| 13       | Shrub—unmanaged | Y | 51 876 | 21 993 | 42 | 8 446 | 62 |
| 09       | Grasslands—low livestock density | Y | 20 584 | 10 081 | 49 | 6 700 | 198 |
| 37       | Bare areas—with mod. livestock density | Y | 10 015 | 8 766 | 88 | 3 600 | 70 |

(Continued)
Within Africa, Asia and Australia, biosecurity measures to slow the spread of *P. hysterophorus* may still be worthwhile. Careful consideration of the present and potential distributions in these regions may assist with targeting education material and regulatory measures aimed at minimising impacts and reducing the rate of spread of this damaging invasive alien plant.

**Table 3. (Continued)**

| LUS Code | LUS Name                        | Suitable (expert assessment) | Area (km²) | Climate Scenario | Change in Area at risk (km²) | Percentage increase |
|----------|---------------------------------|-----------------------------|------------|-----------------|-----------------------------|---------------------|
|          |                                 | Total                       | 1975H      | 2080            | EI ≥ 1                      | EI ≥ 1              |
|          |                                 |                            | Percentage | Percenta           |                             |                     |
|          |                                 |                            | of total area| of total area    |                             |                     |
|          |                                 |                            | Area (km²) | Area (km²)       |                             |                     |
|          |                                 |                            | EI ≥ 1     | EI ≥ 1          |                             |                     |
| 07       | Grasslands—unmanaged            | Y                           | 64 781     | 2 573           | 4                           | 8 459               | 13                  | 5 886               | 229                |
| 30       | Sparsely vegetated areas—unmanaged | Y                           | 89 538     | 2 510           | 3                           | 8 165               | 9                   | 5 655               | 225                |
| 14       | Shrubs—protected                | Y                           | 26 980     | 5 835           | 22                          | 7 238               | 27                  | 1 403               | 24                 |
| 32       | Sparsely vegetated areas—with low livestock density | Y                            | 12 752     | 4 989           | 39                          | 7 115               | 56                  | 2 126               | 43                 |
| 38       | Open Water—unmanaged            |                             | 16 296     | 2 875           | 18                          | 6 519               | 40                  | 3 644               | 127                |
| 34       | Bare areas—unmanaged            |                             | 55 631     | 1 549           | 3                            | 4 990               | 9                   | 3 442               | 222                |
| 39       | Open Water—protected            |                             | 8 078      | 2 394           | 30                          | 3 887               | 48                  | 1 493               | 62                 |
| 27       | Wetlands—protected              |                             | 12 907     | 1 894           | 15                          | 2 586               | 20                  | 692                 | 37                 |
| 31       | Sparsely vegetated areas—protected | Y                           | 21 149     | 737             | 3                           | 843                 | 4                   | 106                 | 14                 |
| 08       | Grasslands—protected            | Y                           | 19 612     | 680             | 3                            | 3 652               | 19                  | 2 972               | 437                |
| 36       | Bare areas—with low livestock density |                     | 3 946      | 351             | 9                            | 577                 | 15                  | 227                 | 65                 |
| 35       | Bare areas—protected            |                             | 15 169     | 222             | 1                            | 566                 | 4                   | 344                 | 155                |
| 01       | Forest—virgin                   |                             | 157 241    | 202             | 0                            | 1 597               | 1                   | 1 395               | 692                |
| 26       | Wetlands—unmanaged              |                             | 51 573     | 49              | 0                            | 2 536               | 5                   | 2 487               | 5048               |
| 28       | Wetlands—mangrove               |                             | 0          | 0               | NA                           | 0                   | NA                  | 0                   | NA                 |
| 29       | Wetlands—with agricultural activities |                       | 0          | 0               | NA                           | 0                   | NA                  | 0                   | NA                 |
| 41       | Undefined                       |                             | 0          | 0               | NA                           | 0                   | NA                  | 0                   | NA                 |
| 00       | No data                         |                             | 48 054     | 18 888          | 39                          | 28 768              | 60                  | 9 880               | 52                 |
|          | **Total (suitable habitats only)** |                             | 3 792 371  | 1 566           | 41                          | 2 883 862           | 76                  | 1 316 143           | 84                 |
|          | **Total (Climatically suitable)** |                             | 5 670 756  | 2 006           | 35                          | 3 660 422           | 65                  | 1 654 526           | 82                 |

† Considered equivalent to the classes identified as suitable using the expert assessment system (Table 2).

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Extending the biological control programme against *P. hysterophorus* to Israel and other invaded countries is worthy of consideration. It may also be economically attractive for European states at risk of invasion by *P. hysterophorus* to co-invest in biological control measures in Israel and other places that pose a source threat.

**Habitat factors**

Irrigation has an important effect on extending the range of *P. hysterophorus*, particularly in Saharan Africa, the Middle East and Central Australia. Conversely, within Europe, restricting
Table 4. A real summary of composite global invasion risk from *Parthenium hysterophorus* by land use system class according to the FAO Land Use Systems of the World database, considering climate with irrigation scenarios applied according to the GMIAV5 database [41]. Habitat classes are listed in descending order of area at risk under the current climate scenario.

| LUS Code | LUS Name                                      | Suitable | Area (km²) | 1975H | 2080 | Change in Area at risk (km²) | Percentage increase |
|----------|----------------------------------------------|----------|------------|-------|------|-----------------------------|---------------------|
|          |                                              |          | Total      |       |      | EI ≥ 1                      | EI ≥ 1              |
|          |                                              |          |            |       |      | Area (km²)                   | Percentage of total area | Area (km²)         | Percentage of total area |
|          |                                              |          |            |       |      | EI ≥ 1                      | EI ≥ 1              |
| 21       | Crops and high livestock density             | Y        | 9 097      | 883   | 7 125| 110 | 78                          | 8 355               | 92                  | 1 230 216               | 17                  |
| 04       | Forest—with moderate or higher livestock density | Y       | 10 586     | 798   | 7 396| 382 | 70                          | 8 565               | 81                  | 1 168 921               | 16                  |
| 20       | Crops and mod. intensive livestock density    | Y        | 5 432      | 072   | 3 443| 212 | 63                          | 4 055               | 75                  | 612 352                | 18                  |
| 25       | Urban land                                   |          | 3 426      | 546   | 2 449| 779 | 71                          | 2 938               | 86                  | 488 425                | 20                  |
| 19       | Rainfed crops (Subsistence/Commercial)       | Y        | 4 664      | 537   | 3 235| 111 | 69                          | 3 609               | 77                  | 373 996                | 12                  |
| 03       | Forest—with agricultural activities          |          | 11 221     | 724   | 7 739| 025 | 69                          | 8 449               | 75                  | 710 766                | 9                   |
| 17       | Shrub—high livestock density                 | Y        | 2 534      | 303   | 2 227| 217 | 88                          | 2 412               | 95                  | 185 272                | 8                   |
| 22       | Crops, large-scale irrig., mod. or higher livestock dens. | Y | 2 533 | 662 | 2 257 | 272 | 89 | 2 274 | 656 | 90 | 17 383 | 1 |
| 11       | Grasslands—high livestock density            | Y        | 3 238      | 334   | 2 279| 038 | 70                          | 2 560               | 79                  | 281 716                | 12                  |
| 16       | Shrub—moderate livestock density             | Y        | 3 524      | 259   | 2 934| 208 | 83                          | 3 261               | 93                  | 326 886                | 11                  |
| 33       | Sparsely vegetated areas—mod. or high livestock dens. | Y | 3 745 | 677 | 2 261 | 729 | 60 | 2 674 | 031 | 71 | 412 302 | 18 |
| 23       | Agriculture—large scale Irrigation           | Y        | 604 594    | 541 522| 551 845| 90 | 551 845 | 91 | 10 323 | 2 |
| 15       | Shrub—low livestock density                  | Y        | 3 307      | 702   | 2 115| 093 | 64                          | 2 330               | 70                  | 215 643                | 10                  |
| 02       | Forest—protected                             |          | 5 116      | 042   | 3 032| 127 | 59                          | 3 373               | 66                  | 341 831                | 11                  |
| 10       | Grasslands—moderate livestock density        | Y        | 3 244      | 887   | 2 057| 197 | 63                          | 2 427               | 75                  | 369 826                | 18                  |
| 40       | Open Water—inland Fisheries                  |          | 2 222      | 456   | 629 368| 28 | 861 165 | 39 | 231 797 | 37 |
| 24       | Agriculture—protected                        |          | 763 630    | 575 494| 607 549| 75 | 607 549 | 80 | 32 055 | 6  |
| 13       | Shrub—unmanaged                              | Y        | 2 306      | 864   | 354 994| 15 | 460 610 | 20 | 105 616 | 30 |
| 09       | Grasslands—low livestock density             | Y        | 2 892      | 336   | 1 211| 031 | 42                          | 1 399               | 48                  | 187 981                | 16                  |
| 37       | Bare areas—with mod. livestock density       | Y        | 2 363      | 935   | 1 031| 611 | 44                          | 1 345               | 57                  | 313 505                | 30                  |
| 07       | Grasslands—unmanaged                         | Y        | 1 818      | 515   | 281 373| 15 | 339 896 | 19 | 58 523 | 21 |

(Continued)
the endangered area by using habitat types refines the area at risk considerably within the climatic range. These analytical elements could aid in refining economic impact analyses, and also perhaps in informing surveillance and rapid responses to incursion detections.

The spatial analysis of the distribution data for *P. hysterophorus* using the FAO dataset was revealing; expanding the range of habitat types beyond those identified by the expert assessment process. The association between the open water and wetland land use classes and *P. hysterophorus* was surprising given that *P. hysterophorus* does not grow in waterlogged situations. However, *P. hysterophorus* does grow on floodplains [56], so it is likely that the location records

| LUS Code | LUS Name | Suitable | Area (km²) | Climate Scenario | Percentage of total area | Change in Area at risk (km²) | Percentage increase |
|----------|----------|----------|------------|------------------|--------------------------|-----------------------------|-------------------|
| 1975H    |          |          |            |                  |                          | 2080                       |                   |
|          |          |          | 1975H      |                  |                          | 2080                       |                   |
| 30       | Sparse vegetated areas—unmanaged | Y | 4 263 852 | 211 897 | 5 | 370 290 | 9 | 148 393 | 67 |
| 14       | Shrubs—protected | Y | 1 248 538 | 679 303 | 54 | 729 522 | 58 | 50 219 | 7 |
| 32       | Sparse vegetated areas—with low livestock density | Y | 4 292 774 | 1 187 823 | 28 | 1 596 742 | 37 | 398 919 | 34 |
| 38       | Open Water—unmanaged | | 309 754 | 110 208 | 36 | 133 015 | 43 | 22 807 | 21 |
| 34       | Bare areas—unmanaged | | 12 841 091 | 624 247 | 5 | 1 260 891 | 10 | 636 644 | 102 |
| 39       | Open Water—protected | | 371 179 | 81 246 | 22 | 100 596 | 27 | 19 350 | 24 |
| 27       | Wetlands—protected | | 320 843 | 179 252 | 56 | 191 790 | 60 | 12 537 | 7 |
| 31       | Sparse vegetated areas—protected | Y | 1 155 717 | 120 862 | 10 | 143 784 | 12 | 22 922 | 19 |
| 08       | Grasslands—protected | Y | 1 459 087 | 434 382 | 30 | 458 149 | 31 | 23 766 | 5 |
| 36       | Bare areas—with low livestock density | | 4 716 441 | 449 284 | 10 | 1 016 832 | 22 | 567 549 | 126 |
| 35       | Bare areas—protected | | 2 722 880 | 101 499 | 4 | 144 151 | 5 | 42 652 | 42 |
| 01       | Forest—virgin | | 13 339 558 | 3 477 434 | 26 | 3 644 973 | 27 | 167 539 | 5 |
| 26       | Wetlands—unmanaged | | 1 890 670 | 851 656 | 45 | 903 999 | 48 | 52 343 | 6 |
| 28       | Wetlands—mangrove | | 62 640 | 57 520 | NA | 61 585 | NA | 4 066 | NA |
| 29       | Wetlands—with agricultural activities | | 27 314 | 27 045 | NA | 27 314 | NA | 269 | NA |
| 41       | Undefined | | 7 050 | 4 622 | NA | 4 869 | NA | 247 | NA |
| 00       | No data | | 821 784 | 453 463 | 55 | 556 233 | 68 | 102 771 | 23 |
| Total (suitable habitats only) | | | 71 952 390 | 42 364 756 | 59 | 48 565 933 | 67 | 6 201 176 | 15 |
| Total (Climatically suitable) | | | 134 497 927 | 64 239 635 | 48 | 74 187 964 | 55 | 9 948 329 | 15 |

† Considered equivalent to the classes identified as suitable using the expert assessment system (Table 2).

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Table 4. (Continued)
Fig 7. Endangered area considering climate (EI ≥ 1) and suitable habitat types in the FAO Land Use Systems database, A) Globally, and B) for Europe and North Africa.

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Fig 8. Change in climatic establishment risk for *Parthenium hysterophorus* comparing the CM10_1975H_V1.1 historical climatology and the CliMond. CM10_2070_CS_A2_V1.1 climate scenario. (A) Global and (B) Europe and North Africa.

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fall within riparian zones within the coarse open water and wetland land use classes. Similarly, during the expert deliberations, forested areas were discounted as suitable habitat on the grounds that *P. hysterophorus* reportedly grows poorly under shaded conditions, and would therefore be unable to persist. The FAO dataset comparison underscores the fact that forests (particularly those that are actively managed) are frequently a mosaic of different seral stages, and that ruderals such as *P. hysterophorus* can persist either through recolonisation or the maintenance of seed banks [57]. The more granular spatial resolution of the CORINE database is reflected in a larger set of habitat classes than the FAO dataset. Both of these factors make the CORINE database inherently less likely to create confusing interpretation problems with spatial intersections, as happened with the FAO dataset. However, the limitation usually lies in the spatial resolution of the location records for invasive alien species, rather than the habitat/land use data. This is especially marked for species location data collected prior to the widespread availability of GPS units. Hence, it is unclear whether chasing a finer-scale, globally-conformal, land use/habitat type classification would result in a more accurate assessment of the non-climatic habitat risk factors.

Whilst the fine spatial resolution of the CORINE database may be highly valued for risk assessment in the EPPO region, the lack of conformal global coverage is clearly a drawback for estimating non-climatic habitat risk factors for invasive alien species that have little or no history in the risk assessment area. The large size of the CORINE database also created practical challenges for spatial analyses in geographical information systems, sometimes requiring the dataset to be split in two for spatial intersections. One option for pest risk analysts is to sacrifice some precision for potentially greater accuracy, employing the FAO method and dataset as we have demonstrated here. Another option is to use a hybrid two-phase method combining the insights gained through the FAO dataset analysis with expert opinion to select classes from the CORINE database.

Responding to climate change impacts on invasion risks

As the rate of change and the extent of future climatic changes are unknown (and largely unknowable), it is impossible and imprudent to use climate change scenarios such as the one presented here to inform future biosecurity policies and plans directly. Rather, the risk exposure revealed here should be used as the basis for understanding the nature of biosecurity decisions and their consequences under an inherently uncertain pattern of changing risks. In those areas where the future climate scenario risk maps indicate a risk of transient populations of *P. hysterophorus*, less effort may be placed on prevention, detection, and rapid response to this weed. However, if the risks might change in the future due to potential climate changes, several
adaptation options present themselves (Table 6). It is imprudent to invest in expensive measures to address a problem that may not eventuate. The fact that the climate change scenario indicates that the risks for Europe are likely to increase in the future adds further weight to the conclusion that the present invasion risks by *P. hysterophorus*, based on historical climate, are significant. In the case of *P. hysterophorus* in the EPPO region, the climate change analysis adds little to the conclusion that there is a significant area at risk. The most cost-effective response may therefore be to consider what measures can be undertaken to stop the spread of *P. hysterophorus* out of Israel, or from other countries into the EPPO region, as well as to prevent its entry in EPPO countries at risk.

### Table 6. Possible responses to potentially emerging pest risks under a rapidly changing climate.

| Response                              | Advantages                                                                 | Disadvantages                                                                 | Exemplar responses                                                                 |
|---------------------------------------|-----------------------------------------------------------------------------|------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|
| Prepare for the worst possible future risk case | Conservative approach, which may yield collateral protective benefits for measures that protect against multiple pests. | Immediate expenditure on protective measures against future risks that may not materialise | Implement measures to prevent the entry and spread of *P. hysterophorus*.          |
| Ignore the emerging risks             | No up-front expenditure due to emerging threats.                             | If emerging risks are realised, then unnecessary biosecurity failures may occur. | Maintain existing policies and practices; reacting to changing risks.               |
| Actively monitor changing risk patterns | Relatively small initial outlay on actively monitoring emerging risks. Little risk of over-investment. |                                                                              | Sentinel experiments, and active monitoring of changing risk patterns in analogue climates intermediate between those where it is presently capable of establishment, and those of the jurisdiction under consideration |

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Model limitations

The CLIMEX model was fitted using the best available data and understanding available at the time of the analysis. However, we should be mindful that climate and distribution data are imperfect. The spatial resolution of the distribution data varied, and the estimated precision was not always reported. The mismatch between the resolution of the land use dataset and the species distribution data had the potential to pick up spurious habitat associations; hence we were careful to scrutinise low frequency associations. We should also be mindful that the CLIMEX Compare Locations model is a simplification of the complex ecological processes that define a species niche. The land use classification in the FAO dataset and the identification of the irrigated areas will doubtless contain minor spatial and classification errors. The mis-fitting points at the dry end of *P. hysterophorus*’ range indicate a limit to the spatial precision in the global irrigated area database. However, despite these sources of potential errors, the analysis appears suitable for its intended purpose—to provide an indication of areas at risk of invasion should *P. hysterophorus* be introduced. Each of the mis-fitting points was in close spatial association with areas that were indicated as being suitable, and for which there were location records. This underscores the notion that the resulting maps should be used in aggregate to inform regional risk patterns, rather than being scrutinised at the level of an individual cell. In the extreme xeric and cold limits habitat suitability will be more subject to unusual micro-habitat variations that cannot be accounted for with global datasets and modelling.

With the climate change scenario it is important to remember that we are not applying observation data about the future. We have selected a single plausible scenario with which to stress-test the biosecurity conclusions of our niche modelling. Biosecurity managers should not make plans on the basis that the climate change scenario results presented here will eventuate. This could lead to an expensive waste of resources. Rather, managers should seek to understand
firstly whether the scenario changes the invasion risks significantly within their jurisdiction. If so, they should consider what adaptive management processes they might prudently implement to monitor and manage that potential emerging threat, taking into account lead times for any adaptation measures.

Advancing pest risk modelling

In this paper we applied two advances in pest risk modelling: spatially-explicit irrigation scenarios, and the inferential derivation of non-climatic habitat classes. Both methods are relatively easy to apply using a GIS with the freely available irrigation and land use datasets. The explicit irrigation scenario method allows the niche model to describe the species niche using biologically realistic parameters. In the absence of this method, the model would be unable to identify correctly the habitats at risk in xeric environments, either under-predicting (biologically realistic parameters), or over-predicting (using biologically unrealistic parameters that allow persistence in xeric environments).

The inferential method of identifying suitable land use classes can clearly provide a degree of rigour to the downscaling process. However, it does not abrogate the responsibility of the modeller or risk assessor to evaluate the resulting list of habitats critically and sceptically. Low frequency or unexpected habitat types should serve as a warning sign of a potential error. Whilst the impact of the downscaling process on the estimated endangered area is substantial, it may have minimal implications for analyses of the economic impacts of invasive alien species where the impacts apply to industries with well-defined spatially-explicit production characteristics. However, for species whose impacts are related to the area occupied, and affect natural environments, these downscaling methods could make a substantial difference to the results.

Dedication

This paper is dedicated to the memory of Robert (Bob) Sutherst, who developed the CLIMEX modelling system, and who was a pioneer in the field of computer-based pest risk modelling. Sadly, Bob passed away the week before the work for this paper commenced.

Author Contributions

Conceived and designed the experiments: DJK SB NO. Performed the experiments: DJK SB NO. Analyzed the data: DJK SB NO. Wrote the paper: DJK SB NO GF AOL FDP RP AS TY.

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