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Matching methods to produce maps for pest risk analysis to resources

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Abstract
Decision support systems (DSSs) for pest risk mapping are invaluable for guiding pest risk analysts seeking to add maps to pest risk analyses (PRAs). Maps can help identify the area of potential establishment, the area at highest risk and the endangered area for alien plant pests. However, the production of detailed pest risk maps may require considerable time and resources and it is important to match the methods employed to the priority, time and detail required. In this paper, we apply PRATIQUE DSSs to *Phytophthora austrocedrae*, a pathogen of the Cupressaceae, *Thaumetopoea pityocampa*, the pine processionary moth, *Drosophila suzukii,* spotted wing Drosophila, and *Thaumatotibia leucotreta*, the false codling moth. We demonstrate that complex pest risk maps are not always a high priority and suggest that simple methods may be used to determine the geographic variation in relative risks posed by invasive alien species within an area of concern.

Keywords
Pest risk mapping, area of potential establishment, area at highest risk, endangered area, *Phytophthora austrocedrae*, *Drosophila suzukii*, *Thaumatotibia leucotreta*, *Thaumetopoea pityocampa*

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Introduction

Pest risk analysis (PRA) provides the context for this paper. PRA is fundamental to plant biosecurity because it is primarily undertaken to assess the risks posed by plant pests that are not officially established in an area and to identify appropriate phytosanitary measures to prevent entry and establishment if the risk is unacceptable. Pest risk analyses that may affect international trade should follow international standards for phytosanitary measures (especially ISPM 11; FAO 2004) because they have been formulated by the International Plant Protection Convention and are recognised by the World Trade Organization. Although the international standards set out clearly what elements need to be assessed in order to evaluate the likelihood of entry and establishment together with the magnitude of spread and impacts, they do not provide clear guidance on the methods to be used in completing the PRA. As a result, a number of schemes have been created to assist pest risk analysts with the production of PRAs based on expert judgement and documented evidence. For example, the European and Mediterranean Plant Protection Organization (EPPO) provides a well known scheme to guide the production of PRAs through a series of questions that require answers in the form of a risk rating, an uncertainty score, and a written justification (EPPO 2011).

The EPPO PRA scheme has recently been enhanced by PRATIQUE, an EU funded research project (Baker et al. 2009), by providing several guidance documents and tools, for example, guidance for rating the level of risk (Schrader et al. 2012) and a computerised procedure for completing the PRA (Griessinger et al. 2012). Additional modules are available to help when it is important for pest risk analysts to quantify risk spatially or at least provide greater detail for particular components of the PRA. These include a decision support system (DSS) for mapping climatic suitability, summarised in Table 1 (Eyre et al. 2012) and a DSS for mapping endangered areas (Baker et al. 2012), the topic of this paper.

Maps provide an important method for visualising, summarising and communicating the risk posed by a pest in the PRA area that can be an officially defined country, part of a country or all or parts of several countries (FAO 2012). Within the PRA area, three different risk areas can be identified by pest risk analysts. These are: (i) the area of potential establishment, where it is likely that there is "perpetuation, for the foreseeable future, of a pest within an area after entry" (FAO 2012); (ii) the endangered area, where "ecological factors favour the establishment of a pest whose presence in the area will result in economically important loss" (FAO 2012) and (iii) the area at highest risk, where impacts are assessed as likely to be greatest, e.g. because particularly valuable or vulnerable hosts are growing in areas where abiotic and biotic factors are most suitable for the pest. Economic loss in the endangered area definition is considered to include environmental damage (FAO 2012). Although areas at risk can be described just by listing the geographical regions that are included, maps can convey a clearer message. Maps can also be deployed to help target eradication and containment actions in the event of an outbreak and set up an effective surveillance programme.

Table 1. Summary of the PRATIQUE climatic mapping decision support scheme.

Stage	Tasks	Detail
1	Decide whether mapping climatic suitability is appropriate	Based on available data for mapping and importance of the pest
2	Gather and interpret key climatic factors affecting distribution	Determine which data sets are important for the pest
3	Determine the quality and quantity of information that is available on the key climatic factors	Provide a rating based on availability and reliability
4	Categorise location data	Diagrams are provided to help the assessor to choose from 13 categories of location data
5	Evaluate pros and cons of different climatic mapping methods	Use tables to show possible drawbacks of the different methods available based on the ecology of the pest and the data available

Although many PRAs already contain maps depicting components of pest risk that have been created without formal models and geographical information systems (GIS), most profit from such tools. Frequently, the PRA just includes a map of climatic suitability. Climatic suitability needs to be combined with factors such as host or habitat distribution firstly to obtain the area of potential establishment and secondly with impact related components, such as host or habitat vulnerability and value, to map the areas at highest risk. NAPPFAST provides a suite of interconnected models that can be used individually or collectively with tailored climatic data to map pest risk for North America (Magarey et al. 2007, 2011). Outputs from the PRATIQUE DSS for mapping climatic suitability (Eyre et al. 2012) and the area of potential establishment and highest risk (Baker et al. 2012) can be linked to models of spread (Kehlenbeck et al. 2012) and economic impact (Soliman et al. 2012) to map the dynamics of invasion and impact scenarios that illustrate possible endangered areas. The DSSs are independent of the models used and the area of concern, although the examples are provided for all or parts of Europe.

The PRATIQUE DSS described by Baker et al. (2012) focuses on identifying the area of potential establishment and the area at highest risk rather than endangered areas. This is because a map of the endangered area should show only where economically important loss is predicted to occur and this is very difficult given the uncertainty surrounding all pest invasions together with the need to predict pest population densities and relate these to poorly defined economic injury levels (Pedigo et al. 1986) while taking into account the effectiveness of pest management practices. Since the areas at highest risk from economic, environmental or social impacts can be mapped without modelling population densities in relation to economic thresholds it is therefore more practical to follow this approach not only to provide evidence supporting the PRA but also to help target actions following outbreaks and to design effective surveillance programmes and contingency plans.

Methods for combining maps of climatic suitability, host distribution, and host value with a simple mapping program (ABARES 2012) are summarised by Baker et al. (2012). The DSS has an introduction and four further stages, see Table 2.

In stage 1, the key factors that influence the endangered area are identified by using the biological, ecological and agronomic information in the pest risk assessment, the geographic data sets are assembled and, where appropriate, maps of the key factors are produced listing any significant assumptions. In stage 2, methods for combining these maps to identify the area of potential establishment and the area at highest risk from pest impacts are described, documenting any assumptions and combination rules utilised. When possible and appropriate, stage 3 can then be followed to show whether economic loss will occur in the area at highest risk and to identify the endangered area. As required, stage 4, provides techniques for producing a dynamic picture of the invasion process using a suite of spread models. Baker et al. (2012) illustrate the functioning of the DSS with two pests: the maize insect pest, *Diabrotica virgifera virgifera,* and the aquatic invasive alien plant, *Eichhornia crassipes*. For both these species, extensive information and maps are available on, e.g. climatic responses and host/habitat distribution, and there was ample time and resources for the analyses. A comprehensive description of the DSS is available in the project report (Baker et al. 2011).

In this paper, we apply the area mapping DSS to four case studies to determine the need for pest risk maps. We propose simple, quick analyses (i.e., shortcuts) to answer questions posed by the DSS and suggest these shortcuts could be particularly useful when risk maps are needed urgently, when an incursion threat seems imminent, or an outbreak has been detected. In addition, many plant health services have limited staff with skills in pest risk mapping and modelling and are faced with budget reductions. If used appropriately, the DSS can guide the production of exploratory pest risk maps created with relatively little time and resources. These exploratory analyses can still be helpful and, at minimum, can justify the need for a more detailed analysis and additional funding.

Table 2. Summary of the PRATIQUE endangered areas decision support scheme.

Stage	Tasks	Detail
Introduction	Decide whether mapping the endangered areas is going to be possible and useful	Based on the value of additional information that this process is likely to lead to and the data available
1	Confirm the factors that influence the endangered area	Describe the area of potential establishment, gather all appropriate data including maps that can influence the endangered area. Put maps into the same resolution and enter into the mapping software MCAS
2	Combine maps to determine areas of potential establishment and areas of highest risk	Guidance is given on how to combine the different data sets to obtain the relevant maps
3	Combine maps to determine endangered areas	
4	Optional module to evaluate rate of spread	Guidance is provided on the application of spread models

The rationale for shortcuts

It is important to tailor efforts according to the priority for which pest risk mapping is needed to provide support for the PRA. Although strict rules cannot be set because maps provide other important functions, we have attempted to identify situations of high and low priority.

High priority situations

In the main, pest risk maps are more useful when the potential for invasive alien species to establish and thrive in the PRA area is highly uncertain. Thus, the highest priorities for pest risk mapping are generally for those species that also require the most attention to detail, e.g. because impacts could be high but the likelihood is uncertain. This could occur when the likelihood of establishment is considered to be uncertain but, if establishment were to occur, the magnitude of impact is expected to be high because the measures available for eradication and containment would be limited and expensive.

Low priority situations

Risk maps can be considered to be a low priority without detailed analysis when it is already clear that:

- widespread establishment is likely, e.g. because the pest is common in neighbouring areas with similar climates and hosts or because pest outbreaks have already occurred within the PRA area demonstrating the potential for establishment and indicating that harmful impacts are likely to be uniformly distributed.
- the area of potential establishment can be identified without risk mapping, e.g. because establishment is only possible on hosts with a well defined and mapped distribution in discrete habitats or crop production systems, such as protected cultivation, and harmful impacts are likely to be uniformly distributed.

In addition to taking these priorities into account when deciding whether or not to map risk, it is also important to identify and apply any shorter or simpler methods of mapping when there is little time (for example, because an outbreak has occurred and emergency action is required in an area where the pest is not established), resources are limited, (for example, because of budgetary cuts or a lack of staff experienced in risk mapping) or the priority for risk mapping is relatively low. We therefore indicate where short cuts may be possible and discuss the implications for the PRATIQUE area mapping DSS.

To show how these priorities and the amount of detailed analysis required can match up when undertaking PRAs, four examples based on recent work by EPPO and by the Food and Environment Research Agency (FERA) and Forest Research in the UK representing a range of risk and uncertainty are explored in this paper.

Case studies

Phytophthora austrocedrae (Oomycetes: Pythiaceae) in the United Kingdom

This pathogen of Cupressaceae originates from Argentina and Chile and has recently been found in the UK on juniper (*Juniper communis*), Lawson cypress (*Chamaecyparis lawsoniana*) and Nootka cypress (*Chamaecyparis nootkatensis*) (Forestry Commission 2013). It is established outdoors, particularly in north-west England and western Scotland. Forest Research (2012) undertook a rapid PRA on *P. austrocedrae* for consultation to assess its risk to the UK. It concluded that the climate is suitable for establishment throughout the UK and that environmental impacts are potentially significant because of the importance of juniper for biodiversity (JNCC 2007). For this species there was no need to produce climatic suitability maps and so the climatic mapping DSS could be ignored.

Since the climate is suitable for establishment throughout the UK, the area of potential establishment can be considered to be equivalent to the distribution of *J. communis* in uncultivated areas and the ornamental Cupressaceae hosts in parks and gardens. Maps of the distribution of *J. communis* and its subspecies are available from the National Biodiversity Network (see Figure 1) and the Botanic Society of the British Isles (Lockton 2012). The endangered area for environmental impacts can be represented by mapping the 1,100 ha of juniper in areas of Special Scientific Interest (JNCC 2007). This pest can therefore be considered a low priority for pest risk mapping because pest outbreaks have already occurred in the UK demonstrating the high potential for establishment and indicating that harmful impacts are likely to occur wherever juniper grows.

Drosophila suzukii (Diptera: Drosophilidae) in Europe

This small fly lays its eggs in a wide variety of ripe and unripe soft skinned fruit and can cause significant damage (Lee et al. 2011). It originates from Eastern Asia and in 2008 it was first found in several locations in Europe (Calabria et al. 2012) and North America (Hauser 2011). In 2010, EPPO conducted a PRA and concluded that this species can establish in a wide area of the EPPO region because its hosts are ubiquitous and only the coldest and most arid climatic zones are unsuitable for survival; economic impacts could occur wherever the pest can establish (EPPO 2011).

Although considerable efforts were made to find and map all the locations where *D. suzukii* had been recorded and to search the literature for any records of climatic responses, these conclusions were based on a relatively simple analysis. *D. suzukii* can survive the long cold winters at its northern limits to its distribution in northern China through its association with human habitation. Since such severe winters occur very rarely in Europe and hosts are very widespread, the principal factor determining its northerly limits in Europe was considered to be the amount of degree days available for development and reproduction. A simple phenology model with a base temperature of 10°C and 250

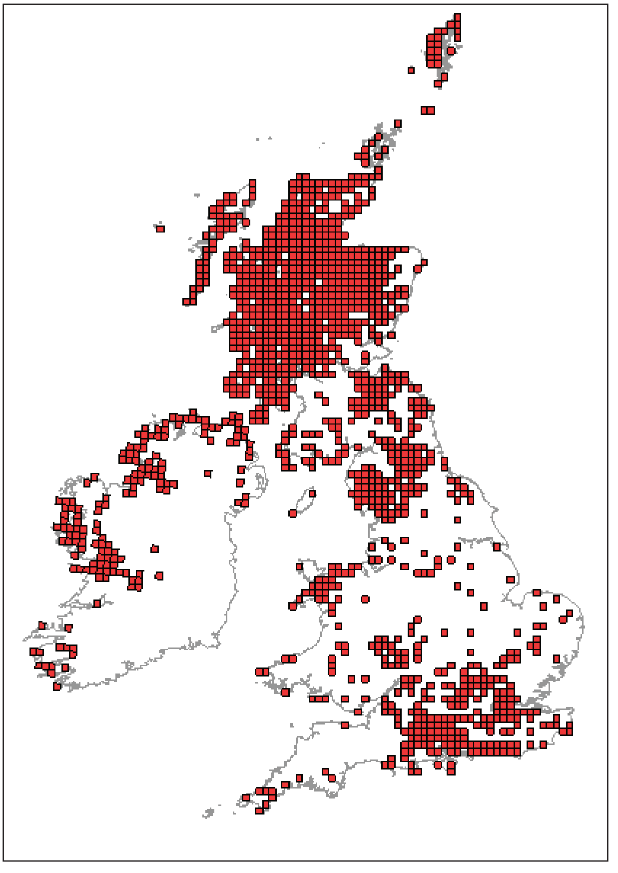

Figure 1. Distribution of *Juniperus communis* in Great Britain and Ireland from the National Biodiversity Network Gateway (NBN Gateway: data.nbn.org.uk) © Crown copyright and database rights 2011 Ordnance Survey [100017955]

degree days was therefore applied to the 1961-90 Climatic Research Unit monthly gridded climatology at 30 minute latitude and longitude resolution (New et al. 2002) and mapped (see Figure 2). Only extreme northern and mountainous areas were found to be unsuitable. Elsewhere there are sufficient accumulated degree days for numerous generations to be completed in the summer. Since oviposition in unripe fruit allows pathogens to enter and causes a serious loss of quality, the presence of *D. suzukii* populations is likely to cause economic loss and the endangered area can be considered to be equivalent to the area where host crops are grown in the area of potential establishment. This pest can therefore be considered a low priority for pest risk mapping in most of Europe because widespread establishment is very likely and pest outbreaks have already occurred demonstrating the high potential for establishment and indicating that harmful impacts are likely to be uniformly distributed. Therefore, on a European scale, the endangered area DSS is not relevant. However, more detailed mapping at the limits to its distribution in Scandinavia and at high altitude is of higher priority and would be justified.

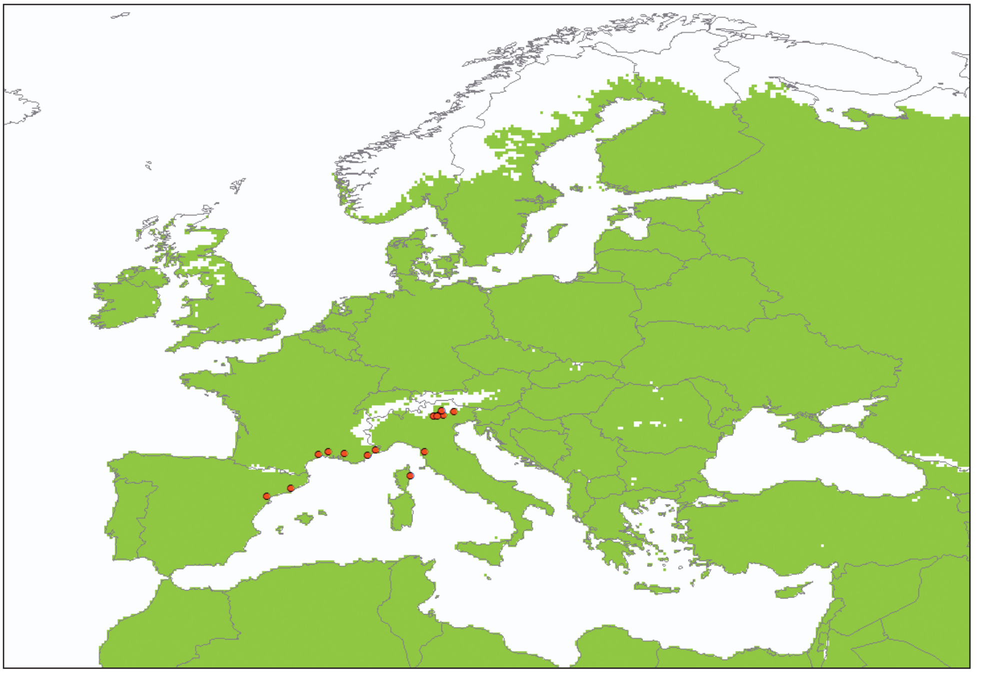

Figure 2. The area (in green) where annual degree day accumulations above a base temperature of 10°C exceed 250 with the locations of *Drosophila suzukii* known in August 2010 (in red).

Thaumatotibia leucotreta (Lepidoptera: Tortricidae) in Europe

This polyphagous fruit pest, the false codling moth, is native to sub-Saharan Africa and can be particularly damaging to a variety of fruits including oranges and peaches. As summarised by Brunel et al. (2013), EPPO undertook a limited climatic analysis on this species as part of a detailed PRA. As with *D. suzukii*, substantial efforts were taken to obtain as many distribution records as possible and collect information on its climatic responses from the literature but climate suitability models, such as CLIMEX, were not employed. This was partly due to lack of time and partly because its presence in the Israeli coastal plain had already demonstrated its ability to establish in the EPPO region. However it was also because the factors influencing winter survival are poorly known and the distribution in South Africa is strongly influenced by non-climatic factors.

A simple rule based on the difference between maximum and minimum winter temperatures above a minimum threshold fitted both the limits to the distribution in South Africa and the area in Israel where it is established. The maps generated by applying this rule to global climatologies could therefore be used to define the area of potential establishment, especially because the hosts, e.g. *Ricinus communis* (castor oil plant), are widespread in southern Mediterranean coastal areas. Areas of highest risk occur where the crops of major economic importance, such as oranges, are grown in the area of potential establishment. This pest can therefore be considered a relatively high priority for pest risk mapping in the EPPO Region. Outbreaks have already occurred in one area (Israel) demonstrating that establishment is possible, but more detailed mapping is required to explore the limits to its distribution in southern Europe. The mapping needs to take into account the magnitude of the potential impact together with the feasibility and expense of eradication and containment.

Thaumetopoea pityocampa (Lepidoptera: Thaumetopoeidae) in the United Kingdom

This pest, the pine processionary moth, defoliates *Pinus* species and the larval hairs can cause severe skin rashes and eye damage. Since it is widespread in the Mediterranean area and is spreading northwards in France assisted by climate change (Robinet et al. 2011), FERA undertook a rapid PRA for consultation (FERA 2012a) for the UK. This PRA showed that, although establishment is unlikely, there is a high uncertainty and a more detailed analysis is required because of the potential for severe impacts. This conclusion was justified by some exploratory analysis. Maps of the main *Pinus* hosts in the UK were obtained from the Botanic Society of the British Isles (BSBI 2012) and visually compared with maps of mean minimum and maximum winter temperatures and sunshine duration for 1971–2000 (UK Meteorological Office 2012a). Coastal central southern England was found to have the highest diversity of host *Pinus* species in the UK and the warmest, sunniest winters. Survival at the northern edge of its range in France is related to nest temperatures (maximum daily temperature and solar radiation) which is correlated with mean minimum winter temperatures (Robinet et al. 2007). FERA therefore (2012a) compared the mean minimum winter (October to March) temperatures over the last twenty years at one location in coastal central southern England (Hurn Airport, 50.7800°N, 1.8425°W) with those in Orleans and Paris where the pest has established damaging pest populations (see Figure 3). The similarity in the winter minimum temperatures at Hurn Airport and Orleans suggests that parts of southern coastal England have sufficient warmth to sustain populations of PPM. Thus for a rapid comparison of the climatic conditions in locations where the pest found and the most southerly locations in England was able to demonstrate some risk. The host distribution provided an indication of the areas at highest risk. These simple methods were sufficient to demonstrate the need for further analysis without the use of either of the DSSs. For this pest the area of potential establishment is still very uncertain and further work is required to try and resolve the uncertainties concerning, for example whether there is sufficient solar radiation for survival in southern England. This pest can therefore be considered a high priority for pest risk mapping because the likelihood of establishment in even a small area of the UK where host crops are grown is considered to be very uncertain but, if establishment was to occur, the magnitude of impact is expected to be high.

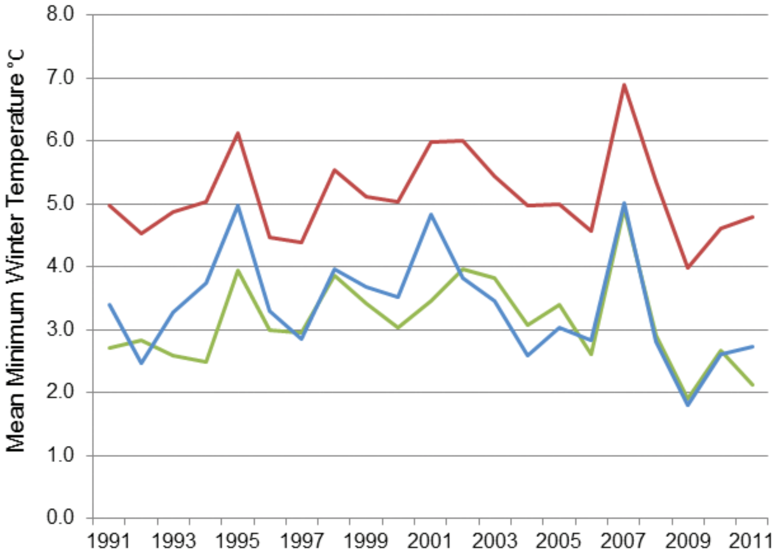

Figure 3. Mean minimum winter (October - March) temperatures from 1991–2011 for one location in southern UK (Hurn Airport) (coloured in green) with Orleans (blue) and Paris (red) in France. Data were obtained from the UK Meterological Office (2012b) and from the Ensembles project (http://eca.knmi.nl/dailydata/index.php).

Discussion

The risk maps used to support these PRAs were all created by using short cuts and none of them utilised all components of the PRATIQUE DSSs for climatic suitability analysis (Eyre et al. 2012) and mapping areas at highest risk (Baker et al. 2012) although detailed investigations of the current distribution of the pest and its climate responses were generally carried out.

Based on the rationale for shortcuts described above, *P. austrocedrae* and *P. pityocampa* can be considered to represent, respectively, low and high priorities for pest risk mapping. For *P. austrocedrae*, distribution maps of juniper for the whole country and for areas important for nature conservation were considered to be sufficient to show the area of potential establishment outside parks and gardens and the endangered area for environmental impacts, whereas even the potential for establishment of *T. pityocampa* is highly uncertain. The risk mapping priorities for *D. suzukii* and *T. leucotreta* are intermediate. The area of potential establishment for both species was assessed with relatively simple methods based on climatic suitability analyses using, respectively, a simple phenology model and the difference between minimum and maximum winter temperatures with the distributions of the host crops primarily influencing the endangered areas and areas of highest risk.

The extent to which limited methods are appropriate to map risk is debatable because PRAs can only be validated when invasions occur. However, by ensuring that the literature has been searched comprehensively to uncover, for example, all that is known about a pest's distribution, host range and climatic responses, greater reliance can be placed on the priority given and the methods used.

Short cuts and limited methods also generate greater uncertainty. Demonstrating uncertainty in maps remains a fundamental challenge (Venette et al. 2010) and so it is very important that pest risk analysts carefully document the uncertainties. For example, the *D. suzukii* PRA (EPPO 2011) noted that, although the 250 degree days above a base of 10°C used in Figure 2 is required for development from egg to adult, a simple division of the annual degree days to obtain a map of the number of generations possible in an area creates uncertainty because: (a) an additional period is usually required by insects before adults are ready to oviposit, (b) considerable individual variation can be expected with overlapping generations occurring and (c) the grid cells both summarise and interpolate climate measured at weather stations, many locations within each grid cell will have different temperature accumulations. In addition, although the higher the degree day accumulation above 10°C, the greater the number of generations expected, the species cannot tolerate high temperatures if humidity is low and, in the southern Mediterranean areas, the species may survive only in irrigated crops. While such uncertainties influence the area at highest risk and the endangered area for *D. suzukii* they do not fundamentally change the overall risk. For *T. pityocampa*, however, the uncertainties concerning winter solar radiation are so critical to the overwintering survival of PPM in southern England that the uncertainties do need further investigation.

Many other shortcuts are available in addition to the examples provided here. In fact the *D. suzukii* PRA also included a visual examination of the global Köppen-Geiger climate zones (Kottek et al. 2006), hardiness zones (Magarey et al. 2008) and day-degree (Baker 2002) maps to help with the assessment. Regional maps of environmental zones, e.g. for Europe (Metzger et al. 2005), may help because they provide greater resolution than global maps. Tools that match the climate at locations that would be novel to the pest with those in the area where the pest is present, irrespective of a pest's known climatic responses, can also be very useful. CLIMEX (Sutherst et al. 2007) provides an application for matching locations and regions that can exploit both weather station and gridded climatologies, e.g. CliMond (Kriticos et al. 2011).

Conclusions and further work

The PRATIQUE DSSs for mapping the suitability of the climate for pest risk analysis (Eyre et al. 2012) and mapping areas at highest risk (Baker et al. 2012) already provide advice and examples for (a) when to map and when not to map, (b) what climate suitability model to use, (c) where to find other relevant spatial data and (d) how to combine other relevant spatial data with climatic suitability to create maps of potential establishment. Some of the issues that require further work are: (i) the representation of uncertainty to pest risk managers, (ii) the incorporation of climate and land use change in risk maps, (iii) linking maps of the area of highest risk with models of pest spread and impacts and (iv) exploring ways of mapping endangered areas. These challenges relate closely to the recommendations for improving pest risk maps identified by Venette et al. (2010).

This paper has focused on the additional challenges of identifying when pest risk mapping is a low and a high priority and relating this to an appropriate reduction or increase in the level of detail employed while ensuring that the uncertainties inherent in simplification are clearly demonstrated. We have shown that a number of approaches for simplifying the DSS and reducing the time taken to produce risk maps can be considered, e.g. (a) using previously published maps to help indicate risk, (b) deploying simpler models and (c) mapping key components for visual comparison without importing them all into a GIS, converting them to the same resolution and using GIS tools to highlight areas at high risk. However, the examples provided in this paper show that, to justify any shortcuts, it is always important to ensure that the literature is thoroughly searched for key information on, for example pest distribution, host/habitat range and climatic responses. In addition, any maps that have been generated from simplified approaches should be clearly documented so that the reader knows why these methods have been used and understands the uncertainties. The priorities for further research should also be indicated.

The future priorities for pest risk mapping DSSs include further testing and enhancements to address the challenges articulated in the roadmap provided by Venette et al. (2010) not only to assist pest risk mappers but also to guide policy makers when interpreting the maps produced. The identification of the situations that are priorities for detailed pest risk mapping with guidance on shortcuts relates closely to the increasing use of shorter PRA schemes that can be completed quickly, e.g. the Quick Scan PRA scheme of the Netherlands (Netherlands Plant Protection Service 2012), the Rapid PRA scheme of the UK (Fera 2012b) and the EPPO express PRA scheme (EPPO 2012).

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