Center for Plant Health Science and Technology

USDA
Plant Protection and Quarantine
Animal and Plant Health Inspection Service

Workshop on Pest Risk Mapping

This is a report on the **APHIS-PPQ-CPHST Workshop on Pest Risk Mapping** held on June 5-7, 2007 in Fort Collins, Colorado.

October, 15, 2007

Key contributors to the workshop report included Darren Kriticos (Introduction, Potential distribution, Modeling), Glenn Fowler (Pathways), Tom Kalaris (Interpretation), Joel Pitt (Spread models), Richard Baker and Frank Koch (Uncertainty) and Roger Magarey (Lead Editor). The document was reviewed by Dan Fieselmann and Robert Griffin of APHIS-PPQ-CPHST.

APHIS-PPQ-CPHST Workshop on Pest Risk Mapping

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Executive Summary

On June 5-7 a workshop on pest risk mapping was held in Fort Collins, Colorado. The goals of the workshop were to: i) review the latest technologies for pest risk mapping; ii) develop recommendations for pest risk mapping; iii) create a plan for international collaboration; and iv) create a workshop report. The workshop was hosted by the Center for Plant Health Science and Technology (CPHST) with invitations being extended to scientists from government, universities and industry. The workshop was attended by 26 scientists (Figure 1) from countries including the Australia, Canada, New Zealand, Norway, United States, and the United Kingdom. A full list of participants is contained in Appendix 1. Organizers were Roger Magarey from the Center for Integrated Pest Management, and Tom Kalaris, Lisa Kennaway and Dan Fieselmann from CPHST.

The first two days of the workshop were mostly individual presentations. The first day was primarily a review of tools, technologies and data. The first day included a comparison of NAPPFAST and CLIMEX, two modeling[1] packages used by participants. The second day focused on risk mapping for forest pests. The final day of the workshop addressed three key issues including pathway and probabilistic models, general modeling and communication of uncertainties to managers and stakeholders. The presentations are available in PDF format from the NAPPFAST.org web site.

Participants at the workshop identified a number of key concerns including:

i) Model assessment, validation and documentation;
ii) Map representation and visualization of uncertainty;
iii) Best practice guide for modeling (including toolkit);
iv) Availability, use and misuse of models;
v) Communication, interpretation and use of risk maps by decision-makers;
vi) Impact mapping;
vii) International/online collaboration;
viii) Climate change;
ix) Gap in how human and biological dimensions interact; and
x) Training in modeling practice.

The group has undertaken several initiatives to improve collaboration and to facilitate the development of recommendations for pest risk mapping. Darren Kriticos, ENSIS, Australia has created a listserver to facilitate group discussions. Rob Venette, USFS will be the senior author on a proposed group publication to be submitted to a peer reviewed journal. Dr. Venette will also be hosting a follow-up workshop to be held next summer in St Paul, MN. This report will also be placed on-line, with the intention of building a repository of knowledge that can be improved and expanded in the future. Both the report and presentations from the meeting are available at http://www.nappfast.org.

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[1] Modeling is preferred over modeling (Websters Dictionary, 2006)

Figure 1. Participants of the APHIS Workshop on Risk Mapping. A full list of participants is provided in Appendix 1.

Workshop Objectives

The specific tasks and critical outcomes for the workshop were:
1) Review the latest technologies and data for pest risk mapping. Identify gaps and recommend strategies to improve or link existing systems.
2) General recommendations for pest risk mapping including: i) data (selection, management and quality control); ii) modeling (selection, parameterization, validation, outputs and uncertainties); and iii) techniques for communication with stakeholders.
3) Create a plan for international collaboration to improve pest risk mapping technologies including model validation.
4) Create a report from the workshop addressing the critical outcomes.

Introduction

Pest risk modeling covers a wide variety of plant protection applications. In this report we focus on pest risk modeling, either pre-border, at the border, or for post-border surveillance in support of phytosanitary decision-making under the International Standards for Phytosanitary Measures (ISPM) 11 (World Trade Organisation 1994). The challenge is to understand the risk posed by an exotic plant pest[2], either prior to it arriving within an area, or soon after it has arrived. The decisions that are typically made by phytosanitary agencies are concerned with:

- pest prioritization and the allocation of resources to restrict an invasion pathway,
- the potential restriction of trade in a commodity that may pose an unacceptable risk either directly, or through contamination of imports or be a pest itself,

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[2] Exotic plant pest After ISPM 5. Exotic - Not native to a particular country, ecosystem or ecoarea (applied to organisms intentionally or accidentally introduced as a result of human activities). Pest - Any species, strain or biotype of plant, animal or pathogenic agent injurious to plants or plant products

- the establishment of standards for disinfestation treatment or import health standards,
- increasing the efficiency of pest detection surveys,
- the decision whether to attempt to eradicate a newly detected exotic pest, attempt to manage it, or ignore it.

In most of these cases, decisions can have extremely costly consequences, time pressures for making the decision are urgent, and relevant information is often scant.

The key questions faced by risk analysts and biosecurity managers under the ISPM 11 framework and the applications of risk modeling are shown in Table 1.

Table 1. Key questions and risk modeling approaches

Key Question	Risk Modeling Approach
Where is the species of interest today?	Current distribution data
By what pathway could a species arrive in a given area (jurisdiction)?	Pathway modeling
Where could it get to (anywhere in the world)?	Potential distribution (habitat) modeling
What is its likely rate of spread after introduction?	Spread modeling
What are the economic consequences of pest incursion versus response options (costs and benefits)?	Economic modeling

The question of current distribution usually arises in two situations: when a pest threat is being assessed prior to a species incursion, and immediately subsequent to a species incursion being detected. When the pest threat is offshore, question 1 is usually addressed using published literature, *ad hoc* mentions of locality information or museum records. More recently, distribution data at the country or state level has become available from sources such as the Crop Compendium (Commonwealth Agricultural Bureau International), Global Pest and Disease Database (GPDD) but this is of little value for addressing the other questions, and is frequently inaccurate (DJK, pers. obs.). When a species has been recently detected invading a new country there is a need to undertake a delimitation survey so as to understand the full extent of the incursion. This work can be assisted by the application of habitat models that can define the habitat types that have been invaded, pointing to other areas that may also presently harbor the invader, or are more likely to face the most immediate threat of being invaded.

To address question 2 and 3, it is usual practice to employ pathway and habitat models if possible. There are few formal model frameworks designed to address question 4 (spread) and 5 (economic impact), and few have been applied in the context of phytosanitary decision-making. It is usual practice in phytosanitary risk assessments to make simple assumptions of sigmoid increases in area and include these in economic impact assessments. The economic impacts can then be estimated from simplistic assumptions of impact should the invader spread.

Current pest distribution

Determination of the current distribution of pests is one of the fundamental tasks of pest modeling. The primary sources for pest distribution data are:

1. literature records
2. herbaria and museum specimens
3. expert opinion
4. pest distribution databases, and
5. phytosanitary records or analyses.

The primary literature sources of most use for pest modeling are published floras and pest distribution lists. In both of these cases it is usual to have to translate town names into geographic coordinates using gazetteers. One of the secondary literature sources for current pest distribution is the Commonwealth Agricultural Bureau (CABI) Crop Compendium (CABI, 2006). Another similar product is the Commonwealth Mycological Institute CMI fungal distribution data sheets. Since these data sources are not updated frequently, additional literature reports can be accessed from abstract databases such as BIOSIS, CAB Abstracts and Agricola. One of the problems with the literature sources is that observations are usually only reported for primary or secondary political units. Their modeling value lies mainly in alerting the modeler to the need to track down better distribution data in that area. Such records can also act as a very coarse validation data source.

The second source is taxonomic databases. One of the most practical sources is the Global Biodiversity Information Facility (GBIF), which allows users to download data from a large number of museums and sources worldwide. Importantly, a large number of these sources have at least some georeferenced data. There appears to be a large quantity of data available for plants but much less for arthropods and very little georeferenced data for plant pathogens.

A third source of data is expert opinion. This can provide the most potentially useful and detailed data but it is the most time consuming to collect. A fourth source of data is dedicated pest distribution databases. These may be maintained by government, NGOs, universities or industry. An example is the US National Agricultural Pest Information system (NAPIS), which although a restricted system, also contains publicly available information. Pest distribution databases are expected to become more widely used in the future with the development of systems such as the Pest Information Platform (Isard, 2006).

A final source of information is phytosanitary records or analyses. Records include pest interception data but these are not widely available and must be used with caution. In many cases interceptions may not indicate the correct origin due to cargo transshipment or passenger stopovers. Phytosanitary analyses, e.g. commodity and other pest risk analyses, may provide a useful summarization of a combination of data sources.

Pathway models

The processes that determine the introduction and establishment of an organism will be: 1) human-assisted, e.g. truck transport, passenger baggage; 2) biological, e.g. flight; or 3) abiotic, e.g. wind dispersal. Human-mediated introductions have been growing at an exponential rate due to global trade (Pimentel et al., 2000). ISPM Nos. 2 and 11, the primary international standards for pest risk analysis (International Plant Protection Convention, 2003) offer guidance on how pathway analysis should be conducted, with emphasis on imported commodities where the pathway is known. However, the pathway is a multi-dimensional concept that encompasses, for example, routes (source and destination); commodities (plants, animals, military equipment, growing media and garbage) or conveyances that harbor contaminating pests (hitchhikers); transport purpose (smugglers, passengers or travelers, mail, overland transit); transport technology (airliners, road freight, ships); and packing material (Hennessey, 2004). Recommendations have been made about what pathways need to be considered for different groups of pests (Anon, 2003).

Pathway analysis can be qualitative, quantitative or a combination of these depending on the nature of the analysis and the data available. In a probabilistic quantitative analysis (Morgan and Henrion, 1990), pathway models are concerned about the probability of the pest establishing through successive events (Hennessey, 2004). Events are represented by nodes in pathway scenarios. Nodes are important because they may identify areas that may be targeted later by risk mitigation measures.

There are many possible outcomes that may be presented by the model depending on several key factors such as: the pest infestation rate, the number and frequency of shipments, the effect of pest reduction measures (if any), and the area of the country where shipments arrive and their subsequent distribution (Hennesssey, 2004). Risk analysis software (e.g. @Risk Palisade Corp, Newfield, NY) is used to analyze the many possible outcomes that the model illustrates to produce a distribution of outcomes: maximum (worst case), minimum and most likely. Outcomes are usually reported as how many viable pests are expected to be introduced into susceptible areas annually.

Examples of published pest risk analyses include hitchhiking pests on passenger baggage (Caton et al. 2006), movement of quarantine insects through garbage (Auclair et al. 2005), and a range of insect pests and plant pathogens threatening New Zealand’s indigenous forests (Ridley et al. 2000). Other examples include a Karnal bunt risk assessment, Mexican border analysis and imported cut flowers (Hennessy, 2004). For most risk mapping applications, simple pathway models are employed. For example, the USDA-FS Forest Health Technology and Enterprise Team and collaborators created a simple introduction potential risk map for *Sirex* woodwasp and other important forest pests (FHTET, 2006). The method assigns weights to ports, markets and distribution centers and uses a distance decay function to account for the probable flight range. Workshop participant Manuel Colunga is developing a database of trade, climate, land use and other data sets to study the introduction of invasive species at the scale of metropolitan areas.

In addition to human-mediated pathways, atmospheric pathways are an important avenue for the introduction of exotic plant pests. There are a number of tools that can be used to assist in assessing atmospheric pathways including HYSPLIT, available from the NOAA Air Resources Laboratory (Draxler and Hess, 1997). Other factors may also be important for specific pests. For example, important factors for evaluating an atmospheric pathway for soybean rust included source strength, transport rate, target size and target susceptibility (Isard and Magarey, unpublished data).

Potential distribution

There are a plethora of habitat models driven by climate or other data (Table 2). Many of these systems have been compared and contrasted previously (Guisan and Zimmerman 2000; Kriticos and Randall 2001; Elith et al 2006). Each of these models or modeling platforms has its own characteristics that affect its suitability for addressing different modeling tasks, and hence for addressing different questions. These computer-based packages vary considerably in the degree to which the model structure is specified. In some cases the model structure is highly specified, and the characteristics of the resulting model projections are well-defined (e.g., Bioclim, CLIMEX). In other cases (e.g., NAPPFAST), the modeling platform provides the user with a large degree of freedom to specify both model structure and parameters. In the latter case, it is impossible to generalize the applicability of a model built using this type of system without a deep understanding of the specific formulation of that particular species' model.

The other main discriminating factor between models in Table 2 is the regression models versus the process-oriented models. Regression-based approaches have been particularly popular among researchers studying native species distributions, where the fundamental assumption that the species is at equilibrium with its environment is likely to be well satisfied. However, when applied to situations where the species is not at equilibrium with its environment, process-oriented approaches can yield more reliable predictions of the potential distribution of an invasive alien species. This is the synoptic view of the invasion, indicating what assets are at risk if the invasion proceeds unchecked. This is a very useful basis for assessing the value of the impacts of the invasion. This information can be combined with estimates of the costs of eradication to help decide whether to attempt eradication within the area, or to let the invasion proceed.

In the early to middle stages of an invasion, regression-based models can be applied to the species distribution to provide a tactical snapshot of the invasion. This will indicate the habitat already invaded and the area that is most likely to be invaded next. This could aid in targeting the distribution of education and awareness material to prepare land managers for the impending invasion, and also for informing targeted surveillance for the invader.

Table 2. Profile of software packages

Package name	**Objective**	**Model style**	**Computer platform**	**Process or regression Oriented**	**Reference**
Artificial Neural Networks (ANN)	ANN can identify relationships between the presence and absence of the insect species and climatic variables at different sites,	ANNs are an alternative modeling technique based on machine learning.	Various	R	Gevrey and Worner (2006)
BIOCLIM/ ANUCLIM	To describe the climatic envelope of a species and to predict its occurrence	Climate pattern-matching with minimum bounding rectangle (MBR)	PC and UNIX	R	Nix (1986), Busby (1991) Hutchinson et al. (1996)
BioMOD	BIOMOD: BIOdiversity Modeling aims to maximize the predictive accuracy of current species distributions and the reliability of future potential distributions using different types of statistical modeling methods.	Biomod computes, for each species and in the same package, the four most widely used modeling techniques in species predictions, namely Generalized Linear Models (GLM), Generalized Additive Models (GAM), Classification and Regression Tree analysis (CART) and Artificial Neural Networks (ANN).	Unknown	R	Thuiller (2003)
CLIMATE	To predict the distribution of an organism based upon climate preferences – mainly weed risk assessment	Climate pattern-matching with choice of several match techniques including MBR and point-to-point similarity indices (Gower 1971)	Apple Macintosh/PC	R	Pheloung (1996)
CLIMATE ENVELOPE	To predict the potential distribution of species using point data from herbaria or museums	Climate pattern-matching using MBR	Web (UNIX)	R	Boston & Stockwell (1994)
CLIMEX for Windows	To compare locations or match climates		Windows 2000, XP		
(Compare locations)	To predict the relative climatic suitability for a species at selected locations	Process-oriented model describing species response to climatic variables, and predicting climatic suitability.		P	Sutherst et al 2007
(Match climates)	To predict the relative climatic similarity between different locations	Climate pattern-matching procedure		R	Sutherst et al 2007

Package name	**Objective**	**Model style**	**Computer platform**	**Process or regression Oriented**	**Reference**
DOMAIN	Conservation ecology, assessing adequacy of reserve design and designing sampling strategies	Climate pattern-matching using a point-to-point similarity index	Windows 95/NT	R	Carpenter *et al* (1993); CIFOR (1996)
ENFA (Environmental Niche Factor Analysis)	The ENFA's principle is to compare the distributions of the EGV between the presence data set (species distribution) and the whole area (global distribution).	The Ecological-Niche Factor Analysis (ENFA) computes suitability functions by comparing the species distribution in the ecogeographical variables (EGV) space with that of the whole set of cells using a multivariate approach.	Part of Biomapper software, Windows (most versions)	R	Hirzel et al. 2002
FloraMap	FloraMap is a specialized computer program (and associated data) that was developed to map the predicted distribution, or areas of possible climatic adaptation, of organisms in the wild.	Principal components analysis of monthly climate data using multivariate and Fourier transformation techniques	Windows	R	Jones and Gladkov (1999)
GARP	To predict the potential distribution of species using point data from herbaria or museums using climatic and non-climatic data	Generates environment-description rules using machine-learning techniques	Web (UNIX)	R	Boston & Stockwell (1994)
GLIM/GAM	To predict the probability of occurrence of species on a fine scale based upon statistical regression models	General statistical procedure for fitting species response functions to survey data	Not applicable	R	Austin & Meyers (1996)
GRASP	A regression modeling is used to establish relationships between a response variable and a set of spatial predictors	Generalized Regression analysis and Spatial Prediction	MS Windows PC	R	Lehman et al. 2002
HABITAT	To tightly define the environmental envelope of a species or other biotic entity and to predict the environments in which it may be present	Creates a convex polytope in n-dimensional space	PC	R	Walker & Cocks (1991)
MaxEnt	To predict species distribution	Machine learning technique based on the distribution of maximum entropy	Java based	R	Phillips et al. 2006

Package name	**Objective**	**Model style**	**Computer platform**	**Process or regression Oriented**	**Reference**
NAPPFAST	A tool for phytosanitary risk mapping.	On-line templates for phenology, infection and empirical models. Simple climate matching tool	Internet explorer	P or R	Magarey et el. 2007
Regression Tree Analysis	A general statistical procedure to analyse the environmental correlates of species distributions	General statistical procedure for defining set membership based upon environmental correlates	Not applicable	R	
STASH	To describe the present and natural distribution of northern Europe's major tree species	Process-oriented model describing species response to climatic variables, and predicting climatic suitability	UNIX; though could be run on any system running FORTRAN	P	Sykes *et al.* (1996)

At the workshop, Rob Venette presented a comparison of the CLIMEX and NAPPFAST systems. CLIMEX is a widely used climate matching tool with over 200 published papers. CLIMEX is a tool developed by CSIRO, Australia and a presentation on the capabilities of CLIMEX was made by Darren Kriticos. CLIMEX contains tools to model climatic stress and growth parameters to project climatic suitability for the species at any given climate station. CLIMEX can derive parameters inferentially from species distribution data and phenological observations or more directly from laboratory studies. It can also be used to match climates from a specified set of known suitable locations to the rest of the world in a manner broadly similar to CLIMATE and Floramap. A recent modification allows users to automatically fit stress parameters using a genetic algorithm.

NAPPFAST (Magarey *et al.* 2007) is a system that allows species models to be specified in a highly flexible manner as a function of daily weather data. The flexibility of this package means that any models developed and applied in this system need to be understood in terms of the details with which the individual model has been built. That is, the NAPPFAST system does not represent a single model, or even a model family. The greatest strength of the NAPPFAST system is its ability to make use of fine temporal and spatial scale weather data. This makes it ideal for identifying spatial and temporal conditions under which plant pathogens can likely infect plants.

For risk assessments of exotic pests, NAPPFAST may be limited in not being able to infer parameters, either through regression approaches or fitting techniques. The current climate matching technique simply fits a distribution from parameter limits. The climate matching tool in NAPPFAST should be improved by utilizing functions and techniques found in other climate matching tools.

Table 3. Comparison of CLIMEX and NAPPFAST (Updated from Venette).

	CLIMEX	NAPPFAST
Inputs (weather)	Monthly normals (30 year average) or daily weather sequences	Daily
Inputs	Lab/field studies Geographic distribution	Lab/field studies Geographic distribution
Model structure	Fixed (consistency)	Flexible (variability)
Complexity	Intermediate	Currently simple*
Output (temporal)	Fixed (multiple statistic)*	Frequency, accumulated
Output (spatial)	Single point Multiple points Pre-analysis interpolation	Single point interpolation Post-hoc interpolation
Sensitivity	Easy	Complicated*

* Currently very limited capabilities

The comparison indicates that both CLIMEX and NAPPFAST have relative strengths and weaknesses and provides a guide for future improvements to both systems (Table 3).

Spread models

The development of spread models began with Fisher (1937) constructing a reaction-diffusion partial differential equation (PDE) that encapsulated the averaged movement of many individuals moving according to Brownian motion, and with a population undergoing logarithmic growth. Although Fisher (1937) used the PDE to model the spread of alleles through a population, Skellam (1951) later applied a similar variation to the spread of introduced muskrats in Europe, demonstrating its use for invasion biology. This eventual constant spread rate has been found to apply to many invading organisms (Hengeveld 1989). Many analytical models since have extended the seminal PDE on population growth and spread to account for other types of dispersal assumptions, such as Allee effects (Lewis and Kareiva 1993) and interacting species (Okubo et al. 1989). Integro-difference equation models are similar, except they treat time discretely whereas PDEs treat it as continuous. They've been used to address questions of how fat-tailed probability distributions affect the speed of population spread (Kot et al. 1996). One issue with these analytical models is that they often assume a homogeneous environment, or work on abstract landscapes making it difficult to apply them to management scenarios. Mechanistic or simulation-based approaches are able to account for heterogeneity in the real world through connection with Geographical Information Systems.

Mechanistic models can simulate the movement of individuals in a population, or the populations themselves. The individual-based model of Gardner and Gustafson

(2004) used a heterogeneous environment and investigated hypothetical management scenarios to assure the persistence of American martens (*Martes americana*). Metapopulation models discretize space into individual population patches and then model the dispersal of individuals between them. Recently, mechanistic metapopulation models that predict the spread of species over large spatially realistic regions have been developed. Two of these frameworks, PestSpread (Overton et al. 2004) and MDiG (Modular Dispersal in GIS, http://mdig.sourceforge.net), have been developed to simulate different modes of dispersal and growth. PestSpread is deterministic, and has difficulty in modeling rare long-distance dispersal events, whereas MDiG allows stochastic processes that better suit some aspects of the chancy invasion process.

Economic models

Unfortunately, economic models were not discussed at the workshop but should be considered to be an important topic for future workshops.

Critical Issues

Workshop participants took a vote to nominate the most important areas in risk mapping that require research, development or international collaboration. The critical issues are listed in order of importance.

1. Model assessment, validation and documentation
2. Map representation and visualization of uncertainty
3. Availability and accessibility of primary data
4. Best practice guide for modeling (including toolkit)
5. Communication, interpretation and use of risk maps by decision-makers
6. Impact mapping
7. International/online collaboration
8. Climate change
9. Gap in how human and biological dimensions interact
10. Training in modeling practice

1. Model assessment, validation and documentation

It is critical that models are carefully selected and applied to address questions to which they are best suited. There are many published examples of models being applied inappropriately. For example, regression models should never be used to extrapolate beyond the domain used to build them. In the case of invasive species, applying a model across a continental boundary is likely to require the model to encounter novel climatic conditions. In this case the model projections could be biased, and the effect may not be obvious. Where the potential distribution of an invasive organism is being modeled, a process-oriented approach is to be preferred for inter-continental projections, or those involving future climate change projections. The potential distribution of an invasive organism provides the synoptic view of the invasion, and an indication of what assets are at risk should the invasion proceed unchecked. On the other hand, regression models can play an extremely useful tactical role, identifying the assets that have been invaded presently, and those habitats that are at immediate risk of invasion.

Selecting parameters for process-oriented climate models should follow a hierarchical set of priorities from geographical data, field phenological data to laboratory based experimental data. The reason for this assertion is that the modeling usually occurs in the climate domain. Where weather sequences are modeled in terms of their suitability as in NAPPFAST or DYMEX models, then phenological and laboratory experiment data may have pre-eminence.

If at all possible, models should be validated using independent data. In the case of widely dispersed pests, this could involve consideration of geographical data across a range of continents, using some continental distributions for model building and reserving some data for validation. Depending upon the model, other sources of data should also be used for validation. For example, where phenological observations are available, then these should also be considered. The modeler should consider as many sources of validation and "reasonability checks" as possible. Where there are inconsistencies between different data sources, the likely possible explanations for the inconsistencies need to be discussed for the target audience.

In some limited circumstances it is appropriate to use so-called ensemble approaches, where the results of several models are provided. When the models are based on exactly the same data, they can provide an insight into model uncertainty. This approach is used when there is a significant uncertainty due to structural model formulation, and when the models are designed to portray the same phenomenon. When different models are portraying different information, it is critical that they are described carefully, highlighting the different phenomena being portrayed. These differences can often be subtle, requiring a fair degree of technical knowledge of the models and their characteristics. As such, model ensemble approaches should not be used as a routine means of avoiding giving appropriate attention to ensuring that the models are being applied to an appropriate modeling situation and to address the appropriate questions. Using ensemble approaches in this manner introduces unnecessary ambiguity into the decision-making arena.

Model shootouts (independently verified comparisons between models using the same data inputs) provide a means for the modeling community to gain a better appreciation of the relative merits and characteristics of different modeling approaches (Moniger et al., 1991). Some participants had reservations about the applicability of a shootout and raised concerns about the correct application of models during a shootout. Also there are issues with selecting the best validation data sets.

Joe Russo suggested the concept of a databunker where modellers can access primary input data, run models and access outputs from other modeling groups. Such an approach would allow models to be linked; for example a pathways model could be linked to a climate model. It would also aid the comparison of models, since models could potentially be created and made available for a web interface.

Another issue raised by researchers was reaching out to the botanical/ecological community where there is considerable expertise in species distribution modeling (Elith et al., 2006). Models should be carefully described. Sutherst (2003) has provided a pro-forma for describing pest risk models (Appendix 2). While this pro-forma was developed for CLIMEX models, most of it is applicable to properly documenting any species distribution model. Careful model description assists peer review and model comparisons. Providing end-users with adequate documentation assists with model transparency.

2. Map representation and visualization of uncertainty

Uncertainty is inherent to all pest risk assessments. However, for many pests, the immediacy of the threat to natural or agricultural resources requires agencies or scientists to complete an assessment despite substantial uncertainty about the biological system in which the pest is a member (Regan et al. 2002, Regan et al. 2005). While many scientists implicitly acknowledge uncertainty in their analyses (e.g., adopting a simple ordinal-scale risk rating system rather than a specific probabilistic one), there is no standard method for communicating uncertainty to distinct target audiences: other scientists, policymakers, regulators, and the public. This suggests a need for guidelines on best practices for handling uncertainty in pest risk maps.

Uncertainty in risk maps may derive from the input parameters, from the model(s) used to represent the system(s) of interest, and from the presentation of model outputs. Parametric uncertainty may develop from measurement and systematic errors, incomplete or sparse data, natural variability in the system, or subjective judgment in the estimation of parameter values (Elith et al. 2002, Regan et al. 2002, Barry and Elith, 2004). Model uncertainty arises from the way in which the model is constructed, i.e., its underlying assumptions as well as its algorithmic components (Barry and Elith, 2002). Uncertainty also arises from which variables and processes are considered critical to risk and thus included in the model (Regan et al. 2002). In terms of presentation of outputs, pest risk maps are subject, at the very least, to uncertainties seen in other types of spatially explicit analyses (e.g., uncertainty due to rescaling, aggregation, generalization, or extrapolation of inputs). The level of uncertainty often goes unrepresented in pest risk maps, so the maps in turn are perceived to convey more certainty than actually exists (Woodbury 2003).

Pest risk modelers may take several steps to address uncertainty. Key recommendations are to provide thorough metadata about parameters; to indicate where expert judgment was used in the analysis, ideally assigning degrees of belief (i.e., subjective probabilities) (FAO 2007; Elith et al. 2002); and to fully document model assumptions and methodologies. It is also important to choose a spatial resolution that is appropriate for all inputs (Woodbury 2003). Sensitivity analyses or Monte Carlo simulation (Johnson and Gillingham 2004, Crosetto et al. 2000, Regan et al. 2003) allow description of the effects of model inputs and structure as well as how robust the model is to variability and stochasticity, while validation and verification allow quantification of model error (i.e., the measurable part of uncertainty). Comparisons between models, ensemble modeling or multimodel inference (e.g., Hartley et al. 2006) may also facilitate assessments of model uncertainty. In terms of visualization, there are several digital cartographic techniques (e.g., animation, variation in color saturation, presenting uncertainty as a third dimension; see Davis and Keller 1997) for techniques for incorporating uncertainty into map products. Visser et al. (2006) outlined four categories of maps that may be useful in communicating uncertainty: difference maps (modeled versus measured values); scenario maps (low-medium-high realizations of the same model, or comparison of different models); ensemble maps (same model with different parameters, e.g., results of Monte Carlo simulation); and statistical error/uncertainty maps (e.g., probability distribution, standard error, or root mean square error maps).

Risk maps may have information value even with high levels of uncertainty. Info-gap decision theory (Ben-Haim 2006), which examines whether uncertainty will actually alter the conclusions suggested by an analysis, is one area of future research. Other future priorities include improving availability of global data and metadata as well as methods for representing the impacts of climate change. As outlined above, numerous tools already exist for handling uncertainty; in order to define best practice guidelines, it would be prudent to engage individuals in other fields (e.g., human or animal health) who regularly create risk maps, and to consult pest regulators, outbreak managers, and policymakers regarding what would best suit their needs.

There is a growing understanding that expert opinion can be extremely biased and misleading. The Australian Centre of Excellence in Risk Assessment (ACERA) has a large research program devoted in part to identifying the optimal means of eliciting information from experts, and characterizing the uncertainty surrounding their opinions.

3. Availability and accessibility of primary data

The accessibility of data is of primary importance to modelers. Critical data elements include pest and host distribution, weather and climate, ecological habitat types, and trade data (Table 4), while other commonly available data such as geographic layers depicting elevation and land use are also very important. In recent years there has been an explosion of data and this is only expected to become more pronounced in future years. A recurrent problem for pest risk modelers has been the paucity of conformal global datasets, i.e. datasets that have global coverage and whose values have the same meaning throughout the globe. These features are required in order to build models based on species distribution and behavior patterns outside of the country for which the risk assessment is being undertaken.

Table 4. Examples of primary data

Data	Example types	Example Sources	References
Pest distribution	Taxonomic records	http://www.gbif.com	Sellers, 2004
	Literature records	http://www.cabi.org	
	Survey data		Kriticos et al. 2007
Host distribution	U.S. Forest Inventory and Analysis (FIA)	http://fia.fs.fed.us/	
	U.S. agricultural commodity data	http://www.nass.usda.gov/	
Weather and climate data	Station observations	http://www.ipcc.org	Mitchell et al., 2004
	Gridded products	http://www.ncdc.noaa.gov	
Trade data	Import statistics	http://dataweb.usitc.gov/	
Pathway data	U.S. Pest interceptions	Restricted	McCullough et al. 2006

4. Best practice guide for modeling (including toolkit)

A best practice guide would identify the most appropriate methods to build risk models and create risk maps. The guide might include the following sections; data sources and availability, model and parameter selection, metadata and documentation map output. The guide should be available on-line and contain links to sites containing downloadable models or data sources. The guide should also address the potential misuse of models and common errors to avoid. A recent book on ecological niche modeling covers many best practice topics including: functions, data, spatial topology, environmental data collections and sources of errors (Stockwell, 2006).

5. Communication, interpretation and use of risk maps by decision-makers

There was unanimous agreement from the attendees that risk communication is difficult for two reasons. One issue is the actual presentation of the map, where poor choices as far as layout, scale, colors, categories and results can create a confused or misinterpreted message. A second issue is that the technical aspects of the risk models can be difficult to explain to biosecurity managers. On one hand, modelers want to discuss all their assumptions including the quality of the data on which their models are based, the algorithms they used, etc., whereas the managers often want simplified answers to facilitate their decisions. Predictions are just one component in the process of decision-making (Pielke and Conant, 2003). Better decisions are made when all the factors involved in decision-making are considered (e.g. participants, institutions, perspectives, values and resources) rather than just the prediction alone. Users should also evaluate other criteria for evaluating the quality of predictions including modeling purpose, model accuracy, model sophistication and experience of the forecasting group (Pielke and Conant, 2003).

The problem of effectively communicating the results of risk mapping will continue to be an ongoing problem and all modelers and managers need to focus their attention in this area. One suggestion by the workshop participants is to engage GIS scientists and risk communicators (and possibly psychologists) who use maps in other fields, e.g. human and animal health, to determine best practices.

6. Impact mapping

Workshop participants identified impact mapping as a key issue for future research. Most models report an index of pest occurrence risk rather than a probable or potential impact. For example, CLIMEX and NAPPFAST can report the number of generations or infection cycles that a pest may develop in a certain climate. The actual impact measured in yield loss or in a dollar value is much harder to calculate. The development of impact maps will require a multi-disciplinary approach and especially involve cooperation with economists and agronomists. Some tentative steps have been taken already (Brinkley and Bomford 2002). A set of research projects is being undertaken presently in New Zealand and Australia to explore techniques for estimating impact values from modeled climate suitability information and geographic data about the assets at risk (D. J. Kriticos, pers comm.).

7. International/online collaboration

International collaboration can be valuable because of the potential for data sharing and model harmonization. For example, data sharing can be helpful not only for determining a pest’s current distribution but also for model validation. It is difficult to validate risk maps and models in the country of invasion because the alien invasive pest is usually not present or is present in a limited distribution. There are now many examples of on-line tools that allow users to share data or to perform analyses using data sets provided by others (Butler, 2007). An ideal system for international collaboration would allow a research group to develop a model and run predictions for either individual years or for historical averages. International cooperators would be able to provide either pest observations or model critique in exchange for being able to use the model output for local decision support systems.

To facilitate collaboration, a follow-up meeting will be held in St. Paul, MN next summer. It would be helpful if invitations could be extended to researchers from countries in Asia, South America, Europe and Africa to try and expand the international diversity of the group. Funding to facilitate participation from developing countries may be helpful.

8. Climate change

Climate change is posing an emerging set of challenges for pest risk mapping. As the climate warms, species distributions are changing (Parmesan *et al.* 1999). However, the ranges of species may not yet be in equilibrium with the current climate (Peterson, 2005). Individuals and populations at the warmer edge of the present range are likely to become restricted to favorable microsites before they become locally extinct at a regional scale. At the cooler edge of the range, it is likely that there are lags due to species having to invade new territory, particularly where there are species occupying a similar niche. A further lag effect lies in the time it takes museums and other collections of species distribution data to sample species changing distributions. The challenge this poses for pest risk mapping methods and practice is that species are assumed to be at equilibrium with their environment. As most climate based habitat models presently use the so-called reference climate (1961-1990 average monthly normals), as climates warm and species distributions change, the relationship between the species known range and the reference climate is likely to diverge. One partial solution is to update the climate databases used for model training. The remaining challenge is to match the known range with the relevant climate dataset.

9. Gap in how human and biological dimensions interact

Most of the risk maps identified risks due to biological dimensions (e.g., the influence of climate on pest or host development). Few of the papers at the workshop addressed human mediated factors such as trade, transportation and human pathways. One exception was the presentation by Manuel Colunga, who has developed a model that uses a combination of human, climate and biological data sets to estimate the risk to U.S. metropolitan areas. In addition, Marla Downing presented risk maps for forest pests that included the influence of sites for pest introduction such as ports, distribution centers and markets. More emphasis should be placed on the human dimension in future workshops. .

10. Training in modeling practice

Training was nominated as a possible priority but did not receive a high ranking from the group. This does not diminish the importance of training but maybe recognizes that some of the needs are already being met or are still emerging as the field matures. Some of the model packages (e.g. CLIMEX) already have established training classes. Other modeling packages (e.g. NAPPFAST) are only used by a relatively small user group who know the technology well. The suggestion has been made to have training sessions linked to next year’s workshop.

Conclusions and Recommendations

- Continued collaboration of pest risk modelers will be facilitated through a listserver and a follow-up meeting in the northern summer of 2007. Participation of scientists from countries in Asia, South America, Europe and Africa should be encouraged if possible with financial incentives to create greater diversity, and broaden the understanding of the capabilities of this area of biosecurity management.
- The development of recommendations for pest modeling will be facilitated through group contributions to a peer reviewed journal article and a 'Best Practices Guide for Pest Risk Modeling'. The guide could be expanded and improved over several years. The guide should include sources for data and models.
- Communication of results and uncertainties to decision-makers was identified as a key issue for risk mapping. It is recommended that a small group of decision-makers be included in the next pest risk mapping workshop.
- Climate change was identified as a key concern to workshop participants. It is recommended this be discussed in greater detail in future meetings.
- A model shootout may be a useful tool for comparing and improving models. Suggestions for implementing a model shootout should be considered at the next meeting. Concerns of participants should be tabulated and carefully addressed.
- A web accessible databunker would allow modelers to access primary and derived data, build and share complex multi-question models and simplify model comparisons. Proposals to implement this concept should be considered in future meetings.
- Most current models only indicate relative pest risk rather than true impacts in terms or dollars or yield loss. To develop generic impact models is potentially difficult and would require interdisciplinary cooperation from economists and agronomists. A session on impacts and economics should be considered at future meetings.

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Appendix 1 List of Workshop Participants

List of Participants 2007

Name	Email	Institution	City	Country
Trond Rafoss	trond.rafoss at planteforsk.no,	Bioforsk	As	Norway
Dan McKenney	dmckenne at NRCan.gc.ca	Canadian Forest Service	Ontario	Canada
Denys Yemshanov	dyemshan at NRCan.gc.ca	Canadian Forest Service	Ontario	Canada
Kevin Porter	kporter at nrcan.gc.ca	Canadian Forest Service	Fredricton	Canada
Richard Baker	r.baker at csl.gov.uk	Central Science Laboratory	York	UK
Dan Borchert	Daniel.M.Borchert at aphis.usda.gov	CPHST	Raleigh	NC, US
Tom Kalaris	tom.m.kalaris at aphis.usda.gov	CPHST	Fort Collins	CO
Glenn Fowler	Glenn.Fowler at aphis.usda.gov	CPHST	Raleigh	NC, US
Lisa Kennaway	lisa.f.kennaway at aphis.usda.gov	CPHST	Fort Collins	NC, US
Darren Kriticos	darren.kriticos at ensisjv.com	ENSIS	Canberra	Australia
Susan Worner	Worner at lincoln.ac.nz	Lincoln University	Lincoln	NZ
Manuel Colunga	colungag at mail.cevl.msu.edu	Michigan State University	East Lansing	MI, US
Amos Zeigler	ziegler2 at msu.edu	Michigan State University	East Lansing	MI, US
Roger Magarey	Roger.D.Magarey at aphis.usda.gov	NCSU/CPHST	Raleigh	NC, US
Nadilla Gomez	gome0046 at umn.edu	Univ. Minnesota	St Paul	MN, US
Bill Hutchinson	hutch002 at umn.edu	Univ. Minnesota	St Paul	MN, US
Jason Beddow	beddow at umn.edu	Univ. Minnesota	St Paul	MN, US
Frank Koch	fkoch at fs.fed.us	NCSU/ USFS FHM	RTP	NC, US
Kurt Gottschalk	kgottschalk at fs.fed.us	US Forest Service	Morganton	WV, US
Rob Venette	rvenette at fs.fed.us	US Forest Service	St Paul	MN
Marla Downing	mdowning at fs.fed.us	USFS FHTET	Fort Collins	CO, US

List of Participants 2007

Jim Elenwood	jellenwood at fs.fed.us	USFS FHTET	Fort Collins	CO, US
Frank Krist	fkrist at fs.fed.us	USFS FHTET	Fort Collins	CO, US
Catherine Jarnevich	jarnevichc at usgs.gov	USGS	Fort Collins	CO, US
Joe Russo	russo at zedxinc.com	ZedX Inc	Bellefonte	PA, US
Erhard Dobesberger	dobesbergere at inspection.gc.ca	CFIA	Ottawa	Canada

Note @ symbols have been changed in email addresses in the table to thwart spammers.

Appendix 2. Template for CLIMEX Species Analysis

This template is provided as an example of model documentation.

Name:
Biology:
Distribution:
    CABI CPC Ref: etc
Comments and literature review related to fitting CLIMEX parameters
Distribution records used to estimate CLIMEX parameter values
Evidence for non-climatic limits to distribution
    Physical barriers
    Hosts
    Vectors
    Other species (competition, predation)
  Artificial environments (eg irrigation or glasshouses)

Stress indices
    Hot
    Cold
    Dry
    Wet
Climatic Constraints
    Obligate diapause
    Length of growing season
Growth
    Temperature
    Moisture
Results
    Goodness of Fit
    Independent Validation
    Source Risks
        Geographical
        Seasonal
    Destination Risks
        Geographical
        Seasonal
Discussion
References
Species Parameters Table