

Novel strategies for assessing and managing the risks posed by invasive alien species to global crop production and biodiversity

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Summary

International actions to combat the threat posed by invasive alien species (IAS) to crops and biodiversity have intensified in recent years. The formulation of 15 guiding principles on IAS by the Convention on Biological Diversity (CBD) stimulated the International Plant Protection Convention (IPPC) to review its role in protecting biodiversity. IPPC standards now demonstrate clearly that the risks posed by any organism that is directly or indirectly injurious to cultivated or uncultivated plants can be assessed and managed under the IPPC. Since the IPPC, unlike the CBD, constitutes an international legal instrument recognised by the World Trade Organization, greater protection from the introduction of IAS is now available. However, phytosanitary measures can only be enacted if they can be justified by risk analysis and we outline some novel strategies to improve the assessment and management of the risks posed by IAS, highlighting some of the key challenges which remain.

Key words: Biological diversity, invasive alien species, pests, risk analysis, risk assessment, risk management

Introduction

Although alien animal and plant invasions have been recognised as a major economic and environmental threat for more than a century, global activity has intensified in recent years with a “rising tide” in publications (Simberloff, 2004). Following the seminal work by Elton (1958), biological invasions have been the subject of numerous scientific studies, reviewed by, for example, Williamson (1996), Mack *et al.* (2000), Sakai *et al.* (2001) and Hulme (2003). Numerous high profile invasions have stimulated efforts to enhance the identification, assessment and management of the threats posed by invasive alien species (IAS) and several reviews have revealed the extent of the problem. Pimentel *et al.* (2001) estimated that 40% of crop pests in the USA, 30% in the UK, 36% in Australia, 45% in South Africa, 30% in India and 35% in Brazil are alien invaders. IAS may cause more than \$314 billion per year worldwide in damage and control costs (Pimentel, 2002).

Over the years, the methods used for assessing and managing the risks posed by alien pests of cultivated plants have tended to differ from actions taken against those alien species which threaten uncultivated plants. These activities are now coming together in the key area of risk analysis resulting in a number of mutual benefits (Schrader & Unger, 2003). Generic risk assessment schemes relevant to all IAS are now being constructed, enabling techniques for the assessment of entry pathways, the potential for establishment and the magnitude of economic, environmental and social impacts to

be developed together. We highlight the principal areas where important new developments are strengthening IAS risk assessment and describe some of the key problems that need to be tackled. The selection of appropriate risk management measures is also benefiting from this integration and we describe how some novel strategies are likely to enhance our ability to prevent IAS introductions and eradicate or contain outbreaks.

Background

Plant health and the International Plant Protection Convention (IPPC)

Plant health, also known as plant quarantine, has a very long history, see Ebbels (2003). Major continental invasions of pests such as the Colorado beetle, *Leptinotarsa decemlineata*, led to increasing international co-operation and the signing of the International Plant Protection Convention (IPPC) in 1951 (see FAO (1997) for the latest revision). Twenty-one International Standards for Phytosanitary Measures (ISPMs) have now been published by the IPPC. Although the IPPC has its own dispute settlement procedures, its standards are given additional authority due to their recognition by the Sanitary and Phytosanitary Agreement of the World Trade Organization (WTO-SPS) (WTO, 1994). Compliance with the IPPC and its ISPMs signifies compliance with the WTO-SPS.

Quarantine pests

Throughout the history of plant health, the principal approach has been to combine the identification and

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listing of those pests that can enter, establish and cause the greatest amount of damage in an area with the utilisation of appropriate measures to prevent their entry and establishment. Quarantine pests, defined as “pests of potential economic importance to the area endangered thereby and not yet present there, or present but not widely distributed and being officially controlled” (FAO, 2001*a*) are the fundamental component of plant health. Nations and trading blocs publish lists of quarantine pests in their legislation together with the measures required to ensure that potential pathways are free from these pests.

Pest risk analysis

However, both the IPPC and the WTO-SPS recognise that phytosanitary measures can be an important barrier to trade. They therefore stipulate that a pest can only be given quarantine status and measures imposed if, following a process of risk analysis based on international standards, it is found that a pest is able to enter, establish and cause significant and unacceptable economic, environmental or social impacts in the area under consideration. The international standards for pest risk analysis (PRA), ISPM2 (FAO, 1996) and the first revision of ISPM11 (FAO, 2003*a*), are thus fundamental to plant health. Commencing in the early 1990s, several years of discussions were required before they could be finalised and revisions were instigated almost as soon as they were published to reflect new developments and improving practice. While providing the structure and the elements to be included in a PRA, the standards do not themselves provide a decision support system that enables the analyst to work through a logical series of questions for each pest or pathway. To meet this requirement, regional (EPPO, 1997) and national (Baker *et al.*, 1999; APHIS, 2000; AQIS, 2001) pest risk assessment schemes based on these standards have been developed. They provide a framework for conducting analyses, ensuring that all factors are taken into account in detailed assessments or highlighting those of key importance when there is time for only a brief appraisal of the information available, e.g. when pests are detected in perishable imports (EPPO, 2002).

The Convention on Biological Diversity (CBD)

International agreement to tackle alien species that are not plant pests has taken much longer to achieve. Although some countries had published regulations to control the movement, import and release of alien species, e.g. Anon. (1981), it was not until the signing of the Convention on Biological Diversity (CBD) in 1992 (UNEP, 1992) that significant international cooperation occurred. Article 8(h) of the convention states that “each contracting party

shall, as far as possible and as appropriate prevent the introduction of, control or eradicate those alien species which threaten ecosystems, habitats or species”. To implement article 8(h), extensive work coordinated by the Global Invasive Species Programme (GISP) to document invasions and identify best practice (Wittenberg & Cock, 2001) prepared the way for detailed discussions at meetings of the CBD in 2001–02. The CBD discussions led to the publication of 15 guiding principles for the prevention, introduction and mitigation of impacts of alien species that threaten ecosystems, habitats or species (CBD, 2002). Six general principles are followed by three principles concerning prevention (border control and quarantine, information exchange and co-operation together with capacity building), two principles on introduction (intentional and unintentional), and four describing measures to mitigate impacts (mitigation, eradication, containment and control). In order to comply with the guiding principles, further action is being taken at regional and national levels. A European strategy has recently been completed (Council of Europe, 2003) while, in Great Britain, a review of non-native species policy, involving consultations with a wide range of interested parties (Defra, 2003) has been conducted. The government is now finalising its response to the review.

The CBD and the IPPC

IPPC standards and the CBD guiding principles on invasive alien species

The CBD guiding principles are non-binding and a review of the international regulatory framework for IAS (CBD, 2001) identified numerous gaps (CBD, 2004). In an attempt to strengthen the basis for action, the CBD examined other international treaties, including the IPPC, to determine the extent to which they constitute legal instruments relevant to IAS. Although the IPPC and the CBD have equivalent status and both put obligations on their contracting parties, only the IPPC through its dispute settlement procedure and its recognition by the WTO-SPS provides an international legal instrument. Accepting its potential wider role, the IPPC has reviewed its standards to determine their relevance to the guiding principles (Schrader & Unger, 2003). The following changes have been made or are being considered.

Plant health pests and invasive alien species

The key initial requirement was to determine the extent to which plant health pests are also IAS. As described by Schrader & Unger (2003), the IPPC (FAO, 2001*a*) reappraised the definition of a pest to include not only those species which directly consume or cause diseases to plants but also

those which are indirectly injurious to plants, e.g. through competition, or by harming those species which are beneficial to plants, such as biological control organisms, pollinators and detritivores, e.g. earthworms (FAO, 2001a, 2003a). This means that plant health pests are also “alien species whose introduction and/or spread threaten biological diversity” (CBD, 2002). However, the IPPC does not use and has no current plans to use terms such as “invasive” and “alien”, partly because it has no need for such concepts in its standards and partly because it finds inconsistencies in the definitions used and seeks clarification from the CBD (FAO, 2001a). This is reflected in the ongoing debate among invasion biologists on how to resolve differences of opinion over the meaning of many commonly used words such as invasive and alien (Richardson *et al.*, 2000; Colautti & MacIsaac, 2004). Efforts to harmonise the IPPC (FAO, 2002a) and CBD glossaries (e.g. IUCN, 2000) face a further challenge in that some key words, especially “introduction”, have very different meanings under each convention. The harmonisation of the IPPC and CBD glossaries is unlikely to occur in the short to medium term. Nevertheless, the IPPC Secretariat and the regional plant protection organisations (RPPOs) are intensifying activities in areas which are particularly relevant to the CBD, e.g. to ensure that standards also reflect the need to assess and manage the risks posed by pests which are indirectly injurious to plants.

Assessment of environmental impacts

The IPPC definition of a quarantine pest (FAO, 1997) only refers to its potential economic importance (see above), implying that pests of potential environmental importance cannot be considered as quarantine pests. To counteract this perception the IPPC has published an annex to the IPPC glossary (FAO, 2003b) that essentially states that economic impacts do include environmental and social impacts because they can be measured in economic terms.

The original detailed standard on PRA for quarantine pests (ISPM11) (FAO, 2001b) has also been extended to include more detailed guidance on the analysis of environmental risks (FAO, 2003b), e.g. by referring to the need to assess the potential impacts on keystone species, endangered species, plant communities and the structure, stability or processes of an ecosystem.

Assessment of indirect plant pests

PRA schemes were constructed primarily to analyse the risks posed by direct plant pests, i.e. those that directly consume or cause disease to plants, such as invertebrates and plant pathogens, and require host plants to be present for them to establish in the area under consideration. Adaptations to the schemes have therefore had to be made to assess indirect

pests, i.e. non-parasitic plants which cause harm to other plants through competition for light, nutrients and water and the predators or parasites of organisms beneficial to plants. Instead of host plants, invasive alien plants require suitable habitats and invasive alien predators or parasites require suitable prey or hosts. In addition to suitable habitats, many plant species also require other species at critical stages in their life cycle, e.g. pollinators, seed dispersers or root symbionts. With these changes, generic questions appropriate to all direct and indirect pests can be constructed, though notes may be added to assist the analyst when considering factors relevant to different kinds of pests. Thus, for a plant, evidence of its potential as a competitor will be demonstrated if, for example, it is known to form monospecific stands or if there are data on parameters such as canopy porosity (USDA, 2004).

Assessment of Intentional Introductions

The objective of the original PRA schemes was only to analyse the risks posed by unintentional pest introductions. Since many potential indirect pests, particularly plants, may be deliberately imported and released in the PRA area, the schemes have had to be adapted to analyse such intentional introductions. For these potential pests, since entry is certain, a detailed pathway analysis is not needed unless unintentional or illegal introduction pathways also exist. The assessment therefore focuses on the extent to which the organism can spread from the intended habitat, e.g. garden ponds, to unintended habitats, e.g. wild ponds and lakes. PRA schemes for intentional introductions can also be used to analyse the risks posed by biocontrol agents and alien pests imported for research purposes.

A Priori consideration of pest status

Until the requirement arose to adapt PRA schemes for indirect plant pests, there was no need for the a priori consideration of the pest status of an organism, since most plants are not pests. However, very large numbers of plant species have been traded and planted worldwide. Manchester & Bullock (2000) quote an estimate of 55 000 plant species or varieties planted in the UK, while the National Research Council (2002) states that 44 000 plant taxa are available for sale in the USA and Hayden & Whyte (2003) give a total of 19 100 for New Zealand. Since these plant species approximately follow the tens rule (Williamson, 1996), where 10% become established outside their intended habitat and only 10% of these become pests, it is logical to add an initial section to PRA schemes to determine (a) whether the organism in its area of current distribution (including areas where it has been spread by man) is a known pest or vector of a plant pest or (b) whether the organism has intrinsic attributes that

indicate that it could cause significant harm to plants. Although Pheloung *et al.* (1999) have been relatively successful in identifying undesirable traits common to invasive alien species in Australia and such an approach has been successfully adopted elsewhere, e.g. Hawaii, several authors, e.g. Williamson (1996), counsel caution. Williamson (1999) notes that surveys of the invasive alien flora of the UK and other areas showed that there are no clear intrinsic attributes for predicting invasive aliens, except that, if an alien species has already caused environmental impacts in one area, it is more likely to pose a threat in a new area. Moreover, there are many examples of species which have no important impact in their native range but are serious pests elsewhere where they escape from biotic constraints or find vacant niches (Mack *et al.*, 2000). Additional concerns are expressed by Smith *et al.* (1999) who note that when an event is rare, the “base rate effect” comes into play, with the probability of predicting an event accurately becoming dependent not only on the accuracy of the predictive system but also on the rarity of the event. Such considerations will need to be taken into account by the prior screening process which is now being recommended by the expert group revising ISPM2. This standard will provide a general introduction to the detailed PRA standards for all organisms which may be included in phytosanitary regulations.

Receptor risk analysis

PRA schemes were constructed to assess the risks posed by pests, entry pathways and the implications of policies (FAO, 2003a). Since they were primarily designed to assess the threats posed to crops, there has been no a priori requirement to consider other vulnerable receptors, e.g. a particular endangered plant species, community, habitat or ecosystem. To enable risk analyses of different receptors, some modification of the initial stage of the schemes is required to enable the analyst to make an initial assessment of the potential pathways and the invasive alien species that might be introduced into the areas where these species or community, habitat or ecosystems exist. When assessing potential impacts, consideration must also be given to the relative vulnerability of the receptors. Numerous attempts, summarised by Parker *et al.* (1999), Mack *et al.* (2000) and others, have been made to identify vulnerable habitats and ecosystems. Although isolated, fragmented, early successional, low diversity and highly disturbed habitats and ecosystems do generally seem more vulnerable, exceptions can always be found. The effects of invading species may also be cumulative with the community becoming more vulnerable (the invasional meltdown hypothesis) or more resistant to invasion (the biotic resistance hypothesis) (Parker

et al., 1999).

Risk management

While most of the modifications to the IPPC PRA schemes are required for risk assessment, some changes to pest risk management also need to be considered, primarily to regulate the sale, holding and release of intentional introductions. Measures to control deliberate illegal imports, e.g. via the Internet and the postal services, may also be required. Although intentional introductions of indirect pests can be regulated as quarantine pests, an alternative approach, using a black list (for prohibited species), a white list, (for permitted species) and a grey list (for those which have yet to be assessed) has also been adopted, e.g. Department of Environment, Transport and the Regions (1997), Randall (2004).

Generic risk analysis schemes

With the key modifications noted above, PRA schemes are being adapted to enable the analysis of the risks posed by all direct and indirect alien plant pests. Such adaptations are already being made to the EPPO risk assessment scheme and the first trials of the new generic scheme, e.g. with *Solidago nemoralis* (Schrader & Baker, unpublished), have been successful. Following recommendations in the Defra Non-Native review (Defra, 2003) work has started to extend this exercise further by constructing a generic risk assessment scheme for all IAS, not just for those that are injurious to plants. The CBD (2004) also supports such initiatives.

Risk Analysis: Novel Strategies and Challenges

Having shown above the effectiveness of the generic approach to risk analysis for all IAS that are injurious to plants, we consider how risk analysis procedures can be further enhanced. Although the process of risk analysis is divided into four sections – initiation, assessment, management and communication (FAO, 1999) – we concentrate on new developments in the techniques of risk assessment and risk management, the key components of risk analysis. We also discuss the influence of major future drivers and trends on risk analysis, since, following successful entry and establishment in an area, both the potential impacts and the management options will change over time.

Risk Assessment

Information sources, decision support systems and the management of uncertainty in risk assessment

Once an initial screening has been made to determine whether an organism is potentially harmful, ideally the risk assessor would then be able to turn to one reliable, current source containing all the information required to undertake the risk

assessment. Considering (a) the rapid speed at which new data are generated, (b) the extremely wide variety of information needed to conduct a risk assessment for IAS, especially data specific to the country of origin and the area under threat, (c) the fact that some data are almost always missing or incomplete, e.g. on trade pathways and pest population densities which cause economic/environmental injury levels, and (d) inevitable uncertainties, e.g. concerning future crop production practices and climate change, such a “one stop shop” will always be an impossible goal. Nevertheless, access to information sources for IAS is improving rapidly. For example, building on Smith *et al.* (1997), the Crop Protection Compendium (CPC) (CABI, 2004) contains full data sheets on approximately 2180 species of pests, diseases, weeds and natural enemies. Weber (2003) summarises information on 450 invasive plant species. Some global datasets of key factors to consider, e.g. interpolated climate data, are now available (New *et al.*, 1999) and, for countries such as the UK, meticulously compiled floras with distribution maps (Preston *et al.*, 2002) greatly simplify the search for host plants. To follow the rapid changes in pest distribution, pest alerts from NAPPO (NAPPO, 2004) and EPPO (EPPO, 2004a) yield important information for initiating and compiling PRAs and even web search engines, such as Google (<http://www.google.com>), may be helpful in unearthing information from the grey literature. However, it remains true that little is known of the biology and distribution of most phytophagous and disease causing organisms and unpredicted introductions will continue, e.g. the arrival and rapid spread of Essig's lupin aphid (*Macrosiphum albifrons*) throughout Europe during the 1980s (Bartlett, 1993a).

There has been little progress as yet in generating some components of the PRA automatically by downloads from relevant databases. However, the CPC (CABI, 2004) already contains components of the information required for a risk assessment in database form and also provides a mechanism for exploiting this by enabling the user to follow a structured commodity pest risk assessment scheme. This selects species that might be present in a commodity based on the pest distribution in the exporting country and the global host range. While useful, care must be taken because the association between a particular pest and host may not occur in every country and host ranges may exclude highly polyphagous species, such as *Bemisia tabaci*, which has been found on over 600 host plant species and may attack many more (EPPO/CABI, 1997).

As noted above, several national and international schemes have been created to assist the risk assessor by presenting the key elements to be considered in a logical sequence of questions based on international

standards. Although these schemes are exceptionally useful, assistance with the sources of information and the analyses required to answer each question is often limited. Responses on a sliding scale of words, e.g. low, medium, high (APHIS, 2000; National Research Council, 2002) or negligible, extremely low, very low, moderate, high (AQIS, 2001) or numbers, e.g. from 1 to 9 (EPPO, 1997), have to be assigned using expert opinion and backed up with a detailed written referenced comment. To assist the risk assessor and to enhance the consistency of responses between different species, examples of each response may be given. MacLeod & Baker (2003) attempted to assign examples for each 1–9 score in the entry and establishment sections of the EPPO scheme but found that it was possible to do this consistently only for the questions where assessments can be based on a numerical value, e.g. the numbers of consignments. Jablonowski (1994) and Theil (2002) show that discrepancies always arise whether experts are asked to provide numerical or verbal qualitative opinions.

Ideally, all questions would be answered quantitatively, with a probability value for assessing entry and establishment potential and with an economic value or a non-market index, e.g. a biodiversity index, for assessing impacts. However, this is rarely possible due to the very high levels of uncertainty and the responses to many questions, e.g. the extent to which natural enemies and competitors will prevent a pest from establishing, can rarely be based on anything other than expert judgement. Some questions, e.g. where the response is based on comparisons of the climate in a pest's current range with the climate in the risk assessment area, can be addressed quantitatively through climatic mapping programs, such as CLIMEX (Sutherst *et al.*, 1999). However, such programs should only be employed if the limits to the distribution of the organism and the role of climate in influencing this distribution are known.

Where information on a particular species is lacking, conflicting or incomplete, evidence from studies of previous invasions by similar species can be used, although this must be taken into account when summarising risk and deciding the strength of any measures proposed. The level of uncertainty can also be expressed by giving a range of responses, e.g. low to medium, rather than having to choose a specific word or number.

Pest categorisation

The pest categorisation stage is included in PRA schemes to ensure that risk analysts are not wasting their time with a pest which is neither invasive or alien and to obtain an understanding of the complexity of the PRA and the resources which may be required before embarking on a lengthy study.

For commodities and pathways it also provides an exceptionally useful method for selecting which of the many species that may travel with the commodity and along the pathway justify a detailed risk analysis. It is important to stress that risk analyses should be fit for purpose and do not have to be long and complex. At one end of the scale, commodity risk analyses can be very lengthy, e.g. the Australian risk analysis for the risks posed by the import of apples from New Zealand runs to 533 pages (Anon., 2004a). At the other end of the scale, a PRA can be conducted in just a few lines if the host plant of a direct pest is absent. For example, a monophagous warmth-loving cotton pest will not pose a risk to Northern Europe (Baker & Dickens, 1993).

Assessing the potential for entry

Although a variety of information is needed to assess the extent to which a pest will be able to remain viable through all the stages of the pathway from the origin to the PRA area, trade pathway and interceptions (detections in consignments) data are most important. Information on trade pathways and statistics is available for some sectors, e.g. international floriculture (Anon., 2003), but, even where available, data for host plants and produce that pose very different risks are often combined. Unfortunately, no readily available compilations of detection datasets exist and, for most purposes, specific enquiries for unpublished data have to be made. With some exceptions, e.g. Frey (1993), MacLeod & Baker (1998), National Research Council (2002) and Kiritani & Yamamura (2003), few attempts to analyse detection data have been made, even though, as Williamson (1996) and Kolar & Lodge (2001) have shown, the numbers of individuals moving along a pathway (propagule pressure) strongly influence the potential for establishment.

However, those countries with very stringent biosecurity legislation, e.g. New Zealand (Hayden & Whyte, 2003), and which require searches of all imports for IAS generate detailed comprehensive consistent detection data for some taxa, e.g. fruit flies, which can be used to analyse entry pathways. Over time, by comparing the number of detections with the number of outbreaks of IAS, a maximum pest limit can even be generated (Baker *et al.*, 1990). In most countries, however, detection data are influenced by so many factors that such analyses cannot be made and expert judgement is a primary requirement when assessing the potential for movement along the pathway. For example, even in the USA where quarantine procedures are very strict and 53 000 plant pests are intercepted every year, only 2% of all conveyances entering the country are inspected (National Research Council, 2002).

Assessing the potential for establishment

Baker (2002) has reviewed the data required and the techniques that can be used both for assessing establishment potential and predicting the limits to the distribution of quarantine pests once established in a country. The suitability of both the abiotic (climate, soils, etc.) and the biotic environment (hosts, natural enemies, etc.) must be considered together with factors intrinsic to the pest itself, such as its reproductive strategy and genetic adaptability.

Even when the responses of a pest to the abiotic and biotic environment are poorly known and little can be obtained from the literature concerning the intrinsic factors, some judgements can still be made. If the area of origin and the host plants are known, climates in the area of origin can be compared with climates in the area under threat and the distribution of host plants can be determined. Several models that predict potential distribution based on the climate in the current distribution of a species exist (Kriticos & Randall, 2001), e.g. CLIMEX (Sutherst *et al.*, 1999), and can be employed even when the responses of an organism to climate are unknown. However, while climatic comparisons are useful, care must always be exercised since many other factors influence distribution. Even where climate is known to be important, the climatic factors selected and the methods used for their measurement and analysis need to be relevant to the species concerned. Over reliance on climatic matching techniques and the apparent neglect of the importance of interactions with other species have led to a number of critical papers, e.g. Davis *et al.* (1998), Gaston (2003) and Hulme (2003). However, Hodkinson (1999) and Baker *et al.* (2000) have emphasised the important role played by abiotic factors, particularly in the early stages of an invasion (Ohgushi & Sawada, 1998) and in crops since few predators or competitors are likely to be present.

For some species, the assessment of the suitability of the abiotic and biotic environment for establishment may be complex. For example, some fungal species, e.g. *Tilletia indica* (Karnal bunt), not only require specific host plants but must also synchronise their life cycles with the phenology of the host plant. In addition, during the vulnerable growth stages of the host, climatic conditions must also be suitable. Jhorar *et al.* (1992) showed that for *T. indica* infection to occur in the Punjab, the Humid Thermal Index (HTI), defined as the mean afternoon relative humidity divided by the mean maximum temperature, must lie between 2.2 and 3.3 during the critical growth stages of wheat. Baker *et al.* (2004) extrapolated Jhorar's model to Europe, using bread and durum wheat models (Miglietta, 1991; Porter, 1993) to define the critical growth stage period and climatic data to calculate the HTI at selected meteorological

stations. Using splines (Hutchinson, 2001) and a geographical information system (GIS), the results were interpolated at low resolution to provide risk maps for Europe and at high resolution for the UK, Denmark and Italy (Tuscany, Puglia and Basilicata).

Lists of the intrinsic factors common to successful invaders, e.g. Pheloung *et al.* (1999), Williamson (1996) and Kolar & Lodge (2001), have many similarities. Assuming an IAS has entered, preferably in large numbers, and survived the ecological factors noted above to find a suitable niche, successful invaders are likely to be species which can disperse easily by themselves or with artificial assistance, reproduce quickly, develop rapidly and readily find mates or are parthenogenetic. They are also likely to be very adaptable, maintaining and evolving viable populations even at low densities following extremes of weather, shortages of food or pest management practices. While such factors do all play key roles in determining the success of invasion, exceptions can always be found (Williamson, 1996). Such lists work best when constructed for an area with similar ecological characteristics, e.g. Western Australia (Pheloung *et al.*, 1999), or for relatively homogeneous taxa, e.g. *Pinus* (Rejmanek & Richardson, 1996).

Spread

As Hulme (2003) concludes, although there have been significant recent advances in modelling local dispersal using reaction-diffusion, cellular automata, agents and metapopulation approaches, long distance movements, which are often assisted by man, are largely unpredictable. They are dependent on knowing, for example, how planting material is transported by the horticultural industry within and between countries. The invasion of the fire thorn leaf miner *Phyllonorycter leucographella* (Nash *et al.*, 1995) in the UK followed a simple model of concentric circular spread with long distance movements by the horticultural trade. The North American maize pest, *Diabrotica virgifera virgifera*, has also shown two mechanisms for spread from its original location in Europe, Belgrade Airport in 1992 (EPPO, 2004b). Natural spread has occurred at up to 80 km per year so that it is now found throughout most of the Carpathian basin, while it has also been trapped near at least 10 other airports in Italy, Switzerland, France, Belgium, the Netherlands and the UK suggesting an association with aircraft (EPPO, 2004b). While man-assisted long distance movements may be monitored by interceptions and predicted by trade patterns, modelling natural long distance dispersal remains a considerable challenge (Cain *et al.*, 2003). In addition, Shigesada & Kawasaki (2002) describe how the rate of expansion in the range of

invading species that display both short and long distance dispersal depends on the relative isolation of the satellite colonies that are created.

Assessing impacts

Following establishment and spread, the assessment of the magnitude of the consequences for plants in the PRA area ideally requires knowledge of the impacts of a pest in its current range, sufficient biological data to predict its population dynamics in the PRA area coupled with financial, economic, environmental and social data for the enterprises, ecosystems and people likely to be affected. While judgements can still be made when data are lacking by using expert opinion, e.g. by consideration of undesirable traits (Pheloung *et al.*, 1999; National Research Council, 2002) and evidence from related species, the impact assessment stage is recognised as the most challenging component of a PRA, particularly if a quantitative estimate is required. Even in relatively simple cases, such as a nursery growing one crop where the effects on gross margins can be calculated with a reasonable degree of accuracy, impacts still need to be predicted over time. While future costs can be estimated using published discount rates, forecasting how an increasing proportion of the industry may become affected as a pest spreads and the influence of new crop protection practices, market forces (both in and between countries) and climate change is much more challenging.

Estimating the environmental consequences of pest introductions is even more difficult. On the one hand, retrospective analyses by Williamson (1996) and others have shown that the few organisms which become pests have little in common apart from being known pests in their area of origin and being given ample opportunity to establish and thrive through multiple introductions. On the other hand, there is a multitude of methods for assessing environmental impacts. They can be assessed using environmental indices, e.g. by measuring changes in biodiversity indices, species abundance (especially of keystone species), extinction dynamics, biotic integrity (a combination of eight to 12 measurements representing community health) or indices representing the functional importance of each community member (Parker *et al.*, 1999). They can also be assessed using economic methods by calculating the direct use value, indirect use value or non-use/existence value of the organisms affected using a range of techniques including assessments of financial/economic value, willingness to pay, travel costs and hedonic pricing (Naylor, 2000).

Summarising risk assessment

The assessor, having answered each question or component of the risk assessment scheme with words or numbers on a sliding scale backed up by a

written comment, must then provide a summary of overall risk. In the USA scheme, assessors generate a cumulative risk rating by adding scores for six sub-elements which have been assessed as low (one point), medium (two points) or high (three points) (APHIS, 2000; National Research Council, 2002). In the Australian scheme (AQIS, 2001), an overall risk rating is obtained by using successive matrices. Although the EPPO pest risk assessment scheme (EPPO, 1997) asks the assessor to assign scores from 1 to 9 for each question, recognising that calculating an average score is inappropriate because questions are not equal in importance and cannot be adequately weighted, it gives no specific recommendation on the method to be used for summarising risk. Zhu *et al.* (2000) show how “mind-mapping” techniques together with mathematical transformations, to account for the greater impact of extreme scores, can allow scores to be combined. Whatever method is used, it must always be borne in mind that the outcome of a risk assessment must be provided in a form that can readily be understood by risk managers and stakeholders. Written summaries, highlighting the key components of the risk assessment together with an appraisal of the uncertainties, are thus still required to communicate findings to risk managers and stakeholders.

In addition to an overall summary of risk, maps outlining endangered areas where establishment is possible, primarily showing where climatic conditions are suitable and host plants are present, are increasingly being created using geographical information systems (GIS), e.g. Jarvis & Baker, (2001). Additional information can also be displayed, highlighting particularly vulnerable crops, uncultivated plants, communities or ecosystems to indicate where impacts are expected to be highest.

Risk management

The acceptable level of risk

Although there may be no consensus on how to summarise qualitative risk assessments, such schemes do have the potential to enable risk assessments for different species to be compared and priorities for risk management to be selected. Estimates of the potential for introduction should be kept separate from those for impacts because the former are probabilities and the latter are expressed as monetary values or environmental indices. Plotted on a graph (see Fig. 1) with impacts on the x-axis and introduction potentials on the y-axis, the risks posed by different species can be visualised together. Logically, quarantine pests will be found in the top right hand corner of the graph and the appropriate level of protection (also known as the acceptable level of risk (FAO, 2003a)), can be illustrated by drawing a curve with asymptotes along both the x- and y-axis. Those pests that lie above and to the

right of the curve pose an unacceptable risk. The risks posed by those to the left and below the curve can be described as acceptable, so, for example, even if the potential impacts are assessed as very high, when the probability of introduction is deemed to be negligible, the overall risk can be categorised as acceptable. In addition, such a graph could also be used as an indication of the severity of measures required to bring the risks to an acceptable level. However, while such graphs are useful for exploring the concept of acceptable level of risk and the stringency of risk management action, they have never been used to justify national policy or the strength of phytosanitary measures, primarily due to the difficulty in quantifying risk and formulating a consistent acceptable level of risk.

Prevention

The prevention of entry and establishment will always be the most important and cost effective method to combat IAS. While the simplest prevention mechanism is to prohibit the entry and movement of produce and plants, in order not to act as a barrier to trade, plant health uses a wide range of measures of differing severity to prevent pest introduction. Any management measures must be justified by risk analysis to avoid challenges under the WTO-SPS and conform to plant quarantine principles such as cost-effectiveness, feasibility, minimal impact, equivalence and non-discrimination (FAO, 1995).

In addition to the publication of standards for quarantine pests and phytosanitary measures, the IPPC has been extended to cover regulated non-quarantine pests (RNQPs). RNQPs are defined by FAO (2002c) as non-quarantine pests whose presence in plants for planting affect the intended use of those plants with an economically unacceptable

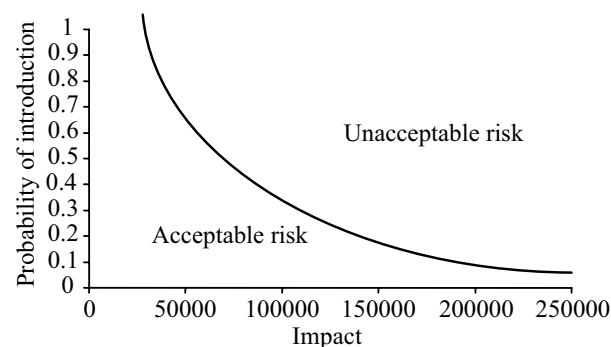


Fig. 1. A conceptual graph showing how the results from the assessments of introduction potential and impacts for invasive alien species can be displayed to compare the risks posed by different species. The x-axis scale is arbitrary. A line can be drawn to display the appropriate level of protection (also known as the acceptable level of risk) as defined by the World Trade Organisation.

impact and which are therefore regulated within the territory of the importing contracting party. Although RNQPs may already be widespread in a country, measures to prevent their import on plants for planting can be justified if, for example, this may have an economically unacceptable impact on an official certification programme. Despite the RNQP being an unfamiliar term, the concept of pests being controlled using certification schemes for propagating material has a long history (Ebbels, 2003). Although the declaration of RNQPs and associated measures are expected to strengthen the management of plant pest risks, with many widespread pests currently listed as quarantine pests being moved to this new category, most states are awaiting clarification of the concept and its application before adding RNQPs to their phytosanitary legislation.

A systems approach for pest risk management, along the lines of the Hazard Analysis Critical Control Point (HACCP) system used in the food industry, has been recommended (FAO, 2002b) to encourage states to move away from the utilisation of one strict measure. Systems approaches provide critical control points where independent management procedures can be monitored and controlled, with established criteria for acceptance/failure, known corrective actions taken when monitoring indicates that criteria are not met and with a review process to validate system efficacy and confidence. The European Community (EC) phytosanitary measures on natural or artificially dwarfed plants (EC, 2000) provide an example of a number of independent procedures that together keep risk to acceptable levels. Before the efficacy of new measures can be evaluated, they need to be tested. Within the EC, this may be undertaken through derogations, which are replaced by legislation if found to be successful.

EPPO (2001) provides a decision support system for selecting risk management measures, logically leading the risk manager through measures of increasing stringency taking into account key factors from the risk assessment. For example, the mobility of a pest can indicate whether pest freedom in the crop, the place of production or the area can be guaranteed and therefore utilised as a management measure. Prohibition, the most stringent measure, is given as the last resort. If no measures, either singly or in combination, have been identified which reduce the risk to an acceptable level, then it is likely that introduction cannot be prevented and phytosanitary measures are inappropriate.

With heightened international biosecurity and biodefence investment (Madden & Wheelis, 2003), it is expected that the intensive development of new technologies will provide new, more effective, quicker and less labour intensive methods both for validating the origin and tracing the movements of plant consignments and also for

detecting and identifying pests. Innovations in labelling, e.g. using radio frequency identification microchips, and analysis, using chemical and biochemical profiling, will provide greater assurance in certifying the area of origin of plants and detecting fraudulent mixing or substitution (Lachenmeier *et al.*, 2003). Visual inspection is increasingly likely to be complemented by alternative techniques. The principal developments are expected to be in detection within an entire consignment, decreasing the current reliance on sampling commodities such as potato tubers. The noses of dogs and rats have been used to detect both narcotics and quarantine pests and diseases (Nakash *et al.*, 2000; Otto *et al.*, 2002; Whitfield, 2002), but animals tire and need to recuperate, which means that there is scope for the utilisation of biosensors. Biosensors can detect volatiles produced by fungal and bacterial diseases and the technology is becoming available for use in harvested crops, e.g. in potato stores (De Lacy Costello *et al.*, 2002). The online biosensor detection of pathogens in gaseous and aqueous environments (Anon., 2004b) will have potential applications for pathogens, such as potato brown rot, which are spread by rivers or through hydroponics. Precision sound analysers may also be used to detect cryptic insects. The detection of unique acoustic signals is being studied for a range of insect pests (Mankin *et al.*, 2000; Chesmore & Nellenbach, 2001; Reynolds & Riley, 2002).

Outdoors, the use of airborne and satellite imagery in the surveillance for pests whose damage to plants creates a specific spectral signature, e.g. Johnson *et al.* (1996), is expected to improve the targeting of control measures (Smith & Thomson, 2003). Allen *et al.* (1999) predict how many of these new technologies, e.g. remote sensing, dogs and unmanned aircraft, may revolutionise pest surveillance and management by 2011.

There will be a continued drive to provide rapid diagnostic methods for use at points of entry and inspection. Portable real-time PCR (TaqMan) and lateral flow devices for detection of a selected range of quarantine plant pests at ports of entry by inspectorates show great potential (Schaad *et al.*, 2002, 2003; Ebbels, 2003; Ward *et al.*, 2004). The ability to distinguish viruliferous from non-viruliferous insect vectors (Boonham *et al.*, 2002) now enables this entry pathway to be monitored.

Although conventional taxonomic skills remain critically important, despite technological advances, the training, recruitment and funding for traditional systematics and taxonomy is becoming increasingly difficult. Advances in genomics and bio-informatics along with emerging technologies such as nano-technology and micro-fluidics are likely to revolutionise diagnostic laboratories, though they will need to have a sound taxonomic basis to

support phytosanitary regulations. In addition to providing greater speed, precision and reliability of identification, high-throughput and highly parallel capability will enable many more samples to be analysed quickly and simultaneously (Boonham *et al.*, 2003).

Over a longer time frame, perhaps within the next 15–20 years, the development and routine adoption of non-invasive or minimal sample preparation techniques for laboratory detection of a wide range of quarantine plant pests can be expected. This would require a scanning device based on perhaps nuclear magnetic resonance (NMR) or similar technologies, coupled to fast processors or neural-networks for data reduction. This would ideally lead to portable non-invasive scanning devices for the detection of a wide range of quarantine plant pests at ports of entry by plant health inspectors.

Eradication and containment

Eradication is the primary objective when combating new introductions or invasions of harmful, non-native pests. For practical purposes, it may sometimes be effective to have an eradication policy for certain high-risk situations, and a containment policy when eradication is very difficult to achieve but there is little or no possibility of further spread. Containment will remain an important management option, slowing pest spread to buy more time, since it offers the opportunity of a pragmatic policy for preventing the spread of a pest in situations where control is either difficult or impossible to achieve without severe disruptions to the status quo. ISPM9 (FAO, 1998) provides guidelines for eradication programmes and states that, in addition to surveillance and control, containment procedures should always be a component of eradication.

Techniques for eradication stand to benefit greatly from new landscape datasets that will enable the rapid mapping of key features in the area surrounding outbreaks. For example, a 25 m² resolution satellite derived map differentiates the UK into 16 land cover classes and 27 sub-classes (CEH, 2004) and a very high resolution vector dataset for Great Britain has become available (Ordnance Survey, 2004). However, field surveys will still be required, e.g. to locate the host plants for crop pests. The exploitation of new mobile computing, GPS, digital photography and telephone technologies will also greatly enhance the management of outbreaks, enabling the rapid transmission of key data between the field, lab and senior staff overseeing operations. GIS for mapping and predictions are invaluable in formulating contingency plans, containment and eradication campaigns (Liebhold *et al.*, 1998; Baker, 2001).

The increasing use of probabilistic approaches to risk assessment will add a further dimension to the

current use of more deterministic methods. Parallel computing and grid technology will allow a greater number of scenarios to be explored and enable cellular automata and multi-agent simulation models to predict pest spread over more realistic landscapes (Parry *et al.*, 2004). The development of more realistic phenology and population models linked directly to spread models and GIS will ensure that eradication methods are better targeted to the times and places where they are most effective (Regnière, 1996; Jarvis *et al.*, 2003).

Economic models are likely to become more widely employed to ensure that resources are efficiently employed. Used dynamically, cost-benefit analyses can monitor the eradication process to determine the time when a particular approach or the eradication effort itself is no longer cost-effective (Myers *et al.*, 1998). Contingency plans can be developed into decision support systems, guiding the eradication effort.

Chemical pesticides will continue to play an important role in eradication and containment for the foreseeable future, but, driven by environmental legislation, the general diminution in the number of registered products is expected to continue, as is the shift towards more environmentally benign alternatives. In addition, the risks of pest and disease resistance, already amply illustrated by many pest introductions (Bartlett, 1993b), will be increased by reliance on products with similar modes of action. For example, there are now three generations of neonicotinoid products, all of which act in the same way, i.e. by binding to nicotinic acetylcholine receptors (Wakita *et al.*, 2003). Certain sectors, e.g. minor crops, and applications, such as fumigants and soil insecticides, are likely to be most affected by the lack of effective products. However, the emergency use of pesticides to combat outbreaks of IAS can be authorised. Although there is also a vast source of largely untapped naturally occurring organisms with the potential to provide new agrochemicals (as well as other antibiotic and chemotherapeutic agents), problems involving formulation, speed of action and efficacy will continue to limit the number of products which are developed. The requirement for novel synthetic chemicals with a more benign environmental and health profile will also become increasingly important. For all of these compounds, commercial viability remains a key factor in determining whether they will be available for use against IAS.

Although biological and physical methods of pest control, e.g. solarisation, UV-absorbent films, flaming and physical barriers (Vincent *et al.*, 2003), are increasingly being used, chemical pesticides and crop destruction are likely to remain the preferred option for eradication. Biopesticides and, particularly, biological control agents are less

likely to drive populations to extinction and are more appropriate for use in containment and control (Hoddle, 2004), although inundation techniques have been applied successfully (Cheek, 1997). While the future of genetic modified crops is uncertain, where authorised, they may have an important role to play in containment and eradication. Sustainable alternatives, based on developments in plant genomics, microbial formulation techniques and the ecological understanding of trophic interactions, can also be expected. In all cases, development is likely to be most rapid in protected environments, e.g. glasshouses.

Drivers and Trends

Climate change and human population growth are expected to have a major and increasing influence on IAS introductions and impacts through a complex interaction of direct and indirect effects (Cannon, 1998). While predictions of the expansion in the areas endangered by warmth-loving IAS, such as *L. decemlineata* (Baker *et al.*, 1998) and the western corn rootworm, *D. virgifera virgifera* (Baker *et al.*, 2003), can be predicted using climate change scenarios, changes in crop production methods, the cultivation of novel crops, markets, trade and plant health policy cannot readily be forecast, although they are very likely to present many additional opportunities for new and existing IAS to enter, establish and cause impacts. Levine & D'Antonio (2003) analysed trends in species introductions from different sources and found that these followed classic species accumulation curves. While few new IAS can be expected from long term trading partners, new trading partners with similar abiotic conditions, e.g. China (National Research Council, 2002), may yield and receive (Yan *et al.*, 2001) many new IAS. There is an increasing demand for audits, peer reviews and stakeholder consultations for PRAs and plant health policy in general. Coupled with the enlargement of trading blocs, e.g. the European Union, the overall effect of this demand is likely to slow down the preparation of PRAs and, in order to take into account a wider range of views, lead to a more precautionary approach to phytosanitary regulation.

Conclusions

This review illustrates the important contribution which plant health in general and plant health PRA procedures in particular can play in developing novel strategies to identify, assess and manage IAS. Not only does the IPPC act as an international legal instrument with its standards recognised by the WTO, the long history of plant health also provides a wealth of experience that can be

applied to all IAS. Although there is now an agreed logical framework for PRA and a slowly growing literature of best practice, many difficulties remain, particularly with the management of uncertainty when faced with gaps in knowledge. Although certain procedures can be adopted in such situations and expert judgement may be sufficient to justify measures (Cannon *et al.*, 1999), quantifying potential impacts remains fundamentally difficult (Parker *et al.*, 1999). Even if estimates of current damage can be confidently predicted, forecasting how impacts will be affected by changing climates, markets, trade patterns, transport methods, etc. is extremely challenging. Reliable IAS risk analysis therefore remains a long-term goal and failures to prevent new introductions are probably inevitable. However, much can be gained by increased collaboration and the setting up of an International Plant Health Risk Assessment (PHRA) list server (PHRA-L), uniting pest risk analysts worldwide, is a very encouraging development. The expansion of PRA procedures from direct to indirect plant pests and even to all IAS, is also likely to be of benefit to all IAS risk analysts.

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