PREDICTION AND PREVENTION OF PLANT INVASIONS – WHAT IS FEASIBLE?

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ABSTRACT

Literature on plant invasion is reviewed. There has been a degree of success in explaining why some plants are more invasive than others within certain groups of species (e.g. pines, woody plants) and a wide range of characters has shown correlation with invasiveness in individual surveys. Few characters have proved to be of consistent predictive value but one of the most useful appears to be weedy/invasive behaviour elsewhere. Based on these types of data, various models have been proposed, to assess the risks from introduction of plant species, and one of these has been officially adopted in Australia. This type of model has utility when applied to limited numbers of individual species, e.g. those proposed for introduction as crops or ornamentals. It is less useful for identifying potential invaders among the large numbers of the world's weedy (and previously non-weedy) species which might be introduced accidentally. A project to address this problem for USA is described which resulted in a list of over 600 potential invasive weeds which could not be readily assessed individually in such a detailed manner. A procedure for ranking these species is under development, so that the highest-ranking can then be subjected to detailed assessment. It is feared, however, that many potential invasives will still have been overlooked. Of over 100 troublesome alien weeds in USA, only 1 in 4 had proved seriously weedy in agriculture elsewhere and many had not been recorded as weeds at all, in any context. Some of the reasons why weeds become more invasive in a new environment are reviewed, and it is concluded that the characteristics involved, in the species and in the invaded habitat, make their invasiveness largely unpredictable, or only predictable with enormously increased knowledge and research. Thus if weeds are known to be aggressive elsewhere it is feasible to predict the likelihood of their invasiveness when introduced, but there will be many other invasions which defy prediction for the foreseeable future.

Once a species is predicted to be invasive and listed as a prohibited species under quarantine regulations, chances of introduction can be very much reduced. The mechanisms for preventing the entry of listed species are briefly reviewed. It is almost inevitable, however, that there will still be many unpredicted, un-prevented invasions, some due to accidental introduction but especially from plants deliberately introduced for cultivation, often after a long lag phase. The continuing difficulty of predicting these occurrences means that education and awareness are immensely important, to ensure that invasive behaviour is recognised early and that there is a policy and mechanism for rapid response and containment and/or eradication.

INTRODUCTION

Invasion by non-native species has been occurring for millennia but has been of steadily increasing concern over the past few decades. This concern arises from the realisation of the costs of these invasions, not only to commercial agriculture, but also and most particularly to natural vegetation and wetlands (e.g. Pimentel *et al.*, 2000). 'Invasive alien species are thought to be the biggest threat to biological diversity after habitat destruction' (Klaus Toepfer of UNEP speaking in Montreal, on 21 May, 2001, International Day for Biological Diversity).

There has been a plethora of conferences and books on the topic of invasive species, many originating from the IUCN (International Union for Conservation of Nature) Scientific Committee on Problems of the Environment (SCOPE) whose project 'Ecology of Biological Invasions' began in 1982 (e.g. Groves & Burdon, 1986; Drake *et al.,* 1989; Mooney & Hobbs, 2000). Another series of meetings, specifically on invasive plants has been held under the title 'Ecology and management of alien plant invasions' (EMAPi), the most recent, 6th International Conference being held in Loughborough in September 2001.

International agreements of relevance to the problem of invasive species include the International Plant Protection Convention (IPPC) which is responsible for harmonising the phytosanitary regulations aimed at controlling spread of pest species, and the Convention on Biological Diversity (CBD) which undertakes to 'prevent the introduction of, control or eradicate those alien species which threaten ecosystems, habitats and species'. Most countries are signatories to both these conventions.

It could be thought that most of the worst weeds of the world are already cosmopolitan and there are few places left for them to invade. It is worthy of note, for instance, that of the 200 species covered in 'The World's Worst Weeds' (Holm *et al.,* 1977) and 'World Weeds: Natural Histories and Distribution' (Holm *et al.,* 1997), well over 90% are already recorded in the wider USA, indicating the extent to which USA has already been invaded, especially by the mainly agricultural weed species covered in these two volumes. But the content of the 2 volumes in question was almost certainly influenced by the mainly North American authorship and there are many countries where these 200 species are less well represented; and equally there are many species, serious in other countries but not yet in USA, especially in non-agricultural situations. There is then the question – if species have not already invaded, why should they do so now? There are many good answers to this question which can include the increased movement of people, equipment and materials, changes in trading patterns and trading methods (including the internet), changes in volume and means of transport, global warming, raised carbon dioxide levels, etc. And there is no shortage of recent examples of new invasive weed problems. In UK, the aquatic weed *Hydrocotyle ranunculoides* has become an acute problem since escaping from cultivation in 1990 (Harper, 2000). Nairn *et al.,* (1996) comment that 'at least 290 plants have become naturalised in Australia during the past 25 years and that the rate of naturalisation is increasing', though how many of these have become 'invasive' is not stated.

While it is to be hoped that the worst plant invasions are now in the past, how confident can we be that awareness and regulation are now sufficient to prevent further damaging introductions? This paper attempts to assess the feasibility of limiting the risks of further invasion to an acceptable level.

PREDICTION

What makes plants invasive?

Among the abundant literature on invasive weeds there have been many efforts to define the characteristics of invasive plants and predict which are most likely to become new problems.

Newsome & Noble (1986) applied cluster analysis to a set of invasive/noxious plants in Victoria, Australia and concluded that there are many different 'suites' of characteristics involved in successful invasion, depending on the particular species/habitat combination. But they did propose 'the following eco-physiological types of successful invaders'. These included: 'Gap-grabbers' – early germinators (including biennials) with fast initial growth in spring, early maturing and/or drought tolerant and with a dormant seed bank; 'Competitors' – species with tall leafy shoots and/or deep root systems; 'Survivors' – species with extended or indefinite longevity; 'Swampers' – species with mass germination of seedlings.

A general appraisal of the attributes of invasive plants by Noble (1989) concludes that 'highly generalised classifications or lists of preferred characteristics are of little help in recognising potentially invasive organisms', but 'Short distance dispersal mechanisms will increase the probability and rate of invasion', and 'Species with high reproductive output........have a high invasive potential'. Also 'The properties of the invaded habitat are a critical determinant of the likely success of any invader' and 'any system (for prediction) will require both studies of the species in its native habitat....... and studies in the target habitat....'.

Roy (1990) provides a list of characteristics of the 'ideal' invader but goes on to note that such a list is of little value for prediction. He echoes the need to consider the recipient habitat and suggests characterising invaders by type of habitat.

Rotherham (1990), considering the characters responsible for the invasiveness of *Rhododendron ponticum* in UK, concluded that the following are of critical importance: prolific production of viable, easily dispersed seeds; capacity for winter photosynthesis; ability to tolerate severe shading; mycorrhizal infection enhancing growth on poor soils; low herbivore pressure, probably due to phenols in tissue; vigorous growth helping to crowd out competing plants; site disturbance allowing establishment.

Richardson *et al.* (1994) concluded that for *Pinus* spp., the three most important factors in separating invasive from non-invasive were: small seeds; short juvenile period; and short intervals between large seed crops. Other factors of more local significance included: relative resistance to browsing and resistance to pests and diseases; longevity; and large areas of planting. Many characters of the habitat to which they are introduced are also important. Rejmánek & Richardson (1996) further refined these initial conclusions and devised an equation based on the three major factors. See also Richardson (1997).

In a paper discussing the importance of *Lonicera maackii* in USA, Luken & Thieret (1996) comment 'species with high and consistent seed output, poorly developed seed dormancy, rapid germination and ability to germinate at low temperatures and low light may be most likely to spread rapidly across a wide range of habitats. Of course these life-history traits must be examined also within the context of environmental conditions common to the most frequently invaded systems.'

Reichard & Hamilton (1997) applied discriminate analysis to a range of characteristics of 114 species of N. American woody plants, some weedy invasives, some not, and also generated Classification and Regression Trees (CART) to test whether it was possible to predict invasiveness based on the attributes measured. The most helpful characters, used in the decision tree were – invasive elsewhere?; native/non-native to N. America?; rapid vegetative spread?; inter-specific hybrid?; in a family or genus known to be invasive in N. America?; length of juvenile period?; seeds require pre-treatment for germination? This system correctly identified 85% of 204 invasive species, suggested further analysis of 13% (27 spp.) and allowed 2% (3 spp.) through. Applied to 76 more serious 'pest invaders', it identified 88%, suggesting further analysis of the remaining 12% and allowing none through. It was less accurate in identifying non-invaders, accepting less than half, rejecting 18% (16) of the 87 total and suggesting further analysis of 36%. The authors admit that this model is not necessarily applicable to a broader range of species, especially annuals. And although it is not a quantitative system suitable for the ranking of a range of species, it does suggest placing relative weight on: invasiveness elsewhere; early maturation; seeds not requiring pre-treatment; rapid vegetative spread.

Maillet & Lopez-Garcia (2000) attempted to define the characteristics which could be used to predict the invasiveness of introduced American species in France and concluded that, for the 78 species surveyed (now either 'common' or 'rare' as crop weeds), the 5 most reliable predictors of 'commonness' were: date of introduction (pre-1900); weed status in America; germination period (summer); month of onset of flowering (July/August); and end of flowering (after August). A model based on these 5 criteria was 87% accurate in its prediction. These authors do, however, conclude that 'In spite of the many studies on invasive weeds, the prediction of invasive success still remains a difficult and imprecise exercise. There is no general predictive theory of invasiveness and we are far from reaching a good overview of invasive mechanisms.......However, the most important criterion for predicting weed status in the invaded area is the weed status in the original range.........In comparison with particular groups of species such as pines......., weeds as a whole possess a high diversity of strategies which prevent us from establishing simple predictive models.'

Reichard (1997) summarised the various factors/predictors used in 6 different predictive models (3 specifically related to woody spp.). These are tabulated below, together with the number of studies in which they proved either useful or not useful.

	Useful	Not useful
Ecological attributes:		
Bioclimatic match	1	0
Climatic/latitude range,	1	0
Problem in native range	1	0
Native congeners	0	1
Congener a problem in introduced range	1	0
Invasive elsewhere	3	0
Fire tolerance	1	1
Degree of serotiny	1	0
Mycorrhizal associations	0	1

Species attributes:

Plant height	0	2
Plant longevity	0	1
Leaf longevity	1	0
Leaf area	0	1
Vegetative reproduction	2	1
Reproductive system	1	0
Self-incompatibility	0	1
Polyploidy	0	2
Juvenile growth rate	4	0
Flowering period	1	1
Pollination mechanism	0	1
Fruiting period	0	1
Seed production	2	1
Seed bank longevity	2	0
Seed dispersal	2	1
Seed size	3	1
Seed-wing index	1	1
Seed germination requirements	1	1
Percent germination	0	2

The differing conclusion from different studies emphasises the shortage of really reliable characters for predicting invasiveness but does reinforce the importance of weediness elsewhere, juvenile growth rate, vegetative spread, and the complex of seed size, production, longevity and dispersal. This review is far from complete or conclusive, but indicates the wide range of methods and opinions that have been applied to the process of predicting invasiveness. Most papers do also have a caveat, warning of the difficulties and uncertainties of the process and the need to consider the issue according to the habitat threatened.

Models for predicting invasiveness

A number of systems have been developed as an aid to decision-making for plant quarantine purposes. The most highly developed methods are from USA and Australia:

1. Hazard (1988). This system is aimed particularly at the risks from deliberately introduced species (e.g. as crops, fodder or ornamentals). It is based on a series of questions, each of which, if answered in the positive, incurs a score ranging from 20 (for any aquatic, or history of being a 'major' weed elsewhere), through 10 points for plants with spines or spiny fruits, or being closely related to known serious weeds, 8 points for being poisonous (or allergenic etc), having vegetative reproduction or seeds dispersed by wind, mammals or machinery, down to 5 points for being spread by water or birds. Only 20 points are required for outright rejection; 12-19 require further examination and only those scoring less than 12 are acceptable.

2. Panetta (1993). This has a very simple sequence of questions requiring yes/no answers, the 'wrong' answer resulting in rejection, the 'right' answer (or 'not known') leading on to the next, or to 'evaluate', starting with

(1) 'weed elsewhere (under same climatic conditions)?' (based on Holm *et al.*, 1979, but not clear what level of importance is critical);

(2) 'free floating aquatic';

(3) 'noxious characters' (e.g. poisonous or otherwise harmful to animals including man; spiny or with burrs; climbing; parasitic);

(4) 'congeneric weed' (if so, evaluate);

(5) 'multiple modes of reproduction' (if so, evaluate);

(6) 'multiple modes of dispersal' (if so, evaluate).

3. Pheloung (1995). This system which has been adopted officially by AQIS (Australian Quarantine and Inspection Service) is based on a series of 49 questions in 3 groups, the answers leading to varying positive, zero or negative scores. Not all questions need to be answered but a minimum number in each must be (2, 2 and 6 in sections A, B, and C).

Section A relates to domestication/cultivation, climate and distribution and weediness elsewhere;

Section B relates to undesirable traits; and

Section C relates to plant type, reproduction, dispersal mechanisms and persistence attributes.

Scoring of some questions depends on answers to others and the scoring is somewhat complex. Highest adverse scores are 5 for any aquatic weed and 4 for weediness elsewhere (not too clearly defined). A final score over 6 requires rejection. Any other positive score (1-6) requires further evaluation. A zero or negative score is acceptable.

4. USDA Weed Risk Assessment Guidelines version 4.1 (USDA, 2000). These 'Guidelines for Qualitative Assessment' are based on 5 elements:

habitat suitability (0-1, 2-3 or at least 4 climatic 'hardiness' zones in USA)
dispersal potential (based on reproductive potential and/or other characters)
economic impact (affecting crop yield, commodity value and/or loss of market)
environmental impact (types of impact on vegetation, health etc)
entry potential.

Each of the first 4 questions leads to a ranking score (maximum 3) and the summation of these to a 'cumulative risk element score', a total of 9-12 indicating high risk, 6-8 medium risk and 2-5 low risk. These categories lead to 'risk scores' of 3, 2 and 1 respectively. Scoring for entry potential involves quantifying the likelihood of entry, survival, detection and establishment via a range of different possible routes. This process leads again to summary scores of 3, 2 or 1 for high, medium and low risk of entry which is added to the cumulative risk score. Added scores of 5 or 6 give a high 'pest risk potential'; 3 or 4 to medium; and 2 to low potential.

5. Champion & Clayton (2000). This is a weed risk model for aquatic weeds in New Zealand, based on 13 questions relating to: environmental versatility, competitive ability, dispersal, capacity to cause obstruction, damage to natural ecosystems, potential NZ habitat not yet occupied, resistance to management, weediness in different aquatic/wetland habitats, seed production/persistence, vegetative spread, weediness elsewhere, maturation rate, and 'other undesirable traits' (including health risks, weediness in terrestrial situation). Each of these is scored on a scale of e.g. 0-10, or 0-3 or 5 for the final 5 questions. This system was compared on a range of species with the standard Pheloung model (3. above) and while the latter satisfactorily identified all noxious species as undesirable it was inferior in terms of quantitative comparison of risk.

The three Australian systems (1, 2, and 3) were compared by Pheloung (1996) for their potential performance using a set of 370 species classed as serious weeds, minor weeds and non-weeds in Australia, as agreed by a panel of local weed scientists. Each system successfully identified the serious weeds and most minor weeds were also rejected. Most non-weeds were not rejected (about 90% accepted by systems 1 and 3 but 26% rejected by the Panetta system). Some 'useful' species were also rejected by all three systems. The proportion of species requiring evaluation were approximately 40%, 20% and 30% for 1, 2 and 3 respectively. Pheloung concludes that 'The WRA system (i.e. 3) performed best overall although, in many respects the Hazard system (1) performed similarly. However, the Hazard system has the disadvantage of making no provision for lack of information pertaining to the questions, which meant that in many cases a recommendation to accept could not be made. The Panetta system was the most severe, largely due to the more rigorous treatment of the weed elsewhere question.'

A further analysis of the performance of system 3 by Smith *et al.* (1998) concludes that 'the accuracy depends somewhat on the sources used to assess weed status of the plants tested. Furthermore the WRA is rather inaccurate at predicting weeds among the Poaceae and Fabaceae, which, being desired for pasture improvement, will provide many of the future candidate species for introduction to Australia.' They also criticise aspects of Pheloung's 1996 comparison, especially his use of a panel of experts to classify weeds into serious, minor and non-weed. Some species described in the literature as weeds of conservation areas were classed as non-weeds in Pheloung's study. Using the literature rather than local experts to define 'weediness' reduced the overall accuracy of system 3 from 85% to 76%.

Can we predict?

On the basis of the above review:

1. Can we predict whether an individual species will/will not become invasive?

2. Can we predict which alien species (of all possibilities) are most likely to become invasive?

The various methods mentioned above, especially that used in Australia, have been well appraised and found to have considerable value in respect to question 1, i.e. when considering individual species, most often when they are proposed imports for agriculture or horticulture. The same system has been adopted by New Zealand (Williams *et al.*, 2000). To Question 1 we might therefore give a qualified YES, though the Pheloung and other systems risk exclusion of harmless species and also require 'further evaluation' in 20-40% of cases. The nature of this further evaluation is not clear.

Question 2 proves very much more difficult, as I have found in the course of a project to advise U.S. Department of Agriculture (USDA) what are the 15 species most likely to become invasive species in the greater USA (including Alaska, Hawaii, Guam and Puerto Rico) in the future. With over 250,000 plant species to choose from, there have to be some criteria for initial selection. In the light of a number of the above studies emphasising 'weediness elsewhere' as a major predictive character, I chose to use the 'Geographical Atlas of the World's Weeds' (Holm *et al.*, 1979) as my starting point, selecting all those (approximately 450) species not yet naturalised in USA but classified as 'serious' or 'principal' weeds in at least one other country. As noted above, this includes very few species from the 200 'world's worst weeds' as defined in Holm *et al.* (1977) and Holm *et al.* (1997). To offset the bias of Holm *et al.* towards purely agricultural weeds, I added a further 200 species from various sources listing plant species already occurring as serious 'environmental' weeds in other parts of the world or otherwise of concern as invasive species in natural vegetation. These sources included Binggeli *et al.* (2000) in which a wide range of woody species is classified as 'highly invasive', 'moderately invasive' or 'possibly/potentially invasive' in tropical and subtropical regions. These are all 'environmental' rather than crop weeds. Other sources included lists of noxious or 'declared' weeds in South Africa, Australia and New Zealand.

The resultant list of about 650 species has been entered into a Microsoft Excel database and as many species as possible scored for a range of biological characters which could influence their invasive potential (e.g. rhizomatous, climbing or aquatic behaviour, small and readily dispersed seeds) as well as for their distribution and seriousness as weeds elsewhere (from Holm *et al.,* 1979 and other sources). The total from this initial scoring provided a ranking order, allowing more detailed scoring to be restricted to the top 150 species. Further biological characters were entered, contributing to a new 'invasive potential' (A). Other characters were scored and totalled under 'damage potential' (B), including competitive, toxic and other damaging aspects; 'geographic potential' (C), a measure of the range of geography or ecologies likely to be invaded; and 'entry potential' (D) assessing the likelihood of entry and establishment in the country, whether accidental or deliberate. A 'final' ranking was then based on the product of A x B x C x D. A product is used rather than an additive formula on the grounds that each of the four potentials are largely independent Thus, however large the invasive potential A, if any of the other potentials are zero (no common geography/ecology; no chance of causing damage; no chance of entry) the species cannot constitute a threat.

The system that I have developed cannot be regarded as especially reliable or definitive, and much further deliberation is needed to allot suitable weighting to different characteristics. As it stands, the 'entry potential', factor D proves especially critical and results in the top 30 species in the ranking all being plants imported deliberately for cultivation, usually as ornamentals. Most surveys conclude that the majority of alien invasives were introduced deliberately, rather than arriving accidentally and it is almost certain that some of the most serious of future invasive weeds will include some species already in USA, being cultivated as ornamentals or for other purposes. The literature repeatedly confirms the importance of this source. Mack (1991) catalogues the history of the seed trade as a source of many of the longer-established invasive species, including *Berberis vulgaris, Eichhornia crassipes, Isatis tinctoria, Cannabis sativa, Eleusine indica, Lysimachia nummularia, Lythrum salicaria*. Other examples from Cox (1999) include *Pueraria lobata, Lonicera japonica, Ulex europaeus, Cytisus scoparius, Gypsophila paniculata, Ipomoea aquatica, Rosa multiflora, Peganum harmala, Eleagnus umbellatus* and *E. angustifolia*. Gregg & Westbrooks (2001) have recently stated that about 85% of all invasive plants in USA are intentionally introduced. Cox also comments that 'about 4275 species of exotic flowering plants are in cultivation in Hawaii, of which about 908 have become invasive in wildlands'. The number of species in cultivation in New Zealand is estimated at about 18,000 (Williams *et al.*, 2000).

Although most introduced species fail to naturalise or become invasive when first cultivated there are many examples of those which 'take off' and become invasive many years or decades after their original introduction (see Kowarik, 1995 and others, reviewed by Binggeli, 2001). Examples include *Casuarina equisetifolia* and *Schinus terebinthifolius* which were each introduced to Florida in about 1900, but were not noticed in the wild until over 50 years later and only perceived as invasive problems after 65-75 years. Another is the invasive tree *Maesopsis eminii* which was introduced to East Africa in 1913 and noticed in the wild 14 years later, but only recognised as a serious weed of forests in the Usambara Mountains of northern Tanzania 65 years after its original first introduction. Some reasons for these time-lags (or apparent time-lags) were postulated by Hobbs & Humphries (1995), including genotypic adaptations, change or disturbance of the habitat, or simply human failure to recognise the steady exponential growth of a species until it is widespread. Whatever its causes, the occurrence of a lag-phase phenomenon means that any species cultivated over a period, has increased chances of becoming invasive, relative to any newly, accidentally introduced species, while cultivation itself (via selection) is likely to further increase its invasive potential. For these various reasons, any plant known to have weedy or invasive tendencies in other parts of the world should be treated with some caution and suspicion, even if it has apparently been safely cultivated for some time.

I am therefore satisfied that the probability of these deliberately introduced species (all with a history of weediness elsewhere) becoming invasive is indeed greater than that of species which have yet to find their way into the country accidentally. USDA preferred that my 'top 15' excluded such cultivated species, so that they could be immediately considered for regulatory listing but they are fully aware that plants in cultivation do also have to be very seriously considered.

I am less satisfied that the top 15 species (non-cultivated) that have emerged from my ranking system present any very significantly greater threat than the remaining 600 or so, and for this reason I do not list them here. This is partly because I lack sufficient data on their biology and ecology and especially, the information from which to quantify their chances of accidental entry via importation of agricultural or other produce. This requires detail of importation statistics, routes, methods, quality control etc., which have not been readily available. However, there are also many other factors which cannot be measured or known, for the large number of species involved.

Appraisal of the species that have already become invasive in USA emphasises the difficulties involved in our attempts at prediction. An analysis of some 123 alien species that are regarded as invasive problems in USA showed that only 27% of these would have been selected on the basis of occurrence as serious or principal weeds elsewhere, as recorded by Holm *et al.* (1979) while 22% were not listed by Holm *et al.*, at all. Much of this discrepancy is due to the agricultural bias of Holm *et al.*, but there are also many among the weeds of natural habitats which had similarly failed to show this type of invasiveness elsewhere. This highlights the problem that plants can show invasive behaviour apparently *de novo* following introduction to a new territory.

Explanations for this behaviour include escape from natural enemies, as might apply to *Eichhornia crassipes,* and is presumed to be largely responsible for the success of *Acacia longifolia* in South Africa and *Chrysanthemoides monilifera* in Australia, where, in each case, seed production is vastly greater than in their native Australia and South Africa respectively, where it is severely reduced by predation (Weiss & Milton, 1984). Unfortunately without detailed knowledge of the natural enemies of large numbers of currently non-weedy species, it is impossible to predict which may be the unexpected invasive weeds of the future.

An even more difficult phenomenon to predict is the greater potency of allelopathic effects against companion species in the introduced range, as demonstrated by *Centaurea diffusa* in N. America. Callaway & Aschehoug (2000) show that companion species in the native range have evolved resistance to these allelopathic effects and are able to prevent *C. diffusa* from becoming dominant, while those in the introduced range are suppressed and allow the weed to flourish.

In many other cases, the explanation of invasiveness is far from clear. In the case of *Lythrum salicaria*, there is evidence that it has demonstrated 'evolution of increased competitive ability ' (EICA) following its introduction to N. America about 200 years ago (Blossey & Nötzold, 1995; Willis *et al.*, 1999). This has not been demonstrated in other species studied so far (Willis *et al.*, 2000) but seems quite likely to occur over time especially after prolonged cultivation and selection for vigour.

I fear that for these and many other reasons, a significant proportion of the potential invasive weeds of the future are NOT being identified by my process, even among the full list of 650. These are just the most readily predicted. Many others are virtually unpredictable at present or could only be predicted on the basis of extremely detailed survey and research on thousands of further species. Such research might be effective and worthwhile if it focuses on a specific ecology but I believe any attempt to select ALL the species most likely to invade a large region such as USA will inevitably be somewhat unsatisfactory. At the more local level there is scope for the use of the latest climatic and plant mapping programmes to provide a much shorter list of the species best adapted to invade that area. Cornutt (2000) used this approach to predict regions of Australia with potentially high numbers of plant species that are climatically pre-adapted to south Florida, USA. Other systems being developed in USA include that by the North American Commission for Environmental Cooperation (NACEC) (Gregg & Westbrooks, 2001).

Further research of this type and steadily improved data bases of information about the world's flora will gradually improve our ability to predict invasions, but I believe this will be a slow process.

PREVENTION

Can we prevent?

Prevention is generally based on legislation, backed by inspection procedures. The legislation may declare a range of species as prohibited, but there are constraints. Guidelines to phytosanitary regulation are provided by the International Plant Protection Convention (IPPC) in the form of International Standards for Phytosanitary Measures (ISPMs). These are being designed to conform as fully as possible to the WTO's Agreement on Sanitary and Phytosanitary Measures (generally known as the SPS Agreement). The SPS Agreement requires that quarantine policy should be the least trade-restrictive available to achieve the country's 'Appropriate Level of Protection' (ALOP) (Anderson *et al.*, 2001). Hence quarantine restrictions are expected to be based on very thorough pest risk analysis, justifying any exclusion or prohibition on thorough economic grounds. In the case of potential pests of agriculture, possible costs of crop loss and/or costs of control have to exceed potential value of the species if imported and cultivated or used in some other way. In the case of species threatening natural environments, especially if they also have value as ornamentals, the economic arithmetic is inevitably more difficult (Mumford, 2001). In this new climate, quarantine regulations are being overhauled and revised in many countries, and the result may be less stringent restriction and a greater risk that potentially dangerous species are allowed to move more freely.

In Australia, the system has been that all deliberate importations of plants have to be approved by the relevant government agency (previously the Australian Quarantine and Inspection Service (AQIS), now the Plant Biosecurity wing of the Department of Agriculture, Fisheries and Forestry, Australia (AFFA). If they fail the Risk Assessment process described above (Pheloung, 1995) they are added to the list of prohibited plant species which now totals many hundred species, and includes a number of complete genera. The Nairn Report (Nairn *et al.*, 1996) recommended that this system be replaced by one involving a 'clean' list of plant species which may be imported and all other species prohibited, but it is not clear just how different this system will be.

The USA currently has no prohibition on any plant species other than those listed under the old 1974 Federal Noxious Weed Act. This list includes about 94 taxa, mainly potential weeds of agriculture, including a number of complete genera (especially parasitic plants) but also some potential 'environmental' weeds, and more are likely to be added in the future.

The Republic of South Africa (RSA) has lists of about 170 'declared weeds' which may not be imported (Henderson, 2001). These include many species of *Acacia* and *Eucalyptus*.

Individual countries in Europe do not have separate prohibited weed lists but under European Union (EU) regulations the genus *Arceuthobium* (dwarf mistletoes) is prohibited throughout the EU.

Assuming one has decided a species is to be prohibited entry, and it is formally listed, how successfully can it be excluded? The chances of importation of bulk quantities (e.g. as crop seed) will be virtually eliminated, but problems of accidental (or clandestine) entry remain. The commonest route for accidental entry will be as seed contaminants of permitted crop seed imports. Exporting countries will be anxious not to have their produce banned for contravention, and will normally endeavour to avoid such contamination but small numbers will very easily be overlooked. There is also the problem of ignorance on the part of exporters/importers, and of individual travellers, unaware of the regulations. In this context a system of inspection is vital. The US Animal and Plant Health Inspection Service (APHIS) is as rigorous as any, and successfully intercepts considerable numbers of contaminated cargoes. Fowler (1998) records that over the 12-year period 1985 to 1997 there were very nearly 25,000 reportable noxious weed interceptions. Noxious weeds most commonly intercepted were *Solanum torvum, Ipomoea aquatica* and *Heracleum mantegazzianum* while consignments of cumin seed were the most commonly contaminated. A high proportion of interceptions were of consumable items in passenger luggage at airports. In spite of these impressive numbers, the ability of an inspection system to detect prohibited species must be limited, as it cannot be economic to inspect all consignments. However, without such a system the regulations are unlikely to be obeyed and the inspection service is therefore vital as a deterrent.

Plants already in cultivation

As noted above, a large proportion of alien invasive weed problems arise from deliberate introduction and cultivation, whether as crops or ornamentals. If a species is found to escape from cultivation and threatens to become seriously invasive, what can be done? It may be listed and any further importation prohibited, but if it has become a commercial commodity and been widely planted, there are enormous logistic and economic implications in any attempt at suppression or eradication of existing populations. The best hope is to achieve a voluntary withdrawal of the species from sale by negotiation with the companies concerned, combined with publicity to encourage growers to destroy the offending species but this will rarely be fully effective. The concept of 'polluter pays' could be applied to the nursery business but I am not aware that any such draconian action has been seriously considered as yet. It could be very difficult to enforce, especially on the internet businesses involved, but the threat of it could be helpful.

Awareness/education

Perhaps as vital as the existence of a quarantine and inspection service, is the need for some methods for creating awareness of the dangers from alien plants and guides to their identification, so that, if they do get past the inspection service, they may still be recognised, either in the produce itself, or following establishment locally in the field (or water body), before they have the opportunity to build up and spread. The *Striga asiatica* problem in USA was only identified (by a student from India) after it had spread to several hundred thousand hectares. It seems unlikely that it could have spread so far in less than about 20 years – a long time unnoticed, especially as it was in a cultivated crop rather than in wild vegetation. The farmers and land-managers of the future need to do better, and to this end the US Federal Interagency Committee for the Management of Noxious and Exotic Weeds (FICMNEW) is developing a new National Early Warning and Rapid Response System for Invasive Plants (Westbrooks *et al.*, 2001). Similar programmes are essential in any country concerned to reduce risks of invasion. Methods may include the distribution of leaflets to growers and farmers, supplemented by campaigns via public events such as agricultural shows, 'weed awareness weeks' (in USA), 'weedbuster weeks' (in Australia), and various media – radio, television, and email. Australia makes use of the 'enviroweeds' listserve to provide a continuous source of news and up-dates on issues relating to invasive weeds, ensuring that workers in the field are alerted to new threats and can receive advice on control and management methods.

Because of the special risks from plants already being grown in cultivation, noted above, education has also to extend to the commercial sector of the ornamental plants business, to ensure that they fully understand the risks from any or all of the plants they are selling and are prepared to restrict or withdraw selected species from sale when an adequate case has been made to justify such restriction. In USA and in Australia, there is increasing dialogue between government and industry at the national and state levels, aimed at voluntary controls of this sort.

CONCLUSION

Once a species is listed as a prohibited plant, there are good chances of preventing it from becoming an invasive alien weed problem, though this will require adequate inspection and educational activity.

Deciding which species are to be added to a prohibited list is the main difficulty. Apart from the obvious species which are already listed by many countries – notably the parasitic *Striga, Orobanche* spp., etc. – there are difficulties of identifying those species most likely to flourish and become a problem in the many different wildlife habitats that are at risk. Weeds of agriculture are the least problem, as most alien crop weeds were already significant crop weeds in their native region, and there is a much greater chance of them being noticed and/or destroyed by routine herbicide or other weed control activity. A possible exception to this is the danger from herbicide-resistant strains of common weed species (native or otherwise), whether these have been selected by repeated herbicide use or resulted from crossing with crops engineered for herbicide-resistance (especially rice). It could be argued that such different races of a weed should be treated as though they were a distinct species for quarantine purposes (discussed by Williams *et al.*, 2000).

Overall one may conclude that prevention depends on prediction, but prediction is still far from adequate. And in the absence of good enough prediction and possible difficulties of prohibition because of WTO/SPS Agreement rules, education is absolutely vital – to raise awareness of the dangers, to raise the botanical and observational skills of all those involved in the management of land, especially wild and semi-wild habitats, so that they recognise their pre-existing flora and spot any threat of invasive behaviour from newly introduced species or one escaping from cultivation, before it is beyond reasonable, economic control. A further requirement will of course be an adequate legal and logistical system for response to such invasions.

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