STUDIES ON WEED RISK ASSESSMENT

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ABSTRACT

The weed risk assessment system (WRA) recently implemented in Australia as part of modifications to its quarantine risk assessment procedures is claimed to be a highly accurate predictor of weeds. Such predictive accuracy is at odds with current ecological theory and with predictive accuracy in other fields such as chronic health risk assessments.

This thesis gives an overview of factors used in weed risk assessments and explores the disparity between the measured high accuracy rate of the WRA and the fairly pessimistic assessments of some workers about the possibility of predicting the weed potential of plant species imported in the future. The accuracy of the WRA may not be as high as previously thought, and it varies with weed definition and with taxonomic groups. The WRA is not a reliable predictor of weeds when it is considered in the context of the base-rate probability of an introduced plant becoming weedy in Australia. As a result a far greater number of non-weeds will be placed on the prohibited imports list than was initially expected.

Cluster analysis and comparative analysis by independent contrasts were employed to determine the value of individual biological and ecological questions on the WRA questionnaire. Results showed that some WRA questions could be deleted from the questionnaire and the scores for others could be weighted differently. I also argue that the 'evaluate further' outcome should be discarded, reducing the possible outcomes of potential importation application assessments to two: 'accept' or 'reject'.

I discuss the management implications of the above findings, including the use of a modified WRA as part of a process to assign priorities to naturalised species for control. I explore the lack of sensitivity of the WRA in detecting environmental weeds and the implications of permitting further imports of naturalised species on the grounds that they are already present in Australia.

Future research should focus on using importation records to calculate the base-rate probability of newly introduced exotic species becoming weedy in Australia; establishing whether there are good predictors of weediness for weeds of conservation areas and for plants in the Rosidae, especially the Fabaceae; and elucidating the factors involved in the transition from establishment to naturalisation and from naturalisation to invasion in Australian ecosystems.

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CANDIDATE'S STATEMENT

This work contains no material which has been accepted for the award of any other degree or diploma in any University or other tertiary institution and, to the best of my knowledge and belief, contains no material previously written or published by another person, except where due reference has been made in the text.

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CHAPTER ONE: INTRODUCTION

1.1 BACKGROUND

Many Australian weeds were either deliberately imported to enable people from Europe to survive in their new land, or were accidental contaminants of deliberate introductions. Our weeds are presently primarily from Europe and the Mediterranean basin and many evolved under the influence of human civilisation (Kloot 1987). In the 20 years after the first European settlement, over 200 plant species were deliberately introduced to Australia (Crosby 1986). Since then no reliable record exists of how many species have been introduced, the frequency of introductions, or the introduction sites. However, it is likely that most introductions fail to produce naturalised populations. Williamson (1996) encapsulates the fate of introductions in a useful rule of thumb known as the tens rule. This rule defines the stages of introduction as: (i) importation, when organisms are brought into a country and contained; (ii) introduction, when imported organisms are in the wild but not breeding successfully; (iii) establishment, when introduced populations are breeding successfully in the wild; and, (iv) pest, when established species have a negative economic impact. The tens rule states that roughly 10% (between 5% and 20%) of imported species will make the transition from one stage to the next. Following this rule, without a quarantine screening process we would expect approximately 0.1% (i.e. 10% x 10% x 10%) of all plants imported to Australia would eventually become pests. Panetta *et al.* (1994) estimate that so far in Australia 0.23% of imported species become weeds.

The tally of naturalised exotic plant species in Australia now stands at 2200 (Hnatiuk, 1990). Half of these naturalised species are now on weed lists of one kind or another, and about 220 have been proclaimed noxious (Parsons and Cuthbertson 1992). The rate of naturalisation of exotic plants appears to be linear (Kloot 1987) with about 11 species becoming naturalised each year and one major weed introduced for every year since the start of European settlement (Panetta *et al.* 1994). Weed control currently costs Australian agricultural industries alone over 3.3 billion dollars a year (Commonwealth of Australia 1997). Leigh and Briggs (1992) name weed competition as the cause of extinction of four Australian native plant species, and consider a further 57 species to be threatened with extinction by the same cause.

Given the cost and magnitude of weed management problems in Australia, it is worth noting that only 18% of our major weeds are known to have been introduced accidentally. Thirty-one per cent of our major weeds were introduced for ornamental purposes, 15% for other uses and the source of introduction of the remaining 36% is unknown (Panetta 1993). Furthermore, very few beneficial species may have been introduced in proportion to the number of weedy species. Lonsdale (1994) compared the fate of 463 legumes and grasses introduced expressly for use as tropical pasture species in Northern Australia. Less than 1% of the species introduced became useful pasture plants without causing weed problems while 13% became a weed. Of the 13% weedy species, about a third were weeds of cropping, one third became weeds of conservation areas and a third were weeds of both cropping and conservation lands. Ninety-six per cent of all introductions served no useful purpose to any sector.

Findings like these have added to the growing number of calls for a revision of plant introduction and quarantine procedures in Australia (e.g. Forcella and Wood 1984, Panetta 1993, Lonsdale 1994) in order to reduce the chance of deliberate introductions becoming problem plants.

1.2 ATTEMPTS AT REDUCING THE RISK OF NEW WEED INVASIONS

Historically, nationally co-ordinated attempts to control the risk to Australian industries posed by weeds has focused on the entry of known weeds. Risk was reduced by reducing incidences of accidental imports and restricting deliberate imports of known weed species, or species closely related to them, from overseas.

This approach has broadened recently and the change is embodied in the declaration of a National Weed Strategy launched in 1997 (the goals and objectives of which are listed in Appendix 1). The National Weed Strategy encompasses national attempts to reduce the impact of existing weed problems and the co-ordinated management of weeds of national significance.

The Australian Quarantine Inspection Service (AQIS) administers the new procedure for assessing importation requests in Australia. The procedure consists of a three tiered screening process, recommended to the Australian Weeds Committee by Panetta *et al.* (1994). The tiers comprise:

1. Checking that the species identification is correct and that it is a species new to Australia. Checking that it has not previously been prohibited or permitted entry.

2. If the species is not already established in Australia, and does not appear on prohibited or permitted lists, assess the risks of the plant becoming a weed. On the basis of this assessment, recommend the application be accepted, rejected or evaluated further. The names of accepted or rejected species are to be added to the permitted or prohibited lists respectively.

3. If the recommendation was for evaluation, the species may be subjected to a post-entry evaluation phase so that ultimately, the species can be put on a permitted or prohibited list.

During the development of the second tier of the process outlined above, new ideas on how to perform the risk assessment were circulated widely. After modification in response to some comments on the draft form, the new procedure was implemented and is now commonly referred to as the Weed Risk Assessment (WRA) procedure. The WRA is currently in use, minor changes being incorporated when they appear justified (Craig Walton, pers. comm.). As was the case for the previous AQIS system and a proposed alternative system (Panetta 1993), the WRA checks the species against biogeographic information, attributes of weeds and biological correlates of weediness. If the species can grow in an Australian climate and it sufficiently resembles known weeds, it is rejected, if it appears innocuous it is accepted, and in cases of reasonable doubt more information or advice is sought before making a decision.

When Pheloung (1995) tested the WRA system it performed about the same as the previous AQIS system in terms of detecting serious weeds, and in not rejecting useful species. The WRA system is felt to be more flexible than other systems such as the previous AQIS system or Panetta's (1993) decision tree, as it does not require that all questions be answered before a recommendation is made. However, it asks a lot more questions than these other systems to start with. The WRA did result in fewer 'evaluation' cases than the previous AQIS system but it also resulted in recommendations to accept more minor weeds into the country (see Table 4 of Pheloung 1995). There has not been a cost/benefit analysis done on the one-off savings incurred by not submitting some species to further pre-entry or post-entry scrutiny, as opposed to the cost incurred controlling some minor weeds for an indefinite period.

The manner in which the third tier of the screening phase will be implemented remains to be satisfactorily resolved. It is unclear what further information could be gathered and used to recommend that a species be prohibited or permitted without the process being costly, time-consuming and (if it is to be done in Australia) hazardous. Historically there has been a mismatch between the number of new plant introductions per year, and the resources available to do preliminary studies of them. There is currently no requirement to prove that the introduction of an exotic species will be of net benefit to the country, but there is some suggestion that cost/benefit analyses be performed on plants that reach the third tier of the proposed introduction procedure (Pheloung 1995).

1.3 THE SCOPE AND STRUCTURE OF THIS THESIS

This thesis studies the weed risk assessment procedure used to assess applications to import new plant species to Australia. An historical and international context for this study will be provided in Chapter 2 through a brief review of the literature on reputed predictors of invasive plants and weeds and of current overseas models for predicting plant invasions. The model used in Australia by AQIS, the WRA, will be tested for its robustness and reliability in Chapter 3. Chapter 4 will explore some refinements to the questionnaire used in the WRA. Changes to the third quarantine tier are suggested in Chapter 5. Chapter 6 discusses some weed management implications of studies on weed risk assessment reported in the previous chapters.

CHAPTER TWO: LITERATURE REVIEW

2.1 DEFINING WEEDS

For the sake of clarity, the word 'weed' when used in this thesis will include non-indigenous plant species that reduce, or are known to threaten, the profit from agricultural, horticultural, tourism, or forestry industries. It will also include weeds of conservation, or environmental weeds (Humphries *et al.* 1991), defined as introduced species which reduce the heritage value of our environment by reducing biodiversity, displacing the native flora, or diluting it to an unacceptable extent. Plants described as 'useful' in this thesis are those to which some measurable economic benefit can be ascribed. A plant may thus be both a weed and useful. The term 'invasive' will be used to describe species which have entered territory in which they have not been present previously *and* undergone a marked range expansion, and the term 'naturalised' used to describe species which persist unaided outside their native range. This usage of 'invasive' is in keeping with much north American and Australian practice, but differs from that of Williamson (1996) who defines 'invasive' as 'coming from outside the area in question' (i.e. naturalised).

2.2 INVASION ECOLOGY

Almost all of Australia's noxious weeds come from other continents (Parsons and Cuthbertson 1992) and consequently a good start to understanding what may contribute to an introduced plant becoming a weed in Australia can be obtained by studying the ecology of plant invasions. Interest in invasion ecology has increased rapidly in the last decade with about 100 papers a year published on this topic since the mid 1980s (Pysek 1995). Biological invasions are both natural and man-made, and species ranges are constantly changing as new species evolve and others become extinct. We need to understand as much as possible about the process of invasion in order to reduce the rate at which invasions are occurring in Australia, the rate at which weeds are invading, and to decelerate the trend towards a homogenised global environment. We need to understand what allows some plants to spread beyond areas they are deliberately planted in as well as what makes them a nuisance when they are present.

The subjective nature of defining weeds and the implied value or use of the invaded ecosystem must be kept in mind when studying weed invasions. In invasion ecology it is possible to differentiate a colonising species, a naturalised species, and an invasive species by classifying its biological attributes and its function in the ecosystem. Weeds and useful plants, however, can fall into any of these categories and are largely a subjective concept (Perrins *et al.* 1992b). Many naturalised exotic plant species seem to colonise interstitial spaces, probably causing little impact on their new environment (McIntyre 1993). Others invade and transform the environment, changing the structure and function of the ecosystem in a way that requires large resources to reverse the damage (e.g. Wells *et al.* 1986, Braithwaite *et al.* 1989, Kruger *et al.* 1989, Hobbs and Humphries 1995). Some Australian native plant species are currently invading new environments, and others are considered weedy in their native range because they hinder changes to land management (e.g. *Acacia paradoxa*, see Parsons and Cuthbertson 1992).

2.3 PREDICTION AND RISK ASSESSMENT

The phrase 'risk assessment' is much in vogue these days but, in pest and weed ecology, is often used in ways that diminish the value of the phrase in its authoritative definition (e.g. Davies 1995). Much of what is claimed to be risk assessment is in fact either hazard identification or dose-response modelling. Both of these terms have precise meanings in the literature of risk analysis, but are only part of the process of risk assessment.

Risk analysis is a general term which encompasses the domains of comparative risk analysis, risk assessment, risk management and risk communication (Davies 1995). The term 'risk' incorporates the concepts of damage or impact as well as the concept of probability. However, as put by Parker *et al.* (submitted): "Impact has rarely been formally defined in the invasion biology literature, much less formally quantified". In that light, it must be stated that truly comprehensive weed risk assessments are currently in the very early stages of development.

Risk assessments are usually employed when there is a small chance of a potentially catastrophic event occurring as a by-product of implementing a new technology or process. They are usually the first step in identifying measures which can be taken to minimise the risk at each stage of the process in question.

Prediction means making a statement about the future. Predictions can be for harmful, benign or beneficial events. The reliability of a prediction can be described quantitatively by using statistical methods. The probability of any given outcome is the ratio of the number of such outcomes to the total opportunity set. All predictive models contain explicit probabilities, and useful models are those that reliably perform in a way that reflects the system they describe.

According to Davies (1996) the most generally accepted formulation for risk assessment was devised by a National Academy of Science Committee (National Academy of Science 1983) and comprises the following four steps:

1. **Hazard identification.** This identifies the type of injury that can be caused. In weed risk assessment this would entail the identification of potential weeds based on their similarity to past weeds, and a description or measure of the harm caused by weeds of that kind.

2. **Dose-response assessment.** This calculates how the degree of injury is related to the amount of hazard. For weeds this would mean calculating the threshold level at which abundance has a negative impact on an ecosystem, and how impact increases with weed abundance.

3. **Exposure assessment.** This is an estimate of how much of the 'at risk' population will come into contact with the hazard. For weeds this would involve calculating the overlap of the potential weed's distribution and the ecosystems susceptible to damage.

4. **Risk characterisation.** This combines the information of (2) and (3) to estimate the amount of damage that will be caused.

Conservation biologists and wildlife managers increasingly use stochastic models to describe natural systems, estimate the risks these systems are exposed to, and test means of minimising these risks. The models they construct are generally of single populations, collections of populations of a single species, or simple systems, in order to determine the critical population levels below which species extinction or habitat destruction takes place (Burgman *et al.* 1993, Adair and Groves 1998). In other words they provide models useful in the dose-response assessment step described above. Although models such as these are implicit in some systems used to rank the risks of naturalised plants (for example that of Hiebert 1997) they have yet to be incorporated in quarantine risk assessments. The weed risk assessment system used by the Australian Quarantine and Inspection Service is more akin to a hazard identification tool than it is to a comprehensive risk assessment system, as it attempts to identify weeds. It does not, however, attempt to estimate the potential impact of a species or the potential exposure of particular 'at risk' areas.

Because each prediction at each step of the calculation of a risk assessment has its associated error, the level of uncertainty in the assessment result of risk assessments can be expected to be high. For example, the statistically calculated uncertainty associated with most chronic health risk assessments is several orders of magnitude (Davies 1995). Usually the predictive power, or lack of it, is not a prime concern when conducting a risk assessment. Instead, risk management is the aim. According to Bernstein (1996):

> 'The essence of risk management lies in the area where we have some control over the outcome while minimising the areas where we have

> absolutely no control over the outcome and the linkage between cause and effect is hidden from us'.

Although it is not possible to predict with certainty that a plant will become a weed, risk assessment and risk management can be used to reduce losses due to future importations becoming weeds. Risk assessments are currently used in other policy areas where governments decide to proceed with ventures that are potentially catastrophic. Risk assessment aims at identifying and, if possible, calculating the risks involved at each step of a process. Risk management proceeds by reducing perceived risks either by avoiding a step or process or by implementing independent safeguards. The risk of a catastrophe is reduced because it becomes the product of the undesired event occurring and the simultaneous failure of the independent safeguard. The results of risk assessments can be compared (comparative risk analysis) and prioritised (risk ranking) to help in decision making, and can be expressed in relation to assessments of commonplace situations to give them a meaningful context. Risk assessment can be an iterative process with our estimates of risks becoming more accurate as knowledge improves.

Australian weed management would benefit from the implementation of a truly comprehensive risk analysis for weeds which encompasses:

1. The risk of future importations of new taxa becoming weeds.

2. The risk of exotic plant species already naturalised becoming weeds in the future.

3. The risk of plants presently in use by one industry becoming the future weeds of another. This would include assessment of the risks involved in using new plant varieties and transgenic plants.

4. The risk of native Australian plants expanding their present ranges and becoming weeds.

5. The risk of accidental plant introductions.

Weed management policies would then aim to devise strategies to reduce or circumvent the risks associated with each critical step of the occurrences described above. At the moment all of these components are being done to some degree, but in a piecemeal fashion (e.g. the risk posed by transgenic plants is assessed using a different protocol from that used for new species, for reasons that have more to do with the public perception of risk than with the risk inherent in the proposed introductions).

Brown and Reinert (1992) describe the major factors involved in environmental risks. These can be restated, for weed management purposes, as follows: the risk of a plant becoming a weed is a function of the properties of the plant, the environment it is released in, and the way it is introduced to the new environment (Figure 2.1). These factors are incorporated in the National Academy of Science (1983) risk assessment formulation model above in the following way:

- **Properties of the plant** are used in the hazard identification stage of risk assessment to determine whether the species resembles models of known weeds.

- **Properties of the environment** are incorporated in models used in the dose-response assessment and exposure assessment stages of risk assessment formulations.

- **Introduction methods** (number and spacing of introductions) form part of exposure assessments.

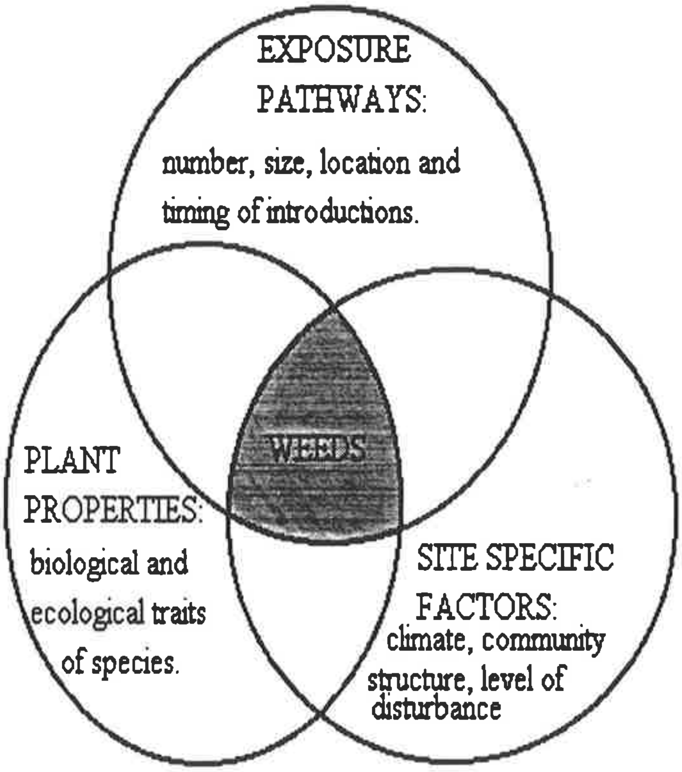
2.4 FACTORS WHICH MAY CONTRIBUTE TO AN EXOTIC PLANT BECOMING A WEED

The factors that may contribute to a plant's becoming a weed are discussed here using the conceptual framework described in Figure 2.1. The literature on predicting weediness provides a great deal of information on the characteristics of the plant, less on the importance of the environment and less still on introduction methods. There are a number of studies on the interaction between the plant and the environment, but few on the other possible interactions (plant x introduction path, environment x introduction path, and plant x environment x introduction method).

2.4.1 Properties of the plant

Plant characteristics that may enable a species to colonise and persist in new environments have been examined at the species biology level and in the context of the way the species functions in its native environment. The biological and ecological characters discussed below are those that may favour plant invasions, or make a plant population difficult to control or eradicate.

Figure 2.1. Risk components of plant introductions



Biological characteristics that would facilitate invasion and weediness include those that enable the plant to colonise new sites, survive and reproduce better than the existing vegetation at the new site, and spread to other sites. The relative importance of each characteristic will always depend on the environment the plant is in.

2.4.1.1 Growth, size and shape

Biological characteristics that may confer competitive advantage during plant growth have not been found to be universally useful in predicting weediness. Grime and Hunt (1975) have shown that the relative growth rate (RGR) of a species reflects phylogeny or life history, with woody species and fine-leafed grasses having low RGR and annuals generally exhibiting higher RGR. Lamberts and Dijkstra (1987) found that ecological advantage is not conferred by RGR; instead there seem to be trade-offs between RGR and other advantageous characters. For example, a low RGR may be coupled with a large investment in palatability-reducing compounds and genotypes from infertile habitats have inherently low RGR in comparison with genotypes from fertile or disturbed sites. Garnier *et al.* (1989) compared the RGR of an invasive and non-invasive species of *Bromus* and found no difference in their RGR or its components.

On the other hand, Gaudet and Keddy (1988) have shown that the competitive ability of wetland plant species is closely related (r^2=0.74) to plant traits. Plant biomass explained 63% of the variation in competitive ability in the plants they studied and plant height, canopy diameter, canopy area and leaf shape explained most of the residual variation.

2.4.1.2 Reproductive strategy

The reproductive strategy of a plant or its genetic determinants may enhance its chances of becoming a weed. The ability to reproduce vegetatively may be one of the distinguishing features of invasive woody plants but may be less useful in distinguishing between invasive and non-invasive plants in other plant groups (Reichard and Hamilton 1997). Self-fertilisation, especially if it is not obligate, may increase the chances of initial establishment and spread of introduced species (Pantone *et al.* 1995). Polyploidy, large genome size and high genetic variability are all thought to assist invading plants in adapting to their new environments but there has in fact been no clear relationship established between any of these characters and capacity to invade (Roy 1990). On the other hand, Forcella (1985) found that species with a high reproductive output (even if normally unsuccessful) in their native habitat have a high invasive potential and weeds of agriculture are often plants with toxins, prickles or spines which protect them from reproductive loss due to grazing (Groves 1986).

2.4.1.3 Seed characteristics

Seed size (Burke and Grime 1996), germination speed and success (Forcella *et al.* 1985, Forcella *et al.* 1986, Reichard, 1994), and light, temperature and moisture requirements for germination may all influence the ability of a species to colonise a new site (Burke and Grime 1996). There is a tendency to look for differences between means, maxima or minima for these characteristics, yet it may be the plastisticity of a critical characteristic that allows a species to prosper (Tucker and Richardson 1995).

Burke and Grime (1996) sowed a mixture of exotic species in natural grassland in Sheffield to which various disturbance (including nutrient addition) treatments had been made and found that species able to germinate in a wide range of light conditions were generally more invasive. They also found that heavier seeds were able to invade undisturbed plots regardless of gap size or disturbance treatments whereas the success of smaller seeded species tended to be confined to disturbed plots. In their plots, species able to germinate at lower temperatures were more invasive and Forcella and Harvey (1988) found the same tendency in alien weed species of the northwestern corner of the USA. If these studies can be generalised, then we would expect weeds in the Australian temperate zone to be capable of germinating at lower temperatures and in a wider range of light conditions than non-weeds. Weeds of conservation areas would be expected to have heavier seeds than weeds of other ecosystems and than non-weeds, and that disturbed areas would be more prone to weed invasion. These predictions remain to be tested critically, but are beyond the scope of the present thesis.

The ability of seeds to survive in a seed bank would be expected to be generally advantageous to plants in many areas of Australia as this would enable some germination to occur under more favourable conditions. Dormancy would be expected to be an especially advantageous trait for weeds, as it would allow populations to survive intermittent control attempts. However, the usefulness of this character in identifying weeds is likely to be strongly habitat dependent. Thompson *et al.* (1995) compared ecological and habitat characteristics of exotic and native plants which have recently expanded in range in England, Scotland, the Republic of Ireland and the Netherlands and found that invasive alien plants were more likely than natives to have a transient seed bank. This information must be viewed in the context of the invasive aliens also being more likely to be clonal, polycarpic perennials, which grow well in the cold, wet and often isolated habitats studied in Thompson *et al* (1995). It may be that long-lived seed banks aid in the establishment of introduced species in the seasonally dry or ephemeral rainfall areas of Australia. Whether naturalised weedy species have greater seed bank longevity than naturalised non-weedy species remains to be seen.

2.4.1.4 Strategies for dispersal over distance or time

Noble (1989) found that plant perenniality is of little consequence to the invasion success of plants introduced to stable environments, but that it may influence the ability of the plant to persist through times of adverse conditions. Thomson *et al.* (1995) compared native and alien invasive plants in England, Scotland, the Republic of Ireland and the Netherlands and found that the alien invasive species were more likely than the natives to be polycarpic perennials. However, they stress that this is more likely to be a reflection of the type of habitats invaded (in this case, essentially closed communities in cool, damp climates) than of plant properties generally required for invasion.

Noble (1989) found in models of the invasion process that short distance dispersal mechanisms increase both the probability and the rate of invasion. However, in South Africa, successful plant invaders tend to have long-distance dispersal agents (Dean *et al.* 1986). A number of studies have examined the importance of the timing and duration of flowering (Forcella 1985, Perrins *et al.* 1992a, Reichard 1994). Weeds tend to flower for a longer period, and over a wider temperature/photoperiod combination, than non-weedy plants.

2.4.1.5 Taxonomic groups

Some families of introduced plants produce a disproportionately high number of weedy species, and others a disproportionately low number (Williamson and Brown 1986). The most important weedy family depends to some extent on the new environment (Table 2.1).

Table 2.1 Largest weed families in three temperate climate regions

Region invaded	Weed status	Families with highest number of weeds	Reference
British Isles	Naturalised aliens	Cruciferae Labiatae Caryophyllaceae	Crawley 1986
South Africa	Transformer weeds	Fabaceae Myrtaceae Pinaceae	Wells *et al.* 1986
Victoria	Very serious environmental weeds	Poaceae Rosaceae Fabaceae	Carr *et al.* 1992

In reality, the intrinsic propensity of a family to invade is difficult to tease out because the measured success rate is confounded with the rate of introduction (Williamson 1996).

Furthermore if, as is often the case, each exotic species is treated as an independent point for statistical analysis of the biological traits associated with weeds, the taxonomic relationships will confound the analysis leading to results which identify the common taxonomic characters of the group rather than characters that make a plant weedy (*cf.* Pagel 1992).

2.4.2 The plant in its environment : ecological characteristics

2.4.2.1 Competitive ability

Identification of potential weeds would be easier if competitive ability of the exotic species could be compared with that of some phytometer such as beneficial plant species. However competitive ability in relation to phytometer species may be site-specific. Merhroff and Turkington (1990) found this from competition experiments in pasture swards, mown experimental plots and glasshouse pots, using four pasture species collected from five different-aged populations. Competitive ability varied greatly between populations of the same species, and overlapped between species, making it impossible to use species performance in one set of experimental conditions to predict community dynamics.

2.4.2.2 Abundance and rate of spread

Insects that are numerically abundant in their native environment make better invaders when released in a new environment (Crawley 1986a, Groves 1989), but this is unlikely to be the case for invasive plants in Australia. Many form a minor part of the flora in their native range (Parsons and Cuthbertson 1992).

Models of successful invaders show that they generally spread at a constant linear speed (Williamson and Brown, 1986). After introduction to a new environment, the rate of increase in the number of naturalised populations (Hobbs and Humphries 1995) and the rate of spread are probably good predictors of invasion. In northeastern America the fastest spreading non-native plants became the most important weeds (Forcella 1985). However, it is only possible to measure spread rate post entry, so it is unlikely to be useful in a quarantine screening process unless a relationship can be established between the spread rates on other continents and those in Australia.

2.4.2.3 Ecological amplitude (history of invasion)

As is the case with insect species (Crawley 1986a) one of the best predictors of plant invasions success is the plant's distribution in its native range (Roy 1990). Invasive plants tend to be those which have managed to persist over large ranges in their areas of origin (Forcella and Wood 1984). They may also have a history of invasion in other areas. For example, of 139 European plants listed as naturalised by the middle of the nineteenth century in Australia, at least 87 had already attained that status in America (Crosby 1985). Similarly, Kruger *et al.* (1989) found that many plant species invasive in South Africa have histories of spreading to other wider climatic areas.

Major weeds of Australia would be expected to tolerate or flourish in a range of environments, including areas of unreliable rainfall and on nutrient-poor soils.

2.4.2.4 Functional groups

Functional groups are groups of species with correlated sets of ecological and physiological characteristics. They are an attempt by ecologists to seek patterns in the vast array of species attributes. For example, Grime (1974, 1979) classifies plants according to the way they respond to stress and disturbance. The three main functional types that result are 'competitors' (which thrive in productive, relatively undisturbed conditions and are usually fast-growing, large, clonal perennials) 'stress-tolerators' (which exhibit a wide variety of growth forms but share the ability to cope with unusual physiological stresses and are often evergreen perennials) and 'ruderals' (fast-growing, short-lived plants of disturbed habitats).

Groves (1989) suggests that colonisers of disturbed sites in their native range may be more likely to be invasive in new environments. Certainly, functional groups based on life form react differently to disturbance types and intensities in Australian pastures. McIntyre *et al.* (1995) found that the proportional composition of functional groups found in temperate grassland in the New England Tablelands varied with disturbance type (soil disturbance, grazing, and irrigated sites). It would be interesting to test their use in identifying the relative risk of potential Australian weeds to different areas or economic sectors.

2.4.3 Properties of the new environment

2.4.3.1 The role of disturbance

Disturbance often plays a major role in plant invasions (Crawley 1986, Williamson and Brown, 1986, Hobbs 1991, Hobbs and Huenneke 1992, Mack 1989, Kruger *et al.* 1989, Ramakrishnan and Vitousek 1989). Any change to an ecosystem may change selection pressures and often provides opportunities for the establishment of species not previously there. Burke and Grime (1996) found that disturbance intensity was by far the most important factor determining the success of introduced species in the initial phase of invasion in their experimental plots.

Invasion and subsequent growth greatly increase (see Hobbs 1989 and references therein) and the diversity of rare native plant species decrease (McIntyre 1993) when physical disturbance is accompanied by an increase in soil nutrient levels, as was the case when hoofed grazing animals were introduced to the Australian native grasslands.

2.4.3.2 Natural enemies

The absence or reduction of specific natural enemies in a new environment may result in a normally benign plant's becoming an invasive weed through its increased reproductive or competitive ability as has been argued in some classical biological control of weed programs (Parsons and Cuthbertson 1992).

2.4.4 Method of introduction

The risk of unwanted plant invasions can be reduced by controlling the number of individual plants imported, restricting the area in which they may be grown (using the knowledge of the role that environment and biology can play), monitoring introductions for signs of naturalisation and spread, and assigning responsibility for control of plants which escape the release area.

2.4.4.1 Release management

The importance of controlling introduction methods and sites in reducing the risks involved in the introduction of new organisms has long been recognised in Australia. We routinely test and quarantine insect and fungal species before making preliminary releases into the environment, and we follow strict procedures for research, often in quarantine conditions, when using organisms that could harm human or animal health. However we do not have a history of requiring post-introduction testing or surveillance of imported plants.

Models of plant invasions show that establishment may be a more important factor than spread (Williamson 1989). Once a plant is naturalised, it may go on to invade other ecosystems or interfere with land management practices in other regions. However, establishment alone does not guarantee either naturalisation (see Crawley 1986a) or invasion. Many agricultural plants grow well in their new ranges and are good reproducers but poor invaders.

Small initial releases are less likely to lead to naturalisation (Beirne 1975) as are releases of plants to be harvested before they reproduce. Plants that are naturalised in their new environment become invasive more rapidly if they are grown in the vicinity of roads, rail or waterways (Pysek and Prach 1993, 1994). Most naturalised exotic species do not go on to become widespread or invasive. Williamson (1996) estimates that about 9 in 10 naturalised species will remain a minor component of the flora in their new environment. The ability of an exotic species to persist without human intervention for 5 years after it was initially sown in its new environment was one of the few distinguishing characters of introduced pasture species which became weeds in tropical Australia (Lonsdale 1994).

Naturalised plants that do invade first undergo an 'establishment phase', sometimes termed a 'lag phase', where the population persists in low numbers in a fixed area before rapidly invading nearby areas (Shigesada and Kawasaki 1997, Fig. 2.2). Kowarik (1995) calculated this phase to last 131 years for shrubs and 170 years for trees introduced to Brandenburg in Germany. The establishment phase of *Mimosa pigra*, a tropical shrub introduced to the Darwin Botanic Gardens in northern Australia, lasted 70-80 years (Miller and Lonsdale 1987). Widespread invasion is the second phase of invasion and is usually preceded by the formation of widely spaced secondary foci (Moody and Mack 1988). During range 'expansion phase' areal spread increases in a linear, biphasic or geometric rate until the species reaches the full extent of its possible range (Shigesada and Kawasaki 1997, Fig. 2.2), the third or 'saturation phase'. Clearly there is an important opportunity of risk reduction at the first two stages of stage of plant invasions.

The roles of timing and chance events are crucial to the establishment and spread phases of plant introduction. They determine what resources will be available for exploitation. However, beyond making plant introductions to areas buffered by environments that are as resistant as possible to invasion, there is not much that can be done to control risks in this part of the introduction process.

2.5 MODELS FOR PREDICTING PLANT INVASIONS OR WEEDINESS

The risk factors described above (section 2.4) have been used in various combinations to construct models for predicting the outcomes of introducing new species to a region or continent. The work in this area is too recent, and the consequences of mistakenly identifying weeds too great, to allow any of these models to be tested experimentally in the field. Instead, testing has of necessity been retrospective: predictions are made about the invasions of plants that have already established in a new range as if they had not yet arrived. Models that rely principally on plant traits have not always taken account of the advantages that many non-natives gain when imported without their native parasites, competitors and pathogens (Elton 1958, Strong *et al.* 1984). Some attributes also change markedly when a species is cultivated. For example, the juvenile period of *Banksia candolliana* may drop from 15 years in its natural environment to 5 years in cultivation (Tucker and Richardson 1995). Models that are statistical do not always discuss their underlying statistical assumptions. For example, the use of discriminant analysis to identify invasive species assumes that the characters of invasive plant species are statistically distinct from other plants, so that their characters can be viewed as having quite different, but overlapping, distributions (Sokal and Rohlf 1995, p.679). This may not in fact be the case: It may be that the biological characters of invasive and non-invasive species form a single distribution, and that the weedy species selected to construct invasion models are chosen from one extreme of this distribution and non-weedy species chosen from the other extreme. We would expect such models to be much less accurate when tested with species taken from the middle of the range of the distribution.

Observation suggests that weeds may have some definable biological characters. Baker (1974) published a list of such characters (often referred to as 'Baker characters') that has since become a familiar starting point in describing weeds. Perrins *et al.* (1992), in an exemplary study, tested quantitatively whether it is possible to identify a plant as an annual weed simply by examining these and a number of other characters. To allow for the fact that weed status is subjective and variable, they surveyed 65 scientists for their opinions on the weed status of the species used in their study (Perrins *et al.* 1992b). They then tested 39 characters, including quantified measures of Baker characters, for their predictive value. Five different methods, including stepwise discriminant analyses, were used to attempt to identify characters that would distinguish non-weeds from weeds. None of these methods produced conclusive results and there was no consensus in the selection of characters by the various techniques (Perrins et al. 1992a). Williamson and Fitter (1996) went on to use the Ecological Flora database (Fitter and Peat 1994), a much larger data set containing information on 1777 native and naturalised

British gymnosperms and angiosperms, to look for biological or ecological characteristics of invading species. They examined 26 quantitative and qualitative characters and found that, in the British flora, invading species are identifiable more by their distribution and morphology (e.g. life form, maximum height, spread and leaf area) than by life history traits (e.g. seedling growth rate, flowering time, season of seed dispersal, season of germination), reproductive mechanisms (e.g. method of fertilisation, incompatibility system) and seed characteristics (e.g. mean seed weight and number of seeds per plant).

Scott and Panetta (1993) have produced the only model of predictors of Australian weeds, and the only study that addresses the effect of time on predictions. They confined their study to plants of South African origin that had been introduced to Australia. They also grouped their test species by introduction date, recognising that insufficient time may have passed for many introduced species in Australia to realise their weedy potential. Instead of using data on biological or ecological characteristics thought to contribute to weediness, Scott and Panetta used an approach they described as 'sociological': they used multiple logistic regression to model weediness (using a dichotomous variable) as a function of potential predictors of weed status (categorical variables for extra-Australian weediness, distribution and taxonomy). The results are useful in identifying potential risk areas but fail to be of predictive use. The best fitting regressions were for species present for more than 140 years in Australia (40% of the variance for all weeds was explained). For species present for less than 140 years the proportion of unexplained variance jumps from 60% to 91%. Although regressions were fitted for agricultural weeds that explained 43% of the variance for agricultural weeds present in Australia for more than 140 years, no variables were found suitable for modelling environmental weeds.

Tucker and Richardson (1995) took a different approach to assessing the risk potential of alien woody plants in the South African fynbos. They developed an expert system to assess the risk of woody species to the fynbos, to support decisions made on importation requests. In the words of Tucker and Richardson (1995) their system "..does not aspire towards a generalised theory of the invasion process. The aim is to produce a set of practical heuristics for better, defendable real-word decisions, in the absence of valid theory and complete data". Their approach is based on a risk assessment protocol (Richardson and Cowling 1992) and their model based on data on invasions of the fynbos ecosystem, by mainly *Pinus* and *Banksia* species, and was strengthened by including information on the history of introduction and dissemination of woody invasive species. It also includes a biological profile of the fynbos environment and perceived boosts or barriers to invasion. All this is incorporated in a flow diagram. The queries and rules for the expert system were generated by repeatedly tracing the paths of unknown invaders and failed introductions through the flow diagram and making changes where necessary. Tucker and Richardson (1995) recommend the expert system approach for decision support in screening potentially invasive non-native plants, and it clearly shows promise in the area of developing risk reduction strategies for well defined 'at risk' ecosystems. They do not recommend generalisations of the system itself even though it has quite a high proportion of correct predictions (68-100% depending on plant group) when tested on the species used to construct it.

Reichard and Hamilton (1996) used two statistical approaches and a decision tree to model invasiveness. They restricted themselves to one functional group, woody plant species, and one part of the world, North America. Their models were constructed using subsets of a data set on plants introduced to northern America before 1930, and tested on the remaining data in their data set. The full data set consisted of 235 species that now maintain self-sustaining populations outside cultivation in America (defined as invasive for the purpose of the study) and 114 species listed in plant catalogues but not yet found outside cultivation (defined as non-invasive). The full data set of invasive species spanned 53 families and 125 genera and the non-invasive species were from 48 families and 80 genera. Nevertheless, conifers and southern Florida species were eventually omitted 'because attributes unique to these two groups obscured patterns present in the remainder of the species' (Reichard and Hamilton 1997).

The first model used stepwise discriminant analysis of 75% of the data to produce a function of five plant variables (four dichotomous, the fifth with three character states) to identify invasion status. When this function was tested on the remaining 25% of the temperate species it identified invasive species well: 94% of the invasive species were correctly classified. However, it was far less accurate in identifying non-invasive species (57% correctly identified).

The second model was constructed using classification and regression trees (CART). This approach was chosen as 'unlike stepwise discriminant analysis, no assumptions about normality are made and ...categorical data are appropriately used' (Reichard and Hamilton 1997). The resulting 'pruned CART' for temperate angiosperms uses just two characters: species origin (north American or not) and whether it is an inter-specific hybrid or not. This model was slightly better than the first at identifying invasive species (96% of 134 species correctly identified, i.e. 96% of the invasive species in the data set used to validate the model were north American hybrids) but worse at identifying non-invasive species (45% of 74 species correctly identified).

The third model is a decision tree constructed using the results of the first two models and results from Reichard (1994). It was only 38% accurate in identifying non-invasive species (in other words a random process like tossing a coin would probably be better at identifying non-invasive plants) but 89% accurate in identifying invasive species. As the decision tree was tested using the same data used to construct it, however, the results of the model's validation may have overestimated its predictive power.

Rejmanek and Richardson (1996) also claim to have developed a screening tool for detecting invasive woody seed plants. They used discriminant analysis to develop a model using 24 (12 invasive and 12 non-invasive) *Pinus* species. The resulting discriminant function requires only three biological variables: seed mass, minimum juvenile period and mean interval between large seed crops. Although the model was highly successful at correctly identifying the invasion status of the 24 species used to construct it, it did not perform so well when it was tested on other species in the genus

(Rejmanek and Richardson 1996, Table 2). Furthermore, the model may be phylogenetically compromised as 11 of the 12 invasive species used to construct the model come from the subgenus *Pinus* and 5 out of 12 of the non-invasive species from the subgenus *Strobus*. Rejmanek and Richardson (1996) do not calculate the accuracy of the identifications of the 34 species used to test the model, but this can be done readily from their published results. The model fitted species in the subgenus *Pinus* very well: 11 of the 14 (79%) of the invasive and all five non-invasive species were correctly identified. However, only 3 of the 6 invasive species of the *Strobus* subgenus were correctly identified, the same accuracy as could have been obtained by tossing a coin. If we examine the results for the two subgenera together we see that 70% (14 out of 20) of the invasive species were correctly identified, and 57% (8 out of 14) non-invasive species were correctly identified. A model which simply identified all species in the subgenus *Pinus* as invasive species, tested with the same 34 species used by Rejmanek and Richardson (1996), would have produced more accurate results: Such a model would result in 75% of invasive species and 64% of non-invasive species being correctly identified.

Rejmanek and Richardson (1996) went on to test their model on 40 invasive plants from 40 different genera and found that it correctly identified 38 of these species as invasive. They list 13 non-invasive species correctly identified as such by the discriminant function. However, there is no information given on how many non-invasive species were tested and failed to be correctly identified, and no attempt to test non-invasive species from the same genera as the 40 invasive species. They do not state whether the variables used in the model were measured in the native or exotic range.

Rejmanek and Richardson (1996) claim that the *Pinus* discriminant function, together with a few tentative rules, represents 'the first really general screening tool for detection of invasive, woody, seed plants'. However, the wider application of their model has yet to be rigorously tested. It is noteworthy that none of the biological predictors for woody invasive species found by Reichard and Hamilton (1996) were used in the 'pine discriminant function'.

2.6 SUMMARY

Australia is a vast land area covering a broad range of biogeographic zones. As the country develops, and as world markets change, our desire for exotic species to fill a range of niches continues unabated. Historically, many of our noxious weeds began as deliberate introductions to fulfil some perceived need. We must have some system in place to ensure that the best possible decisions are made about future introductions to reduce the risk of continuing to import plant species that eventually turn out to cause high levels of damage to our environment and agricultural industries.

A review of the literature reveals that a wide range of predictors of invasion or weediness have been postulated, and recently some of these have been incorporated in models for predicting invasion or weediness. Although the evidence that biological or 'sociological' characters can be reliably used to predict future plant invasions or problem weeds is not entirely convincing, they may be used in a risk assessment framework.

Clearly risk assessment of new plant introductions to screen out potential weeds is in a rudimentary stage of development. No models are yet able to estimate the potential impact of new introductions, and none incorporate effects due to introduction method such as the effects of propagule pressure and the timing and location of introductions. In terms of the National Academy of Science's (1983) description of risk assessment formulations, there are no weed risk assessment models that include dose-response assessments (or something analogous), exposure estimates or damage estimates. Nevertheless, even a procedure that simply identifies and screens out potential weedy species would reduce some of the risk associated with plant importation.

This thesis will examine Australia's current plant importation procedures, particularly the WRA administered by AQIS, to see how they reduce risk given the somewhat variable results of other attempts to predict invasion or weediness. It will explore:

- The development and structure of the WRA: its accuracy, robustness and reliability, and its ability to detect weeds across the phylogenetic spectrum.
- Possible refinements of the WRA.
- Options for third stage (further evaluation) screening.
- Weed management implications of the WRA.

In addition, areas requiring further research will be suggested.

CHAPTER THREE: TESTING THE WRA

3.1 INTRODUCTION

The primary aim of the Weed Risk Assessment system (WRA) is to reduce the risk of deliberately importing new species to Australia that will later become naturalised and weedy beyond their intended range.

Although referred to as a risk assessment system, the WRA actually entails only the first of the four phases generally accepted as comprising a risk assessment formulation (Section 1.4; National Academy of Science, 1983). It attempts only to identify species with weedy tendencies. It does not attempt to estimate the relationship between the size, frequency and location of introductions and the resulting level of damage, nor does it attempt to estimate the potential impact of weedy species.

The WRA was developed and tested with the cooperation of a wide range of weed scientists and weed managers. It assesses the risk of a plant becoming a weed by answering, for each species proposed for introduction, 49 'yes/no' questions pertaining to its biology, ecology or agricultural history (Pheloung 1995). Points are given for positive answers to questions implying weedy attributes and deducted for answers indicating attributes of non-weeds. A minimum of ten questions must be answered across the biogeography, undesirable attributes and biology/ecology sections of the questionnaire before an assessment can be made. There is no requirement to answer all 49 questions. The resulting score is used to recommend that the application is either accepted and the plant allowed entry to Australia, evaluated further, or rejected and placed on a list of prohibited imports. The questionnaire and scoring system is reproduced in Appendix 2, and the Excel® spreadsheet that lists the questions and calculates the WRA score and recommended outcomes is currently available on the INTERNET at

http://www.agric.wa.gov.au/progserv/plants/weeds/Weedsci.htm.

The effectiveness of the WRA system was tested (Pheloung 1995) by calculating WRA outcomes of 370 plant species that are currently either crops or naturalised species or listed as declared noxious weeds in Australia. These outcomes were then compared with the weed status of each species, determined as either 'non-weedy', 'minor weed' or 'major weed' by averaging the ratings given to the species by a panel of twelve weed scientists. The panel members were not obliged to give an opinion on every species, and some species were rated by only two panel members.

The WRA performed well in these tests. It was as effective in screening out major weeds (weed status derived from Pheloung 1995 survey) as the previous AQIS protocol or the decision tree proposed by Panetta (1993). It also performed better than both of these systems at allowing non-weeds to enter Australia (Pheloung 1995). It is the most flexible protocol of the three as it does not require that all the questions posed be answered, and assessments result in a recommended decision in most cases, leaving relatively few cases that require more complex assessment. However, this ability to predict weediness is at odds with most current ecological theory (see Roy 1990, Perrins *et al.* 1992a, Williamson 1996, Crawley 1996). Moreover applied ecologists are finding that predictions of weediness require restricted plant groups and/or carefully defined habitats (Scott and Panetta 1993, Tucker and Richardson 1995, Reichard and Hamilton 1996), whereas the WRA aims to be applicable, without modification, to plants coming from anywhere in the world, to the whole of Australia. This chapter will test the WRA further in an attempt to understand how and why it appears to work so well.

3.2 GENERAL MATERIALS AND METHODS

Throughout this chapter, the WRA questionnaire, test species list and weed status categories (non-weed, minor weed and major weed) are those used by Pheloung (1995). Where more than one questionnaire had been completed for a species, one was randomly selected to be used in analyses to give 370 test species in total.

3.3 TESTING THE ROBUSTNESS OF THE WEED STATUS CATEGORIES USED TO TEST THE WRA

The accuracy of the WRA was tested using a list of plants already naturalised or planted in Australia (Pheloung 1995). Accuracy depends on the ability to correctly identify weedy and non-weedy species. In considering the results of the accuracy tests of the WRA, we must also consider how widely acceptable is the weed status allocated to the species used in the tests. There is of course no universal agreement on the magnitude of the problem each naturalised plant species may pose. Pheloung (1995) addressed this problem by averaging the opinions of 2-12 weed management professionals to derive weed status categories of 'non-weed', 'minor weed' and 'major weed', and used these categories (referred to as survey categories) exclusively in reporting on the accuracy of the WRA. Five weed management professionals assessed the 370 test species, but four of these also participated in the survey that derived weed status categories used for testing the accuracy of those assessments. Using the same people to answer the WRA questions as were used to construct the weed status categories may have confounded the findings as both the assessments and the survey categories rely to some extent on opinion. How universal are the weed status opinions used to test the WRA? Are they very different from those obtained by referring to published literature, and does the use of information from the literature alter the measured accuracy of the WRA?

3.3.1 Methods

To construct additional weed status categories for comparison with those derived by Pheloung (1995), four references, each of which is a compilation of information from many sources, were used (Parsons and Cuthbertson 1992, Carr *et al.* 1992, Humphries *et al.* 1991, Swarbrick 1983, Kleinschmidt and Johnson 1977, and Cowie and Werner 1987). Combined, these references provide information on all Australia's noxious weeds plus some other weeds of Australian agriculture, and information on which economic sectors are most affected by the weeds. Humphries *et al.* (1991) in particular compile published and unpublished data to produce lists of environmental weeds of Western Australia, South Australia, Victoria, Tasmania, northern Australia, tropical lowlands, subtropical rainforest and south-east Queensland. Table 3.1 describes weed status categories constructed using these sources. To avoid confusion with those used in Pheloung (1995), these categories will be denoted 'weed status (litt.)', and those used in Pheloung (1995) 'weed status (survey)'.

The accuracy of the WRA in assessing risk can be considered in a number of ways. Its capacity to identify and reject weeds outright (i.e. without requiring that they be evaluated further) can be calculated by dividing the number of weeds rejected by the total number of weeds assessed. Similarly, its ability to correctly identify non-weeds outright is calculated by dividing the number of non-weedy species accepted by the total number of non-weeds assessed. Its overall accuracy is calculated by dividing the sum of the number of non-weeds accepted and the weeds rejected by the total number of species assessed. A measure of how well the WRA acts as a quarantine screen in the second tier of the AQIS plant introduction procedure, or what I will call 'screening accuracy', can be calculated by summing all weeds rejected or given an 'evaluate further' outcome and the non-weeds accepted, and then dividing the result by the total number of plants assessed.

Estimates of the variation in these accuracy measures were obtained by randomly assigning all the WRA test species which had more than the minimum set of questions answered (359 species in all) to four groups of 72 and one group of 71. The process was then repeated once, giving a total of ten subsets of the test species data. The mean, standard deviation and 95% confidence intervals of the above accuracy estimates of the WRA were calculated using these subsets as replicates. These re-samples are thus not completely independent and may underestimate variability.

Table 3.1 Criteria used to construct weed status categories. from literature

Weed status category	Criteria
Environmental weed	Listed as a weed of the environment in Parsons and Cuthbertson (1992), Carr *et al* (1992), Humphries *et al* (1991), Swarbrick (1983), Kleinschmidt and Johnson (1977), or Cowie and Werner (1987).
Weed of cultivation	Listed as a weed of cultivation in Parsons and Cuthbertson (1992), Swarbrick (1983), or Kleinschmidt and Johnson (1977).
Pasture weed	Listed as a weed of pastures in Parsons and Cuthbertson (1992), Swarbrick (1983), or Kleinschmidt and Johnson (1977).
Other weed	Listed as a weed of some other type (eg. aquatic) in Parsons and Cuthbertson (1992), Carr *et al* (1992), Humphries *et al* (1991), Swarbrick (1983), Kleinschmidt and Johnson (1977), or Cowie and Werner (1987).
Non-weed	Not listed as a weed by any sources cited above.

3.3.2 Results

There are some important discrepancies (Table 3.2) between the weed status categories derived from the literature and those constructed for the purpose of testing the WRA. Twenty per cent of plants described as non-weeds in the WRA report (Pheloung 1995) are described as weeds in the literature, most of them (88%) as environmental weeds. Environmental weeds are well represented in the test species list, being 25% of the species tested. Half the plants not listed as weeds at all in the literature were described as minor (40%) or serious (10%) weeds in the WRA report.

The screening accuracy values for the WRA when calculated using weed status categories derived from the literature barely lie within the 95% confidence intervals of those calculated using the survey-derived categories (Table 3.3). The general effect of the weed status definitions derived from the literature was to produce higher accuracy values for weed identification but lower overall accuracy figures.

The accuracy of the WRA is at best 75% in rejecting weeds outright (Table 3.3), but as low as 40% in accepting non-weeds.

Table 3.2 Breakdown of weed status for the species used to test the WRA.

Weed status categories derived from the literature	Weed status categories derived from the opinions of up to 12 weed management professionals			
	Total	Non-weed	Minor weed	Serious weed
Non-weed	134	67	53	14
Weed of cultivation	16	0	7	9
Environmental weed	89	15	41	33
Pasture weed	26	0	6	20
Other weed	8	1	6	1
Weed of both cultivation and the environment	25	1	18	6
Weed of both cultivation and pasture	26	0	8	18
Weed of both pasture and the environment	28	0	4	24
Weed of cultivation, pasture and the environment	28	0	10	8
All weed categories	236	17	100	119
Total species categorised	370	84	153	133

Table 3.3 How the apparent accuracy of the WRA changes with the way weediness is defined.

Function tested	% Accuracy if survey is used to identify weeds			% Accuracy if literature is used to identify weed		
	Mean	S.D.	95% C.I.	Mean	S.D.	95% C.I.
Weeds rejected	70	6.7	±4.8	75	7.0	±5.0
Non-weeds accepted	54	10.2	±7.3	40	11.2	±8.0
Overall accuracy	65	6.8	±4.9	62	5.7	±4.1
Screening accuracy	85	5.6	±4.0	76	6.6	±4.7

3.3.3 Discussion

The difficulty of defining the word 'weed' is highlighted by the discrepancies between the weed status assigned by a panel of 2-12 weed management professionals and that obtained by consulting weed lists in the published literature. The survey derived categories for weed status were obtained by averaging the opinions of 2-12 people, whereas for the literature-derived categories a species was called a weed if it appeared on one or more of the weed lists cited. In this way the 'minor weed'(survey) category used to assess the WRA (Pheloung 1995) could include a large number of cases where a plant is considered to be a major weed by one or two panel members and not to be a weed at all by an equal number of panel members.

What is more noteworthy is that about half of the plants described as non-weeds in published literature (67 of 134 species in Table 3.2) were not considered to be so at all by the survey panel. Perhaps these species have increased in importance since the publication appeared.

The difference in identities of 'non-weeds' is important as one of the advantages of the WRA was thought to be the fact that it allows more non-weeds entry to Australia.

Clearly it would be politic to be certain that it does do that, rather than just giving the appearance of doing so by slightly altering the perception of 'non-weed'. It also influences the calculation of accuracy, resulting in a screening accuracy of 85% if the survey derived categories are used and 76% if the literature derived categories are used (Table 3.3).

3.4 THE EFFECT OF ANSWERING MORE THAN THE MINIMUM NUMBER OF QUESTIONS

A minimum set of ten questions (two questions from the biogeography/historical section of the questionnaire; two from one the undesirable traits section and six from the remainder of the questionnaire; see Appendix 2) must be answered for an assessment to be made. Generally points are given on WRA questionnaires for answering 'yes' to a question on a weedy trait and either 0 or -1 is given for answering 'no'. There is no penalty for not answering a question except for two questions (questions 2.01 and 2.02) on how suitable the Australian climate is for the species being tested where a maximum of two points are awarded to each question if the question is left unanswered. Recommendations of 'accept' (i.e. allow entry) are given to applications with total WRA scores of less than 1, while those with scores greater than 6 are rejected. Scores from 1 to 6 are given 'evaluate further' recommendations (i.e. they are not allowed entry unless further investigation indicates that the risk is acceptably low). Does the likelihood of rejection therefore increase with the number of questions answered?

3.4.1 Methods

Kruskal-Wallis one-way nonparametric ANOVAs were performed on the number of responses of 359 WRA questionnaires to detect the effect of the number of responses for each questionnaire on its assessment outcome. *P*-values were calculated using χ^2 approximation (Sokal and Rohlf 1995).

3.4.2 Results

There was no apparent penalty for answering a greater number of questions. In fact species which achieved 'accept' recommendations had had more questions answered than those with 'evaluate' or 'reject' outcomes (Table 3.4). Although the minimum number of questions that could be answered for an assessment to be made is 10, the lowest average number of the weed status x outcome groups was well above that: an average of 23 questions were answered by rejected non-weeds.

3.4.3 Discussion

The clear relationship between the number of answers given per questionnaire and the outcome obtained (Table 3.4) is evidence of the precautionary principle underlying the WRA. Most importation requests can be expected to be for species that are suited to an Australian climate and have propagules likely to be intentionally dispersed by people. These characteristics would give most applications a starting score of 5 points (2 points for question 2.01, 2 for 2.02 and 1 for 7.02). An additional point would be awarded to plants that produce viable seed (question 6.02). Plants with a total WRA score of less than 1 are recommended for importation. In order for that to happen, the number of negative answers to questions on the questionnaire on weedy traits would have to outnumber the number of positive answers by at least 5. The onus is therefore on the importer to show that the plant does not possess characteristics thought to contribute to potential weediness.

Table 3.4 Average number of questions answered by outcome type and weed status. Kruskal-Wallis one-way nonparametric ANOVA were used to test the hypothesis that there was no difference in the number of questions answered between outcome groups. *P*-values were calculated using χ^2 approximation.

Weed status	Number of species	Mean number of questions answered by WRA outcome			*P*-value
		Accept	Evaluate	Reject	
Survey derived categories					
Non-weeds	80	38	27	23	0.0000
Minor weeds	146	37	32	28	0.0003
Serious weeds	133	-	39	33	0.0007
Literature derived categories					
Non-weeds	127	36	28	24	0.0000
Weeds	232	33	32	30	NS
Total	359	35	30	28	0.0000

3.5 THE EFFECT OF PHYLOGENETIC PATTERNS PRESENT IN THE AUSTRALIAN WEED FLORA ON TESTS OF THE WRA PERFORMANCE

The naturalised flora of Australia was not introduced through a phylogenetically random selection of exotic species. The first European settlers introduced a disproportionate number of crop and pasture species, mainly from Europe and around the Mediterranean Sea. Many of these species, or their close relatives, now constitute our present weed flora. Were each of our present weedy species taken as an individual data point in analyses of weedy traits, it is possible that the traits found to be significant will reflect attributes common to the families best represented in the naturalised flora from Europe, without their being traits that explain weediness (*cf.* Rees 1995, Harvey 1996).

The source of our future weed problems is likely to be very different. In contrast to the majority of previous plant introductions, most plants introduced to Australia over the past 25 years have been of ornamental species, and the majority have come from Africa and the Americas (Groves 1998). For the WRA to provide an effective quarantine screen for future weeds, it must be able to detect weeds across the phylogenetic spectrum.

I will therefore address the following questions. Was the species list that was used to test the WRA representative of the Australian weed flora? Does the likelihood of a favourable WRA outcome change substantially with the taxonomic group a plant may belong to? For example, does the WRA detect weeds amongst broadleaf species better than it does amongst grasses?

3.5.1 Methods

The phylogenetic composition of the test set of species was compared with that of the Australian naturalised and weed flora to see how well it represented the non-indigenous flora. Then test species were grouped by family and the accuracy of the WRA in screening for weeds from the largest families represented was compared using the same accuracy measures described in section 3.3.1.

The appropriate way to analyse data that may be phylogenetically linked is to use comparative methods (see Harvey and Pagel 1991, and Rees 1995). The WRA test species data were therefore analysed using a method derived from Felenstein (1985) in the Comparative Analysis by Independent Contrasts (CAIC) software developed by Purvis and Rambaut (1995). In order to partition the among-species variance into phylogenetically independent comparisons, the package requires an estimate of the phylogeny of all species in the data set. The strict consensus trees in Chase *et al.* (1993) were used to describe the inter-family relationships, and sub-family relationships were mapped according to Stace (1991), Mabberley (1990) and Gibb Russell (1991). All branch lengths in the phylogeny were set to the same length.

CAIC software is unable to analyse clades more than 20 nodes long (Purvis pers. comm. 1998). However, when the WRA test species were coded for phylogeny many codes were more than twenty nodes long. The data set was therefore analysed after dividing it into four major groups of common ancestry according to the phylogeny given in Chase *et al.* (1993, p.551), which reduced the number of nodes to below that accepted by the software. These groups comprise: (a) The Asteridae including Ericales, Primulales, Ebenales, Santales, Apiales, Cornales, and some Rosales; (b) The Rosidae including Violales, Malvales, mustard-oil families, and higher Hamamelidae; (c) Monocots and (d) The remaining groups ie. caryophyllids, Gunnaraceae, hamamelids, ranunculids, paleoherbs, Magnoliales, Laurales, Ceratophyllaceae, gnetophytes, Pinaceae, other conifers, *Ginkgo* and cycads. Because of their prominence in the Australian weed flora the Asteraceae, Fabaceae and Poaceae were also analysed as separate groups.

WRA scores in each group (a-d) were checked for normality. Then the comparative method was used to compare the values of the WRA scores between the weeds and naturalised non-weeds in each group. Weed status was analysed in two separate analyses using a dichotomous variable (either naturalised but not weedy or naturalised weed) and as a three-state categorical variable (1 = naturalised non-weed, 2 = naturalised non-noxious weed and 3 = naturalised noxious weed according to the literature sources given in section 3.3.1). Under the null hypothesis that WRA scores do not differ with different weed status, we expect half the contrasts calculated for WRA score to be positive (indicating that scores increase with increasing weediness) and half to be negative. The sign test (a nonparametric alternative to the paired *t*-test which requires only that the samples are random and independent) was used to test the significance of departures from this relationship (see Crawley *et al.* 1996).

3.5.2 Results

A third of Australia's noxious weeds belong to the Asteraceae or Poaceae (Table 3.5), and 40% of the species used to test the WRA came from these families. However non-weeds from the Asteraceae and Poaceae were not well represented in the test species.

The Fabaceae were well represented among the test species comprising 17% of all species tested.

Table 3.5 Breakdown by family of the WRA test data set, Australian noxious weeds (Parsons and Cuthbertson 1992) and Australian naturalised flora (Hnatiuk 1990).

Family	Proportion of species (%)				
	WRA test data set			Noxious weeds	Naturalised flora
	weeds	non-weeds	total		
Asteraceae	12	2	14	22	11
Fabaceae	17	10	17	8	9
Poaceae	26	8	26	8	16
Other families	43	16	43	62	64

The ability of the WRA to identify weeds may depend on what family a plant belongs to: the accuracy levels for the largest weedy families are quite different from each other (Table 3.6). Species from the major weedy families frequently received 'further evaluation' outcomes indicating that the WRA is unable to distinguish between weeds and non-weeds for a large proportion of plants in the families that provide most of our noxious weeds.

When the literature was used as the authority on weed status (Table 3.6), no non-weeds from the Poaceae or Asteraceae were predicted as non-weeds by the WRA. Relatively few non-weedy species were tested from these families although 25% and 17% of the total species used to test the WRA were drawn from the Poaceae and Asteraceae respectively. Similarly, when the Pheloung (1995) survey was used as the authority on weed status no Asteraceae were given ‘accept’ outcomes.

Although one of the advantages of adopting the WRA was thought to be the minimisation of the number of importation requests requiring further evaluation, this is not the case for all plant families. A large number of requests for importation will be received for grasses and legumes because of their importance in pasture improvement programs, yet a very high proportion of these (34% and 85% respectively of all species tested in these families) could not be assessed outright by the WRA and would require further evaluation. This lack of certainty in distinguishing weeds and non-weeds contributes to the lower overall accuracy of prediction for these families.

Table 3.6 Comparison of the accuracy of the WRA in distinguishing between weeds and non-weeds in the major weedy families (see section 3.3.1).

Function tested	Asteraceae (n=53)	Fabaceae (n=57)	Poaceae (n=90)	Others (n=159)
Accuracy using weed status categories from the literature				
% Overall accuracy	79	33	52	72
% Weeds identified	95	40	70	77
% Weeds requiring further evaluation	2	44	27	20
% Non-weeds identified	0	28	0	62
% Non-weeds requiring further evaluation	56	53	57	16
Accuracy using weed status categories from Pheloung (1995) survey				
% Overall accuracy	85	38	58	74
% Weeds identified	90	42	66	71
% Weeds requiring further evaluation	10	42	32	20
% Non-weeds identified	0	33	26	85
% Non-weeds requiring further evaluation	67	58	42	15

The WRA scores are higher for weeds than for non-weeds in the Asteridae, Rosidae and Monocots, after phylogenetic relatedness was controlled using CAIC (Table 3.7). WRA scores also increase with increasing weediness in these groups, naturalised plants having lower WRA scores than non-noxious weeds which in turn have lower WRA scores than declared noxious weeds (Figure 3.1). The CAIC analysis produced fewer independent contrasts for the remaining groups in Table 3.7, and although their signs are all positive, indicating that WRA score increases with increasing weediness at each node where a contrast was calculated, they are not significantly so for differences between weeds and non-weeds. The relationship between WRA scores and weediness in the three largest weedy families was strongest in the Poaceae, less so in the Asteraceae and not significant in the Fabaceae ($P = 0.1$, Table 3.8).

3.5.3 Discussion

The importation of plant species to Australia has not occurred in a taxonomically random way, and a large proportion of Australia's present noxious weeds come from only three plant families. This fact was considered in designing the WRA questionnaire, and there is a series of questions (eg the 'plant type' questions on the questionnaire form) which result in an increase in the WRA score if the plant belongs to a perceived high risk family. It was also considered in selecting species to use in tests of the WRA. However, the test species did not include a reasonable proportion of non-weeds from these families (Table 3.5), and this may have had the effect of inflating estimates of the accuracy of the WRA and reducing estimates of the number of applications which will require further evaluation.

Table 3.7 Phylogenetically controlled contrasts for weed status and weediness for major taxonomic groups of higher plants, comparing the WRA scores of non-weed with weed species.

If WRA scores do no differ with different weed status, we would expect half the independent contrasts calculated for WRA score to be positive (indicating that scores increase with increasing weediness) and half to be negative. The sign test was used to test departures from this relationship. (* = P<0.05 *** = P<0.001).

Taxonomic group	No. of species tested in taxonomic group			Trait tested	No. of Independent Contrasts			Significance
	non-weeds	weeds	noxious weeds		Positive	Zero	Negative	
Asteridae	18	8	65	Weed or not	20	0	0	***
				How weedy	20	1	2	***
Rosidae	57	12	2	Weed or not	21	0	2	***
				How weedy	24	0	2	***
Monocots	57	23	34	Weed or not	24	1	2	***
				How weedy	30	1	3	***
Other taxa	19	1	7	Weed or not	4	0	0	N.S.
				How weedy	7	0	0	*

Figure 3.1 The relationship between WRA score and weed status for three major plant groups. Independent contrasts were calculated for WRA scores using CAIC. Phylogenetic groups follow Chase *et al.* (1993, p551) Categories on the x axes are: non-weeds=naturalised species not listed as weeds in literature cited, weeds=plants described as weeds but not declared noxious, and noxious=declared noxious weeds.

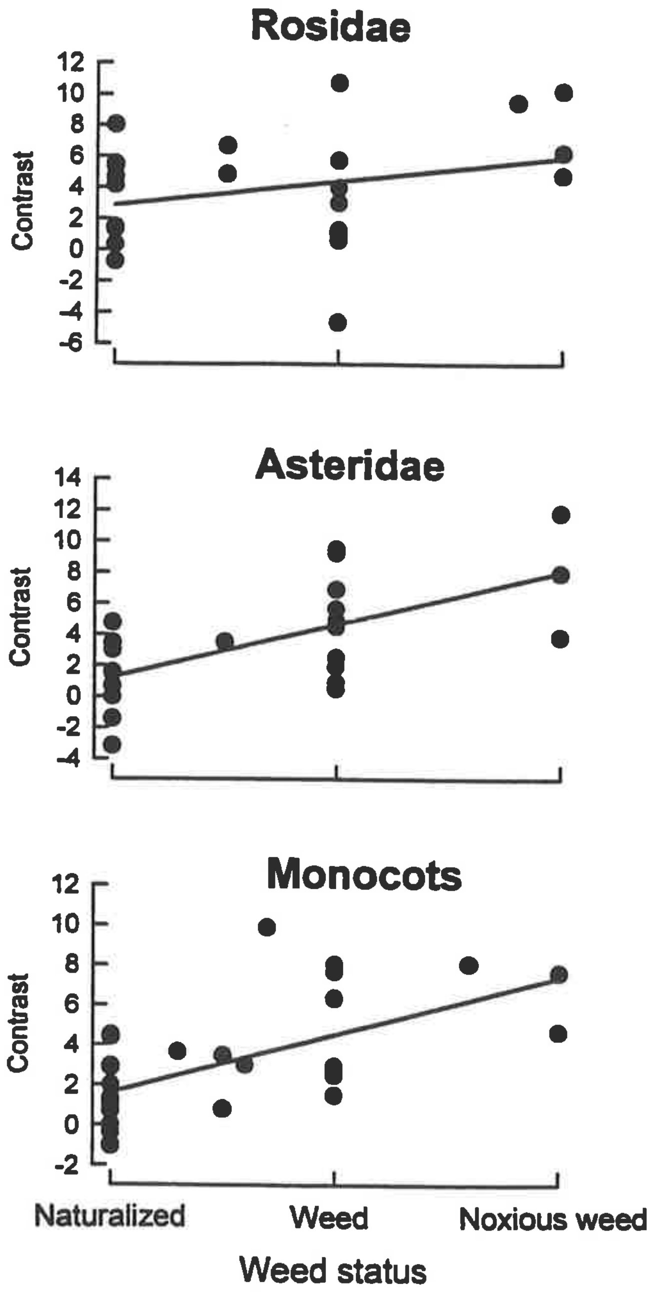


Table 3.8 Phylogenetically controlled contrasts for weed status and weediness at the family level, for the three largest families in the Australian weed flora, comparing the WRA scores of non-weed with weed species (* = P<0.05 *** = P<0.001).

Family	No. of species tested in taxonomic group			Trait tested	No. of Independent Contrasts			Significance
	non-weeds	weeds	noxious weeds		Positive	Zero	Negative	
Asteraceae	7	2	44	Weed or not	9	0	0	**
				How weedy	9	0	1	*
Fabaceae	43	8	2	Weed or not	6	0	1	N.S.
				How weedy	6	0	1	N.S.
Poaceae	47	21	19	Weed or not	17	1	2	***
				How weedy	18	1	2	***

The WRA is not uniformly accurate in identifying weeds and non-weeds from different families (Table 3.6). Although the accuracy in identifying weeds in the Asteraceae is high (95%, Table 3.6) the accuracy of identifying a non-weed in that family is 0. Despite the fact that all applications for grasses attract an additional point (question 5.02 of the questionnaire) the accuracy of assessment outcomes is lower for grasses. Only 70% of weedy grasses are recognised as such and again, the level of accuracy of detecting non-weeds is 0. Accuracy is also low in the Fabaceae: less than half of the weedy and non-weedy species were correctly identified (40% and 28% respectively).

One of the advantages of adopting the WRA was thought to be the minimisation of the number of importation requests requiring further evaluation, and yet 85% of all Fabaceae assessments and 34% of Poaceae assessments of the test species could not be made using the WRA alone, and these cases would all require further evaluation. These figures may seriously underestimate the quarantine administrative implications as the test species included few non-weeds compared with the likely situation for importation requests. There will be a large number of future applications for introductions for plants from these families, for the horticulture and pasture industries. Clearly, the accuracy of initial assessments of plants in these families needs to be improved.

The high rejection rate of non-weedy plants from the Poaceae and Asteraceae suggests that the WRA may reduce the risk of new weeds from these families entering the country, in part by refusing entry to plants that have taxonomic similarities to these families, rather than by detecting weedy tendencies *per se*. However, when the responses of the WRA test species were analysed using comparative methods (thus controlling for their taxonomic similarities), WRA score was significantly higher for weeds than for non-weeds and increased with increasing weediness in these families (Table 3.7). In other words the WRA score does generally detect differences in weediness independent of phylogeny. The CAIC analysis tested WRA scores and not WRA outcomes. It is possible, and may be the case within the Poaceae, that although weeds generally have higher WRA scores than non-weeds, the majority of both weeds and non-weeds score above the cut-off score required to reject an importation application.

There was no significant relationship between the WRA score and whether the plant was a weed or not when plants in the Fabaceae were analysed using comparative methods (Table 3.8). Hence the risks of allowing a potential weed into Australia are unlikely to be reduced should the WRA alone be used to screen plants from this family. Clearly the Fabaceae require further study in order for us to be able to identify more confidently the most likely future weedy species in this family.

The results of the CAIC analysis in Table 3.7 support the usefulness of the WRA score in distinguishing between weeds and non-weeds among the Asteridae, Rosidae and Monocots. The negative contrasts from the analysis could fruitfully be used to pinpoint nodes in the phylogeny where the relationship between WRA score and weediness is negative. This could provide starting points for work on if, or how, these groups should be assessed separately for their weed potential.

3.6 DOES IMPROVED ACCURACY MEAN MORE RELIABLE PREDICTION OF FUTURE WEEDS?

The probability of a plant species ever being considered to be a weed is quite small. Williamson and Fitter (1996) estimate that around 10% (between 5% and 20%) of plants introduced to a new environment become casual, 10% of these become naturalised and about the same proportion of these naturalised species go on to become pests. When an event is as rare as this it is much harder to forecast it accurately because the probability of correctly predicting an event is a function not only of the accuracy of the system used to predict the event, but also the frequency of that event occurring at all. This phenomenon is referred to as the 'base-rate effect' and has wide applicability for understanding rare events, but its effects are often counter-intuitive (see Matthews, 1996). For example, the ability of a weather forecaster to predict rain with 90% accuracy would sound superficially very impressive. However, to understand the usefulness of this level of accuracy, we would also need to know the base rate probability of rainfall – the average probability of getting rain. If rain normally occurs on only 1% of days, then the 10% of times that the forecaster makes a mistake by identifying dry days as rainy will swamp the very few days (90% of 1 %) when he correctly predicts a rainy day as rainy. In other words, at such a low base rate, even if the forecaster predicts rain, we would be far better off ignoring his forecast unless we were morbidly afraid of rain (Matthews 1997). Similarly, because of the rarity of weeds in the introduced flora, and the low rate of naturalisation of introduced species, there is a base-rate effect involved in calculating the probability of correctly predicting weediness. What is the probability that future WRA assessments will be correct given the generally low base-rate probability of a plant becoming a weed in Australia?

3.6.1 Methods

Reliability as defined here is not the same as accuracy. One aspect of accuracy is, as shown in 3.3.1 above, the proportion of correctly identified weeds and non-weeds to the total number of plants assessed. Reliability is different. Any sample of plants rejected by the WRA will include a proportion of non-weedy plants wrongly identified as being weedy. The proportion will vary with the accuracy and the base-rate of weediness, and is what we use here to measure reliability. We are concerned with two aspects of reliability:

1. the probability that a plant allowed in by the WRA will become a weed (P_{aw}), where

$$P_{aw} = \frac{\text{(number of weeds allowed entry)}}{\text{(number of plants allowed entry)}} \qquad \textbf{(Eqn 1)}$$

and

2. the probability that a rejected plant would have been a weed (P_{rw}), where

$$P_{rw} = \frac{\text{(number of weedy species rejected)}}{\text{(number of plants rejected)}} \qquad \textbf{(Eqn 2)}$$

Note that, because reliability depends on the base rate of weediness, it does not make sense to calculate reliability for the WRA with respect to the data set of Pheloung (1995). The 370 test species used by Pheloung (1995) were not a random sample of plant species – 77% of them were weeds, giving an artificially high base-rate for weediness. The theoretical reliability of the WRA will be derived here using accuracy (which is not base-rate dependent) calculated from the Pheloung data set, together with a range of base-rates for weediness likely to be found in nature.

Crawley *et al.* (1996) estimated that 0.53% of all intentional and unintentional introductions to Britain resulted in naturalisation. The rate at which naturalised plants have become weeds in Australia has been calculated for plants from South Africa as 28% (Scott and Panetta, 1993) for pasture plants as 17% (Lonsdale 1994) and declared noxious weeds as 10% (Panetta *et al.* 1994). Williamson (1996) also estimates that this figure is likely to be on average about 10% and vary between 5 and 20%. Using these published data we obtain estimates of the base-rate probability of an introduced plant becoming a weed that range from at least 0.053% (= 0.53% x 10%) to as much as 5.6% (= 20% x 28%). Deliberate plant introductions, which is after all what the WRA will be dealing with, can be expected to establish and become naturalised at a higher rate than accidental introductions, because they will be assisted to establish. Therefore, the rate at which naturalised plants become weeds will depend, in part, on the origin of the exotic species and the broadness of the definition of the word weed. Consequently, the true base-rate figure for deliberate introductions to Australia is most likely to be between 2% (Panetta *et al.* 1994) and 5.6%. These values are the products of the highest chance of establishment (20% from Williamson 1996) and the various calculated rates of naturalised plants becoming weeds in Australia given above.

Table 3.9 is an example of how to calculate outcomes at a given level of accuracy and a given weed base-rate. It gives the probability of correctly predicting that a plant will be a noxious weed or not if it has already become naturalised in Australia. A base-rate probability of 2% was used to provide the totals in the bottom row of Table 3.9 (ie. for every 1000 introduced plants 20 will become noxious weeds and 980 non-weeds). The first column is calculated assuming an 85 % 'screening accuracy' of the WRA: 85% of 20 weeds, or 17 species, will be correctly identified as weeds by the WRA and either rejected outright or provisionally (i.e. require further evaluation) and the remaining 3 species will be allowed entry to Australia. This is clearly an effective initial screen. The main problem is the false positives: the second column shows that 147 of the 980 non-weeds would be rejected. Thus, of a total of 164 species rejected as potentially weedy, only 17 (roughly 10%) would in reality have turned out to be weeds. Despite an apparently high accuracy, roughly nine out of ten plants identified as potential weeds are not likely to be so.

The effect of varying base rate and accuracy on P_{aw} and P_{rw} (Eqns 1 and 2) was then explored for each level of accuracy and each base-rate by constructing contingency tables, following the method described by Matthews (1997).

3.6.2 Results

Figure 3.2a, constructed using the results of the contingency tables described above, shows how the base-rate probability for weediness interacts with the accuracy of screening weeds to reduce the reliability of weed assessments. Using the maximum base-rate estimate of 5.6% , and referring to Fig 3.2a, it is likely that only 25% of all plants rejected using the WRA will in fact be weeds. If even the widest definition of weed is used, the accuracy of the WRA would have to be 94% or greater before more than 50% of the plants rejected by the WRA were weeds. If noxious weeds only are of interest, then the accuracy of the WRA would have to be 98% or higher before more than half the plants not allowed entry were correctly predicted as potential noxious weeds. However, more positively, the base-rate effect also means that there is a much smaller probability of an accepted plant actually being a weed than the accuracy of a screening system alone would imply (Fig 3.2b). Taking the 74% accuracy curve for example, we see that if the base-rate probability is 5.6%, then only 2% of plants assessed and accepted by the WRA will in fact be weeds. This drops to 0.71% if the 2% minimum estimated base-rate probability of plants becoming weeds is used.

3.6.3 Discussion

Between 75 and 90% of a random sample of species rejected by the WRA would never have been weeds, according to the estimates presented in this Chapter. Once a plant species has been rejected by the WRA it is appended to the list of prohibited imports. It remains to be seen whether this level of reliability proves acceptable to horticulturists and to agencies attempting agricultural improvement, and to Australia's trade partners.

Table 3.9 The base-rate effect and the reliability of the WRA.

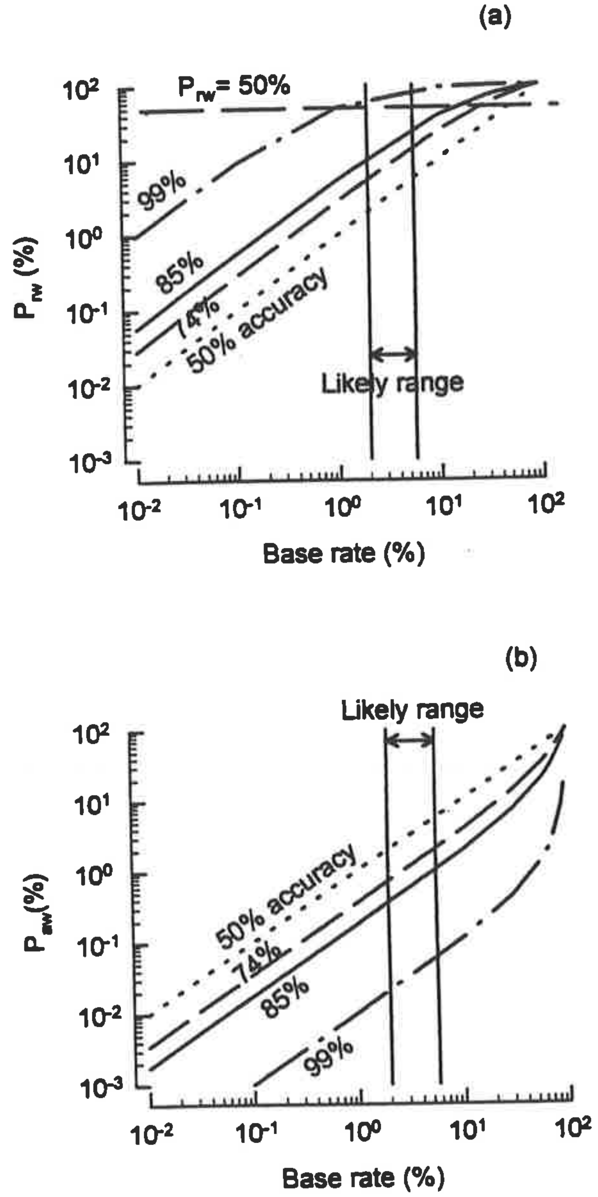
Contingency table to calculate the reliability of the WRA, assuming in this example a 2% base-rate probability of an introduced plant becoming a weed and that the WRA is 85% accurate in screening out weeds and accepting non-weeds. Despite a very high accuracy, only 17 out of 164 "weeds" identified are actually weedy. See section 2.2 for definitions of accuracy and reliability.[†]

	Number of weed species	Number of non-weeds	Totals
Predicted weed (not accepted by WRA)	17	147	164
Predicted non-weed (accepted by WRA)	3	833	836
Totals	20	980	1000

[†] For this example I have used the best-case 'screening' accuracy rate of 85% (see Table 3.3). However, the accuracy of the WRA in correctly identifying non-weeds is actually 54%, while that for rejecting weeds outright is 70% (Table 3.3). If these values were used, the rate of false positives would be far worse - perhaps only 14 of about 550 rejected plants would be true weeds, at a base-rate of 2%.

Figure 3.2 The relationship between accuracy and the base-rate probability with which imported plants become weeds..

Figure 3.2 (a) shows the proportion, P_{rw} , of weeds amongst species rejected by screening systems of 50%, 74%, 85% and 99% accuracy. Figure 3.2(b) shows the proportion of weeds, P_{aw},, amongst species permitted entry by screening systems of 50%, 74%, 85% and 99% accuracy.



An alternative view (Lonsdale 1994) is that almost any species has the potential to become weedy, given the right combination of chance and environment. This is likely to be particularly true for environmental weeds, which tend to be marked less by the noxious characters of the individual plant and more by their great abundance in natural systems. Under this view we would be better advised to reduce the number of introductions by predicting which species are likely to be useful (perhaps an easier task than predicting weeds) and allowing in only them. It does however seem that, at present, such an inversion of quarantine philosophy is too radical to be acceptable.

3.7 SUMMARY AND CONCLUSIONS

While the WRA has been adopted the studies reported in the Chapter show clearly that some of its value may be illusory. The WRA was tested using plants already present in Australia. There was an implicit assumption in doing so that the factors that enable a plant to become naturalised in a new environment largely overlap with those that allow it to become a weed. This assumption can not be tested at present because of the lack of reliable information on species permitted entry that failed to establish or naturalise.

Nonetheless, the WRA is fairly accurate at identifying weeds and non-weeds from a group of naturalised plant species. The level of accuracy depends somewhat on whether one accepts the weediness classification of the twelve experts or that of the literature. Furthermore, the choice of test species may have artificially elevated the apparent accuracy – for example the preponderance of weedy Poaceae amongst the test species, given that Poaceae are automatically given a high weediness score by the WRA, would have had this effect.

The accuracy of the WRA is not uniform across taxonomic groups. It is particularly poor when assessing weedy Fabaceae, which are already becoming naturalised in Australia at an alarmingly high rate (Groves 1998) and are likely to be a major taxon amongst future importations, given the desire to introduce legumes for pasture improvement throughout Mediterranean and tropical Australia. The accuracy of the WRA is higher when it is used to detect weeds than it is when used to detect non-weeds. None of the non-weedy Poaceae or Asteraceae were accepted by the WRA. That means that although it may screen out weedy species, the WRA will also screen out the large number of potentially beneficial and benign species from these families.

The WRA does provide a good quarantine screen as it will reduce the flow of new weed species into the country. It does this in part by implicitly assuming that each new introduction is a potential weed and placing the burden of proof is on the applicant to show in what ways the plant does not resemble a weed.

CHAPTER FOUR: REFINING THE WRA QUESTIONNAIRE

4.1 INTRODUCTION

The requirement for information on the extent of species distribution in and away from its area of origin is a common component of many weed screening systems. Plants that have managed to become widely dispersed from their area of origin, or have become weeds in other places, are likely to become widely dispersed or weedy in a new environment if that new environment resembles its original range climatically (Reichard and Hamilton 1996). The WRA is unusual in that it considers information on geographic distribution and the responses to a large number of questions on species biology and ecology, and then uses these responses to modify the predictions made mainly on historical and biogeographical information.

Certain traits have been suggested as good predictors of weediness but are not included in the WRA questionnaire (for example those listed by Roy, 1990). Other traits have WRA questionnaire response rates in the test data set too low to detect significant trends, e.g. longevity of propagule bank. Seed weight is thought to be a character that may be particularly useful in distinguishing potential environmental weeds because it is easy to measure, is positively correlated with invasiveness (Burke and Grime 1996, Rejmanek and Richardson 1996), and perhaps also drought hardiness (Baker 1972).

The WRA was developed without testing whether the questions it asks are of predictive value for screening plants before they are imported to Australia. However, once the WRA was adopted, it was envisaged that 'such details would be evaluated so that questions can be reworded, added, deleted or replaced on the basis of accumulated experience' (Pheloung 1995).

This chapter aims to provide information to assist in that process. In particular I will attempt to detect questions that test for the same trait, and to show the biological, ecological and historical questions most useful in identifying weeds. I will discuss the need to use analysis of phylogenetically independent contrasts to assess the value of biological and ecological questions, and will also explore a source of possible additions to the questionnaire.

4.2 METHODS AND RESULTS

Throughout this section the WRA test species list and questionnaires are those used by Pheloung (1995). Where more than one questionnaire had been completed for a species, one was randomly selected to be used in analyses to give 370 test species in total. Weed status was ascertained through the literature sources used in Chapter 3 (i.e. Parsons and Cuthbertson 1992, Carr *et al.* 1992, Humphries *et al.* 1991, Swarbrick 1983, Kleinschmidt and Johnson 1977, and Cowie and Werner 1987). As there are no reliable data on plants that have been allowed entry to Australia and failed in the field, only species that are already growing in Australia could be used in the following tests. Unfortunately, this may mask the effect of questions aimed at identifying the risk of a plant becoming naturalised outside its site of initial introduction.

4.2.1 Redundant questions

It is arguable that many of the questions in the WRA are different ways of obtaining information on the same weedy trait. We would therefore expect that responses to these questions may be similar for the same plant. For example, species that are weeds elsewhere are more likely to become weeds in a new environment (Scott and Panetta 1993, Reichard and Hamilton 1996). We may therefore also expect to find that the questions related to the 'weed elsewhere' questions (questions 3.02, 3.03, and 3.04) in the WRA questionnaire are useful in distinguishing weeds from non-weeds.

PCORD Cluster Analysis software (Mc Cune and Mefford 1997) was used to determine whether the same questions tended to be answered in the same way by test species. Typically, in community ecology, various sites are ordinated based on the presence or absence of species so that groups of similar sites can be identified. The methodology here is analogous, except that the sites are WRA questions, and instead of species presence or absence at a site, we have the yes or no responses for each species to the questions as a means of characterising the latter. Ten 'replicate' re-samples of 255 species (255 cases is the maximum number of cases permitted by the software) were randomly selected from the 370 test species and response data were analysed using Sorensen distances and farthest-neighbour clustering to test the robustness of the observed links (Roberts 1986). Dendrograms were truncated at a level where approximately 80% of the variation had been apportioned to individual questions or groups of questions. This is an arbitrary stopping rule but it appeared that the more significant differences were above this level. The number of times that the same questions occurred in the same groups was noted for the ten 'replicates'.

Table 4.1 lists results of PCORD analysis showing the ten sets of questions most commonly answered in the same way. The ten groupings seem intuitively sensible. For example, we would expect highly domesticated plants (question 1.01) to have propagules that are dispersed intentionally by people (Question 7.02). However, the scoring for answers to these questions currently either minimises the importance of the common trait (as in the example just given, where answering 'yes' to both questions would result in a score of -2 points and answering only the second question would result in a score of 1 point) or exaggerates it (as is the case in most of the other sets shown in Table 4.1).

Overall, questions thought to target environmental weeds (see Appendix 2) were not frequently correlated with Question 3.04 ('Is the species an environmental weed elsewhere?). Question 3.04 was linked with question 4.09 ('Is it shade tolerant for part of its life-cycle?') in 5 out of ten re-samples, and with 4.12 ('Does it form dense thickets?) in 3 out of ten re-samples. In none of the re-samples, however, did question 3.04 ('Environmental weed elsewhere') cluster with the rest of the questions thought to target environmental weeds (these are questions 4.08 'Creates a fire hazard in natural ecosystems'; 4.10 'Grows on infertile soils'; 4.11 'Climbing or smothering growth habit'; 5.03 'Nitrogen fixing woody plant'; 7.05 'Propagules buoyant'; 7.06 'Propagules bird dispersed'; and 8.05 'Effective natural enemies present in Australia').

Table 4.1. WRA questions ranked by frequency (out of ten re-samples) with which the questions were linked in dendrograms of similarity The similarities were calculated on the basis of how similar were the responses for 255 species to each question.

Trait in common	Questions (WRA points scored for 'no' / 'yes')	Frequency of linkage
Domesticated plant	1.01 Is the species highly domesticated (0/-3) 7.02 Propagules dispersed intentionally by people (-1/1)	10
Cannot be controlled by cultivation	6.06 Reproduction by vegetative fragmentation (-1/1) 8.04 Tolerates, or benefits mutilation or cultivation (-1/1)	10
Unintended range expansion possible	7.06 Propagules bird dispersed (-1/1) 7.08 Propagules survive passage through the gut (-1/1)	10
May colonise new areas	1.02 Has the species become naturalised where grown (0/1) 3.01 Naturalised beyond native range (*/*)	9
Produce contaminant	3.03 Weed of agriculture elsewhere (*/*) 7.03 Propagules likely to disperse as a produce contaminant (-1/1)	9
Difficult to contain	3.03 Weed of agriculture elsewhere (*/*) 8.01 Prolific seed production (-1/1)	9
Unassisted persistence in the field	8.01 Prolific seed production (-1/1) 8.02 Evidence that a persistent seed bank is formed (-1/1)	9
Requires continued effort over time to control	3.03 Weed of agriculture elsewhere (*/*) 8.02 Evidence that a persistent propagule bank is formed (-1/1)	8
Common contaminant	3.05 Congeneric weed (*/*) 2.05 History of repeated introductions outside its natural range (*/*)	8
Unintended range expansion possible	7.01 Propagules likely to be dispersed unintentionally (-1/1) 7.05 Propagules buoyant (-1/1) 7.07 Propagules dispersed externally by animals (-1/1)	8

4.2.2 Identifying the most and the least useful questions

The relative usefulness of individual questions in identifying weeds was determined as follows. Firstly, the test species were divided into weeds and non-weeds according to the literature (Parsons and Cuthbertson 1992, Carr *et al.* 1992, Humphries *et al.* 1991, Swarbrick 1983, Kleinschmidt and Johnson 1977, and Cowie and Werner 1987). All the questions with 'yes or no' answers to which more than 50% of all weeds and all non-weeds responded were examined further because the most useful questions, and those likely to contribute to informed decisions about potential weediness, are those for which there is a high response rate.

Two methods were used to analyse the data on these questions: χ^2, which is appropriate to use if the test species are considered as data points unrelated except for their weed status; and CAIC which controls for phylogenetic relationships between species. Questions that were intended to identify high risk taxonomic groups (e.g. question 5.02 'Is it a grass?') were not included in the CAIC analysis, nor were questions that were obviously compromised by the fact that all test species already grow in Australia (e.g. question 2.01 'Species suited to Australian climate? ') because these, by their nature, would result in few or no independent contrasts. Each remaining question with response rates of 50% or more was tested using CAIC to see whether weeds are more likely than non-weeds to give a response that contributes to a higher WRA score. The data and methods are as described in Chapter 3 (section 3.5.1) and standardised linear contrasts were analysed following methods employed by Crawley *et al.* (1996). Only the

Asteridae, Rosidae and Monocots (as described in Chase *et al.* 1993, p.551) were analysed this way as there were insufficient species in the remaining groups to produce enough contrasts to test for significance. Table 4.2 lists the results of the χ^2 analysis and Table 4.3 lists the CAIC results for questions that showed a significant difference between weeds and non-weeds in at least one of the phylogenetic groups tested. When each species is considered to be an independent data point and analysed using χ^2 (Table 4.2), the responses for weeds appear to differ significantly from those of non-weeds for 18 questions. If the phylogenetic relationships in the data set are controlled for using CAIC, only two questions appear useful in distinguishing between weeds and non-weeds across all three taxonomic groups (Table 4.3). These two questions ('Propagules likely to be dispersed unintentionally' and 'Propagules water dispersed') were also found to be significant in the χ^2 analysis results.

4.2.3 Possible additions to the WRA questionnaire

A number of traits that have been suggested as good predictors of weediness are not included in the WRA questionnaire or have response rates in the test data set that are too low to detect significant trends. The longevity of the propagule bank is an example of the former, and seed weight and seed weight an example of the latter.

Table 4.2 'Yes/No' questions with a response rate > 50%

Significance of the difference between the 'Yes' : 'No' ratio of answers for weeds and non-weeds.

Question (score for 'No'/score for 'Yes')	% weeds answering 'Yes'	% non-weeds answering 'Yes'	Significance : * P<.05 **P<.01 ***P<.001	X^2 (d.f.=1)
7.01 Propagules likely to be dispersed unintentionally (plants growing in heavily trafficked areas) (-1/1)	77	27	***	59.68
3.03 Weed of agriculture [a]	75	18	***	58.03
7.05 Propagules water dispersed (-1/1)	68	17	***	53.52
7.03 Propagules likely to disperse as a produce contaminant (-1/1)	57	10	***	46.49
3.01 Naturalised beyond native range [a]	98	82	***	24.01
8.04 Tolerates, or benefits from, mutilation or cultivation (-1/1)	67	34	***	23.41
7.04 Propagules adapted to wind dispersal (-1/1)	56	26	***	21.32
6.06 Reproduction by vegetative fragmentation (-1/1)	58	33	***	19.18
4.01 Produces spines, thorns or burrs (0/1)	21	5	***	18.77
1.01 Is the species highly domesticated? (0/-3)	34	59	***	17.31
3.02 Garden/amenity/disturbance weed [a]	79	51	***	16.63
3.05 Congeneric weed [a]	53	29	***	15.51
4.05 Toxic to animals (0/1)	41	18	***	14.05
4.04 Unpalatable to grazing animals (-1/1)	39	17	***	12.88
8.01 Prolific seed production (>2000/m2) (-1/1)	45	24	**	9.55
4.12 Forms dense thickets (0/1)	24	8	**	9.59
2.05 Does the species have a history of repeated introductions outside its natural range? [a]	70	57	*	6.16
5.01 Aquatic (0/5)	6	2	*	4.08
5.02 Grass (0/1)	36	25	N.S.	3.17
4.11 Climbing or smothering growth habit (0/1)	16	10	N.S.	2.33
2.04 Native or naturalised in regions with extended dry periods (0/-1)	57	62	N.S.	1.13
6.02 Produces viable seed (-1/1)	97	98	N.S.	0.72
2.03 Broad climate suitability (environmental versatility) (0/1)	14	11	N.S.	0.59
4.09 Is a shade tolerant plant at some stage of its life cycle (0/1)	27	31	N.S.	0.47
5.03 Nitrogen fixing woody plant (0/1)	5	4	N.S.	0.29
4.03 Parasitic (0/1)	1	2	N.S.	0.15
5.04 Geophyte (0/1)	6	7	N.S.	0.00

[a] Score for this question depends on answers given to other questions

Seed weight is thought to be a character that may be particularly useful in distinguishing potential environmental weeds as it is easy to measure, has been found to be positively correlated with the ability to invade undisturbed plots (Burke and Grime, 1996), and may be advantageous in areas of high drought risk (Baker 1972).

The Ecological Flora of the British Isles database (Fitter and Peat 1994) provides data on a range of traits for British plants, including seed weight and seed bank longevity, which may be analysed for their potential predictive value. All species that are listed in the VIRIDANS Victorian Flora Database (Department of Conservation and Natural Resources 1996) as naturalised in Victoria and also listed in the Ecological Flora of the British Isles database (Fitter and Peat 1994) or by Hodgson *et al.* (1995) were selected for analysis. This resulted in a data set consisting of non-indigenous plants naturalised in Victoria and data on their seed weight (136 species) and seed bank longevity (155 species) in their area of origin. CAIC was used to test the significance of differences in seed bank longevity (classified as: less than 1 year, 1-5 years or 5 years or more) and seed weight data between species of differing weed status (categorised as: naturalised non-weeds, non-noxious weeds, declared noxious weeds) in Victoria. The strict consensus trees in Chase *et al.* (1993) were used to describe the inter-family relationships, and sub-family relationships were mapped according to Stace (1991), Mabberley (1990) and Gibb Russell (1991). All branch lengths were set to the same length. Only plants naturalised in Victoria were included in the data set in order to reduce variation due to climatic differences, and because data on weed status in Victoria are well defined and documented.

Table 4.3 Comparative analysis of responses of weeds and non-weeds to WRA questions

Question (# = weeds significantly different from non-weeds in X^2 analysis results -see Table 3)	Number of species			Contrasts (+ve/zero/-ve)			Significance of response difference: * $P<.05$ ** $P<.01$ *** $P<.001$		
	Asteridae	Rosidae	Monocot	Asteridae	Rosidae	Monocot	Asteridae	Rosidae	Monocots
# 1.01 Is the species highly domesticated?	86	64	74	10/2/1	8/3/5	11/3/5	*	N.S.	N.S.
2.04 Native or naturalised in regions with extended dry periods	87	94	109	10/4/6	11/3/4	1/1/8	N.S.	N.S.	*
#2.05 Does the species have a history of repeated introductions outside its natural range?	76	92	112	0/1/0	8/5/2	16/9/4	N.S.	N.S.	N.S.
#3.01 Naturalised beyond native range	24	31	39	2/0/1	1/1/1	4/2/0	N.S.	N.S.	N.S.
#3.02 Garden/amenity/disturbance weed	42	51	53	8/0/4	8/1/1	6/0/1	N.S.	*	N.S.
#3.03 Weed of agriculture	54	38	43	10/0/2	7/2/1	10/1/0	*	N.S.	**
#4.04 Unpalatable to grazing animals	67	81	83	10/6/4	9/1/4	6/0/7	N.S.	N.S.	N.S.
#4.05 Toxic to animals	55	70	84	11/2/0	10/3/2	6/2/2	***	N.S.	N.S.
#6.06 Reproduction by vegetative fragmentation	83	78	100	8/6/5	10/7/4	14/5/4	N.S.	N.S.	**
#7.01 Propagules likely to be dispersed unintentionally (plants growing in heavily trafficked areas)	78	57	62	12/1/1	10/3/2	13/2/1	***	**	**
#7.03 Propagules likely to disperse as a produce contaminant	70	47	55	10/2/0	6/1/1	10/2/0	*	N.S.	**
#7.04 Propagules adapted to wind dispersal	53	56	81	9/1/2	3/0/1	5/3/4	N.S.	N.S.	N.S.
#7.05 Propagules water dispersed	65	52	56	14/0/0	10/1/1	13/2/0	***	**	***
#8.01 Prolific seed production (>2000/m2)	69	52	61	5/6/3	6/3/1	9/2/1	N.S.	N.S.	*
#8.04 Tolerates, or benefits from, mutilation or cultivation	61	62	69	9/3/3	10/7/2	10/3/4	N.S.	*	N.S.

Table 4.4 Comparative analysis of some seed characters of weeds and non-weeds.
(Blank cells indicate that there were insufficient data to perform the CAIC)

Comparison	Number of species				Contrasts (+ve/zero/-ve)				Significance of response difference: * P<.05 **P<.01 ***P<.001			
	Asteridae	Rosidae	Monocot	Others	Asteridae	Rosidae	Monocot	Others	Asteridae	Rosidae	Monocots	Others
Seed weight *ln* (g)												
weeds compared with non-weeds	44	56	31	24	7/0/8	9/0/6	5/0/1	4/0/4	N.S.	N.S.	N.S.	N.S.
environmental weeds compared with non-weeds	31	50	-	-	4/0/7	10/0/5	-	-	N.S.	N.S.	-	-
Seed bank												
weeds compared with non-weeds	35	43	35	23	5/3/4	5/4/3	7/3/0	2/3/2	N.S.	N.S.	N.S.	N.S.

There was no significant difference ($P > 0.05$) between weeds and non-weeds for these two traits in plants in the Asteridae, Rosidae, Monocots or the remaining groups when phylogeny was controlled for using CAIC. The seeds of environmental weeds were not significantly heavier than the seeds of naturalised non-weeds (Table 4.4).

4.3 DISCUSSION

4.3.1 Redundant questions

There is redundancy in the questions on the WRA questionnaire (see Table 4.2). One of the requirements of the WRA is that 'the cost in time and money to the importer and the administering body (AQIS) should be as low as possible (Pheloung 1995, p.7)'. The costs of administering the WRA could be reduced if the questionnaire were simplified and shortened in the light of the results in Table 4.1, using the word 'or' to combine linked questions. This would also reduce double scoring for the same trait, and thus potentially improve the accuracy of the WRA. On the other hand, the redundant questions could be retained and instead of their scores contributing to the assessment, the responses could instead be used to learn more about the data quality of applications.

Environmental weeds were well represented in the test data set (Table 3.2) yet none of the questions thought to target potential environmental weeds was frequently correlated with question 3.04 ('Is the species an environmental weed elsewhere?). This suggests that the characteristics of conservation areas in Australia are very different from those overseas, or that the questions thought to target environmental weeds do not in fact do so.

4.3.2 The best method for detecting useful questions

Is it really necessary to use CAIC when other methods such as discriminant analysis may result in the construction of assessment criteria with high levels of accuracy, for example those of Reichard and Hamilton (1996), or Rejmanek and Richardson (1996)? I believe so. Whenever ecologists attempt to understand which traits or characteristics allow different taxa to be successful in different ecological circumstances, phylogenetic information should be incorporated in their analyses whether data are experimental or observational. Closely related species share many traits in addition to those responsible for ecological success in particular circumstances, and phylogenetically controlled analyses help eliminate the effects of such confounding variables (Harvey 1996).

Rees (1996) uses an analogy of a blocked field experiment to explain why comparative methods should be used in analyses of ecological data. Blocks would be included in the analysis of data from a blocked field experiment because they control for many possible confounding variables, and allow more accurate comparisons to be made between the treatments of interest. Likewise phylogenetic information must be used in the analysis of ecological data to clarify ecological relationships that would otherwise be obscured.

Ecologists have been slow at picking up the statistical tool of comparative analysis and, in the words of Crawley (1996), 'this problem is so widespread in ecology that statisticians have despaired of chastening us'! He went on: 'In most cases where species are compared, the number of species doing one thing is counted, and the number of species doing another thing is compared with it, using a χ^2 test. The problems with this are threefold: (i) there is often no statement of the null model; the distribution of species numbers that would be expected if nothing was happening; (ii) contingency tables usually do not contain all the necessary explanatory categories, and this means that dangerously spurious, but highly plausible, significant results can emerge; and (iii) count data can be pseudoreplicated, just like measurement data. For example it makes no sense to compare six species of chrysomelid with one pyralid as if there were seven data points. In this example there is just one phylogenetically independent contrast (chrysomelid versus pyralid) and just one degree of freedom' (Crawley 1996). Simulations have shown that analyses in violation of the assumptions of χ^2 tests have often have greatly elevated type I error rates (i.e. they reject the null hypothesis of no difference when in fact it is true; Grafen 1989, Purvis *et al.* 1994). Comparative analysis of independent contrasts is also prone to type I errors if the phylogeny estimate contains non-monophyletic groups, and prone to type II errors (i.e. acceptance of the null hypothesis of no difference when there is in fact a difference) if all true sister-taxon relationships are not shown. However, these error rates tend to be far lower than those found in χ^2 analyses when its assumptions are violated (Grafen 1989, Purvis *et al.* 1994).

In Table 3.5 we saw that taxonomic representation of weeds and non-weeds in the WRA test data set is conspicuously unequal. Tables 4.2 and 4.3 show that when χ^2 and CAIC are used to analyse that data, many differences that seem significant in the χ^2 analysis turn out not to be so, once phylogenetic relationships in the data are corrected for.

Following the precautionary principle we shall use the results in Table 4.3 as the more authoritative guide to the differences between weeds and non-weeds, with the caveat that it would be desirable to have independent confirmation of findings near the threshold of significance or with few contrasts.

4.3.3 The best and worst questions

In reviewing efforts to use Baker characters to predict weeds, Williamson (1996) concluded that Baker characters are not good predictors, partly because weeds do not have a single set of characters. He explained that it is of more practical benefit to view weeds as distinct groups of plants which behave in different ways in the ecosystem, like the weedy invaders defined as 'Gap-grabbers', 'Competitors', 'Survivors' and 'Swampers' by Newsome and Noble (1986). The results in Table 4.3 would support that view. There were only two questions which showed weeds consistently answering in a significantly different way to non-weeds in the Asteridae, Rosidae and Monocots. These were questions 7.01 'Propagules likely to be dispersed unintentionally (plants growing in heavily trafficked areas)' and 7.05 'Propagules buoyant'. The first of these questions is highly subjective. The data analysed here were on well known Australian weeds and non-weeds, and responses may have been unwittingly influenced by knowledge of those species in Australia. The accuracy of responses to this question may drop markedly when it is used to assess future imports, as it requires an estimate of post-entry distribution more precise that that obtainable by climate modelling software. It is somewhat surprising that propagule buoyancy was an almost universal indicator of weediness, and again the selection of species for the test data set may have influenced this outcome. On the other hand it may be a true indication of an advantageous character to have for dispersal in the Australian environment. The rapid range expansion of *Mimosa pigra* in the wetlands of northern Australia in the early 1980's, for example, was attributed to dispersal of its seed pods by water (Lonsdale 1993). It would be interesting to test further its usefulness as a predictor of weediness, though this is beyond the scope of the present thesis.

For screening purposes, questions that distinguish between weeds and non-weeds in the same taxonomic group can be useful because a positive response to these indicates an increase in the risk of potential weediness for plants in that group. Table 4.3 shows there may be 9 such questions on the WRA questionnaire. The accuracy of the WRA may increase if scores for these questions were linked in the questionnaire to a question on taxonomic group. For plants in the Asteridae these questions are: questions 1.01 'Is the species highly domesticated'; 3.03 'Weed of agriculture'; 4.05 'Toxic to animals'; and 7.03 ' Propagules likely to be disperse as a produce contaminant'. All these questions may reflect the history of importation of plants from this group for agriculture and this could be tested by comparing the answers given for plants that were agricultural introductions with those introduced for other purposes.

In the Rosidae, weeds responded to the two following questions in a significantly different way from non-weeds: questions 3.02 'Garden/amenity/disturbance weed' and

8.04 'Tolerates or benefits from, mutilation or cultivation'. In the Monocots, the following questions were answered differently for weeds and non-weeds: question 2.04 'Native or naturalised in regions with extended dry periods'; 3.03 'Weed of agriculture'; 6.06 'Reproduction by vegetative fragmentation'; 7.03 'Propagules likely to disperse as a produce contaminant' and 8.01 'Prolific seed production (>2000/m^2)'.

When CAIC was used to examine the value of the rest of the questions on the questionnaire no significant differences were found between weeds and non-weeds. For some questions this may reflect the fact that the data set consists of plants already in Australia (e.g. question 3.01 'Plant naturalised beyond native range'). For others, it may be a rare trait or reflect a weedy trait that is difficult to estimate prior to importation (e.g. 'Creates a fire hazard in natural ecosystems') or potential weed management problem (eg. 4.04 'Unpalatable to grazing animals') that is difficult to estimate. The precautionary principle would require that these questions remain because, though because keeping them may serve to screen out non-weeds, it is unlikely to result in allowing more weeds into Australia. Other questions are used as a way of weighting the responses to other questions. For example, 'Does the species have a history of repeated introductions outside its native range?' modifies the score given to 'Naturalised beyond its native range'. Yet others may serve no useful purpose in screening future imports and may be safely deleted from a revised questionnaire (e.g. 7.04 'Propagules adapted to wind dispersal', and 6.02 'Produces viable seed'). Question 4.09 ('Is it a shade tolerant plant at some stage of its life cycle?) may be superfluous if it serves no purpose in distinguishing between environmental weeds in Australia and non-weedy naturalised exotic species.

The method of scoring the answers to the WRA could be improved in the light of above results. Ideally, scores for linked questions should not be summed (see Table 4.1). Scores for questions given the same response by weeds and non-weeds, but with a significantly different ratio of yes to no answers (questions 1.01, 2.04, 3.02, 3.03, 4.05, 6.06, 7.01, 7.03, 8.01, 8.04 Tables 3 and 4) should score points for weediness if answered positively but no points for non-weediness if answered negatively, unless a question on taxonomic group is added to weight the responses to these questions on the questionnaire. Questions 7.01 and 7.05 were generally given 'yes' answers for weeds and 'no' answers for non-weeds in the test data set. If these results prove general these questions should attract positive WRA points for 'yes' answers and negative for 'no' answers.

4.3.4 Possible additions to the questionnaire

The Ecological Flora of the British Isles (Fitter and Peat 1994) and similar databases on biological and ecological characters of plants may provide a good source of data to validate the usefulness of the questions in the WRA or provide information to support the use of additional questions. Using data such as these has an additional advantage in that it provides data on the character measured in the plant's area of origin. Characters such as seed weight and seed number might be substantially different for the same species in a new environment. Ultimately, we are interested in predictors measured prior to arrival in Australia, if we are to have a reliable hazard identification system.

CAIC analysis of data taken from plants in their native range shows no difference between the seed size or seed bank longevity of naturalised species which are not weedy in Victoria and those that are weedy. It may be that these traits are advantageous in allowing introduced plants to become naturalised in Victoria but, as there is no reliable data on species which have been introduced and not established, we can not test this yet.

4.4 CONCLUSIONS

The value of biological and ecological traits as predictors of weed status was untested for plants introduced to Australia at the time the WRA was devised. Due to the lack of information on plants that were introduced to Australia but failed to establish, the WRA can only be tested at present with a biased and small subset of all the plants that have been introduced i.e. the 10% or less that have became naturalised. All results of tests of the WRA must be tempered with the knowledge of this bias.

In the light of the results in this Chapter, it could be argued that unless allowance is made for the phylogeny of the plant, most of the remaining questions on the questionnaire could be removed without substantially altering the reliability of the WRA. If the WRA were revised to control for phylogenetic effects then the results of this Chapter would support the deletion of some questions, the consolidation of others and an adjustment in the scores given to individual questions.

At its inception it was envisaged that the WRA would be revised periodically. The contribution of the questions on plant biology and ecology were examined in this chapter to see which of these contribute the most to identifying weeds and non-weeds. Only two questions from this section of the questionnaire proved to be of consistent value. One of them is highly subjective. It asks for an opinion of where the plant may end up growing after introduction ('will the plants grow in heavily trafficked areas?') and so may prove harder to answer correctly for future plant introductions. The fact that distribution in the area of origin, and history of invasion elsewhere, remain the best predictors of weediness is already reflected in the way that the scores for questions on these traits are weighted by the WRA.

CHAPTER FIVE: THE 'EVALUATE FURTHER' OUTCOME

5.1 Introduction

It is necessary when assessing the components of the WRA, to review the kind of outcomes it produces. There are four possible recommended outcomes for importation applications assessed by the WRA: 'accept' for species with WRA scores of zero or less; 'reject' for species with WRA scores of 7 or more; 'evaluate further' for species with WRA scores between 0 and 7, and 'more information required' for applications where the minimum set of 10 questions has not been answered. The accept and reject cut-off points would logically be reviewed when individual questions or their score are revised, and starting points for some such changes have been suggested in Chapter 4. It is my intention in this Chapter to examine the function and value of having an 'evaluate further' outcome for the WRA.

The use of a further evaluation outcome is not unique to the WRA. The AQIS system used prior to the WRA also had one, as does Panetta's (1993) decision tree and the decision tree developed by Reichard and Hamilton (1996) for predicting invasions of woody plants in Northern America. In all these systems and in the WRA the function of the 'evaluate further' categories is to reduce the number of non-weeds rejected outright. When WRA scores for weeds and non-weeds in the test data set were plotted it was evident that there is a large area of overlap between the two groups (see Pheloung 1995 Fig. 2 and 3). The lowest WRA score given to a minor weed on the test species list is -7, and the minimum for major weeds is 1. The WRA scores for non-weeds substantially overlap with the lower bounds of the WRA scores for weeds: 15% of all non-weeds tested had WRA scores between 6 and 12 (Pheloung 1995, Table 9). The precautionary principle states that ' It is better to erroneously reject a plant species that would confer net benefit than erroneously admit one that would yield a net disbenefit.' If the precautionary principle were applied to WRA scores, all species with a score of -7 or above would be rejected and the rest accepted. However, when plants are rejected by the WRA they are placed on a list of prohibited imports. Now, some useful species have scores in the same range as those of known noxious weeds (eg. *Avena sativa* and the declared noxious crop and pasture weed *Themeda quadrivalvis* both have a WRA score of 1). Presumably, the fear of erroneously rejecting a useful plant led to the abandonment of the precautionary principle and the adoption of a 'third way', the 'evaluate further' outcome. This allows species with a score between 0 and 7 to remain off the list of prohibited imports at least until they are evaluated further.

5.2 Options for further evaluation

Further evaluation, as envisaged in Pheloung (1995), includes a number of options:

1. Repeat the WRA system, using updated information,

2. An economic cost/benefit analysis to justify the risk,

3. Post-entry evaluation in the form of field studies supervised by an expert panel to examine more directly weed potential (and verify potential benefits).

5.2.1 *Repeat the WRA system, using updated information*

The first option would be of real use only in cases where the WRA score is positive but close to zero. It would be used if there were new information discovered about the plant. However, the outcome in most cases will not change if re-evaluated under this option because their starting scores will be too high, or because all possible questions have already been answered and the resulting score is still in the 'evaluate further' category.

5.2.2 *Conducting a cost/benefit analysis*

The second option is also problematic. It will be difficult for interested parties to agree on an estimation of cost when there is no clear indication of potential impact. The WRA makes no claim to assess impact (Pheloung 1995) and there is serious difficulty in devising an agreed method of assessing and ranking the impact of plants already naturalised and weedy in Australia. These difficulties will be compounded when naturalisation and spread rates also have to be estimated as well as the value for impact per unit area. Similarly, the potential benefit of introducing a new species may also be difficult to determine without conducting post-entry field trials.

5.2.3 *Post-entry evaluation*

The third option is the most dangerous and certainly the most costly of the three, and may not yield any additional information useful in making a further assessment of the species. The danger is that we intentionally introduce and nurture a potential major weed. Because the WRA does not really estimate impact, it cannot be assumed that a lower WRA score means lower potential impact. Naturally any post-entry evaluation protocol would include stringent measures to contain the species until a full assessment could be made. Recent events in Great Britain, however, show how difficult it can be to enforce such constraints. Field evaluations of genetically modified crops are conducted under clearly defined conditions for obvious reasons. These have been found to be breached so frequently by leading biotechnology companies that the Advisory Committee on Releases to the Environment resorted to a practice of 'naming and shaming' the companies involved because fines did not seem a sufficient deterrent (Coghlan 1998). Examples of breaches of conditions for consent to field trials include: the buffer zones being too small or planted with the wrong species of plant; failure to notify conservation officials or the public about the trial; failure to implement measures to limit the escape of pollen; and seed found scattered outside the designated area (Coghlan 1998).

We can expect a great demand for 'further evaluation' studies, because a large proportion of outcomes of applications for plants in the Asteraceae, Poaceae and Fabaceae will fall into this category. The expense of running field evaluation trials would be high, and there would be perhaps unreasonably long delays before applicants receive a definitive assessment of a species proposed for introduction. In order to obtain a meaningful assessment of potential cost, one that was well replicated and considered the full ecological amplitude of its expected range, each species would need to be tested at multiple sites. One possibility is that botanic gardens could be used for this, although given their present sizes and geographic locations in Australia they may not cover all the requirements of multi-site testing for invasion potential. Even if there are adequate field sites and experimental resources, it is highly unlikely that such trials will produce clear or critical answers within a reasonable time-frame (Mack 1996, Kareiva *et al.* 1996). For example, Crawley *et al.* (1993) used the results from three sites over three years to assess the risk of invasion posed by genetically engineered oilseed rape. However, Kareiva *et al.* (1996) haave cleaarly shown that, given the variation in the data, results from those three sites would need to be studied for a period spanning at least 10 years in order for there to be sufficient opportunity to assess the invasion potential of that species. The Australian climate is more spatially and temporally variable than that of England, which suggests that field assessments here would have to run over an even longer period and involve a larger number of sites.

What indicators of invasion would be measured in post-entry evaluation studies? Kareiva (1996), in summing up recent advances in invasion ecology, found that there is a paucity of manipulative experiments on which to draw when attempting to design such trials. Two *post-hoc* indicators of invasion often cited (e.g. Roy 1990) are the number of new population foci produced (Moody and Mack 1988) and the initial rate of spread (Forcella 1985). However, although there are significant relationships between final distribution and these factors when measured in the first decade after initial establishment, there is a tremendous amount of scatter (r^2=0.21 and r^2=0.17 respectively; Fig. 3 of Kareiva *et al.* 1996). After examining the primary data for these findings Kareiva *et al.* (1996) conclude that 'if initial velocity of weed spread and the initial prominence of a weed invasion, measured at the scale of several states, tells us little about the weeds impact in terms of ultimate extent, it is hard to imagine that small scale, short term ecological experiments will offer accurate predictions regarding invasions'. One or a combination of factors may result in establishment, spread and persistence of a plant species. The factors that render a plant noxious to humans (toxins, thorns, latex) may be different from those that cause establishment. Any properly replicated field trial is limited to studying the effect of a small number of factors. To attempt more than that is generally not feasible unless there is a large skilled labour pool to draw on at minimal cost. There is no guarantee that the factors tested in a field study will be those crucial in determining the final distribution and status of the plant.

Clearly the understanding and prediction of the mechanisms involved in invasions when population levels are low is very rudimentary. Should we risk importing potential weeds when it is so unlikely that our final decision-making will be any better informed for it? The most likely fate of most species placed on the 'evaluate further' list is that they stay there for an undefined period until we are better able to decide their fate. In other words, they function as a 'reject for the time being' group, as distinct from the species put on the prohibited species list.

5.3 Conclusions

The number of non-weeds rejected by the WRA in the future is going to greatly exceed the 10-15% estimated by Pheloung (1995) because of the base-rate effect on predicting weeds (see Chapter 3). Given this fact, it may be safer, fairer and more efficient not to have an 'evaluate further' outcome for WRA assessments. It would be a sounder and more transparent procedure if, instead, the 'reject' cut-off point was reviewed, and that plants with scores below that are accepted outright. Rejected species would all be placed on the prohibited plant list until the WRA was revised. At that time applications could be made for individual species to be reassessed using the revised protocol. If the WRA remains easy to use and widely accessible, potential importers could conduct test re-assessments themselves. If encouraged by the results they could apply to have the species reassessed by AQIS. After re-assessment by AQIS if the species remained with an unacceptably high risk of becoming weedy, it would stay on the prohibited list, and if not it would be allowed entry.

It is likely that removing the 'evaluate further' category, but allowing periodic reassessment of rejected species would not impede the rate of entry of species given 'evaluate further' outcomes. At present the system gives the appearance of not rejecting non-weeds in the 'evaluate further' category, but the real effect of obtaining this outcome is that of indefinite rejection. Post-entry field trials are unlikely to yield results in a reasonable time-frame, and the results will not be able to be generalised. A better use of time and resources would instead be to encourage research into areas of weed prediction and invasion ecology that will yield results of use in regularly improving the WRA. Research into whether there are predictors of weediness in the Rosidae, especially the Fabaceae, is urgently needed. Work on assessing the risks and ranking the weed control potential of plants already naturalised in Australia should yield results valuable in improving the WRA. Moreover, the driving forces in the transitions from the introduction of a new species to its establishment, naturalisation and subsequent weediness in Australia is currently poorly understood. In particular, research into early warning of the transition from naturalised to weedy would potentially be more cost effective than trying to pick weeds from amongst importation applications (because we would be trying to identify 1 in 10 species instead of 1 in 100 or 1000 - *cf.* Williamson and Fitter 1996), and may also provide information to support or improve the WRA.

CHAPTER SIX: WEED MANAGEMENT QUESTIONS

Several current challenges to Australian weed management will be discussed in this chapter, drawing on the results of weed risk assessment studies reported in earlier chapters. In particular, the present and future role of the WRA within the National Weed strategy, the effect of allowing further importations of naturalised species, and the use of risk assessment for detecting environmental weeds will be discussed.

6.1 WILL THE WRA REDUCE FUTURE WEED MANAGEMENT PROBLEMS?

The WRA will reduce the number and scope of future weed management problems in Australia, and is a valuable and important part of Australia's National Weeds Strategy (see Appendix 1). The nature and magnitude of the role of the WRA within the National Weed Strategy must be clearly recognised in order to maintain public support and co-operation. However, the WRA will not make reliable *predictions* of the future weed status of species proposed for introduction to Australia.

The above statements may at first appear contradictory, but only if the predictive powers of the WRA are seen as essential to its working.

The first goal of the National Weeds Strategy (Appendix 1) is to prevent the development of new weed problems. There is no doubt that the WRA will contribute towards this goal by reducing future weed management problems and their associated costs. It will do this mainly by reducing the number of new plant species entering the country. Those that are allowed entry will be less likely to possess traits currently held to be noxious, but a small proportion of these species may nonetheless become pest plants in the future. In order to ensure continuing public support, the attributes tested in the WRA must be good indicators of weediness and not confounded by other factors such as phylogeny. Returning to the vehicle roadworthy test analogy above, 'yes' answers to a question on a roadworthy test that asks 'Is the car a powerful red sports car?' may be significantly correlated with road accident rate in some statistical tests. However, it is not appropriate that the question appear on a vehicle road-worthy test if it is not found to have a significant effect once the effect of the driver is controlled for.

In Chapter 3 we saw that many, perhaps most, plants rejected by the WRA would probably not turn out to be weeds. However, the number of weeds allowed entry will become very small and this certainly represents progress from the era when all species were allowed entry unless they were known weeds. There is a need for some kind of WRA in order to reduce the number of deliberate introductions of species which will incur future weed management costs. Adoption of the WRA alone however, will not be sufficient to obtain continuing reductions in weed management costs. A suite of complementary risk assessment and risk reduction mechanisms, such as those envisaged in the National Weed Strategy, must also be in place and functioning well for that to occur.

6.2 SHOULD NATURALISED SPECIES BE REMOVED FROM THE AQIS PROHIBITED PLANTS LIST?

The International Plant Protection Convention defines a Quarantine Pest as 'A pest of potential economic importance to the area endangered thereby and not yet represented there or present but not widely distributed and being officially controlled' (FAO 1996). Regardless of whether this definition makes sense in ecological terms, AQIS is bound to adhere to it and may not prohibit entry of plants that are already naturalised in Australia unless they are under active control.

Yet Australia's next major weed problems are far more likely to come from species already naturalised in Australia than they are from species that are not yet here: Naturalised species have already overcome the initial hurdles to invasion, and traits that have contributed to their naturalisation will sooner or later make some species difficult to contain or control in their new range. In Australia at present about one in ten naturalised species becomes a noxious weed (Panetta *et al.* 1994, Williamson 1996). Furthermore, the risk of a naturalised species becoming an invasive weed will increase with each new importation permitted (Moody and Mack 1988).

The number of species naturalising in Australia has increased over the last 25 years (Figs 3 and 4 of Groves 1998) and there are at present about 2,200 species naturalised in Australia - clearly too many to control with the available resources.

The likely consequences of removing plants from the AQIS prohibited plants list on the sole grounds that they have already become naturalised, would be increased dispersal of naturalised species, followed by greatly increased weed management costs, and reduced Australian land values.

6.3 CAN THE WRA BE MODIFIED FOR USE IN THE MANAGEMENT OF NATURALISED PLANT SPECIES?

The magnitude of the naturalised flora in Australia, the shortfall in resources to control naturalised species, and the knowledge that they include many benign species, can weaken the will to instigate control measures for this nonetheless high risk group. Yet great potential savings can be made if naturalised weedy species are controlled or eradicated before invading the full extent of their potential range. Because AQIS is bound to allow entry to naturalised species that are not officially controlled, it is imperative to make the best possible decisions in identifying targets for official control programs. Can a modified WRA be used in this process?

Environment Australia has recognised the potential savings to be made in the early detection and control of environmental weeds in the naturalised flora (Csurhes and Edwards 1998). It generated environmental weed control priorities by first asking for public nominations of potential environmental weeds. Nominated non-native species with histories as weeds outside Australia were identified as a higher risk group and the likelihood of their being eradicated was assessed. Species considered not to be beyond eradication were listed as eradication targets (see Fig. 1 of Csurhes and Edwards 1998).

A similar process using a modified WRA could be considered for use in assigning priorities for initiating official control programs of naturalised species. The advantage of using a modified WRA to define higher risk groups instead of using the history of weediness overseas is that some biological and ecological information may be used in addition to information on distribution and history of weediness outside Australia. This makes some allowance for the fact that many future weeds will be less well-known before introduction, and will tend to be non-agricultural introductions (Groves 1998). WRA predictions for plants already in Australia can be expected to be much more reliable than predictions for species new to Australia for two key reasons.

First, because the base-rate of weediness is about 10 times higher for naturalised species than new introductions (Williamson 1996), a much smaller proportion of species will be incorrectly identified as weeds when the WRA is used to assess naturalised plants than when it is used to assess new introductions.

Secondly, because the WRA was designed and calibrated using species already established or naturalised in Australia (Pheloung 1995) it is more likely to detect major factors affecting the transition from establishment to weediness than it is from introduction to weediness. Additionally, the questionnaire could be shortened for use in assessing naturalised species. As seen in Chapter 4, some questions in the current questionnaire are not useful in distinguishing between weeds and naturalised non-weeds once phylogeny has been controlled for. These questions could be safely deleted in a WRA modified to assess naturalised plant species, and the cut-off score for rejection adjusted accordingly.

Figure 6.1 outlines one possible system for assigning priorities and responsibilities for the control of naturalised species. The modified WRA would be the first step in the process. It could be used to define a higher risk group of plants as being those with WRA scores above that of a minimum cut-off score for weeds. WRA scores are positively correlated with degree of weediness, from naturalised non-weeds to problem plants to declared noxious weeds, when the phylogeny of the plant has been controlled for using CAIC (see Table 3.7). This relationship could be used to estimate the relative risk of naturalised plants by comparing their WRA scores with those of known weeds in the same taxonomic group:

Relative Risk Estimate = WRA score / Mean WRA score of noxious weeds in the same family

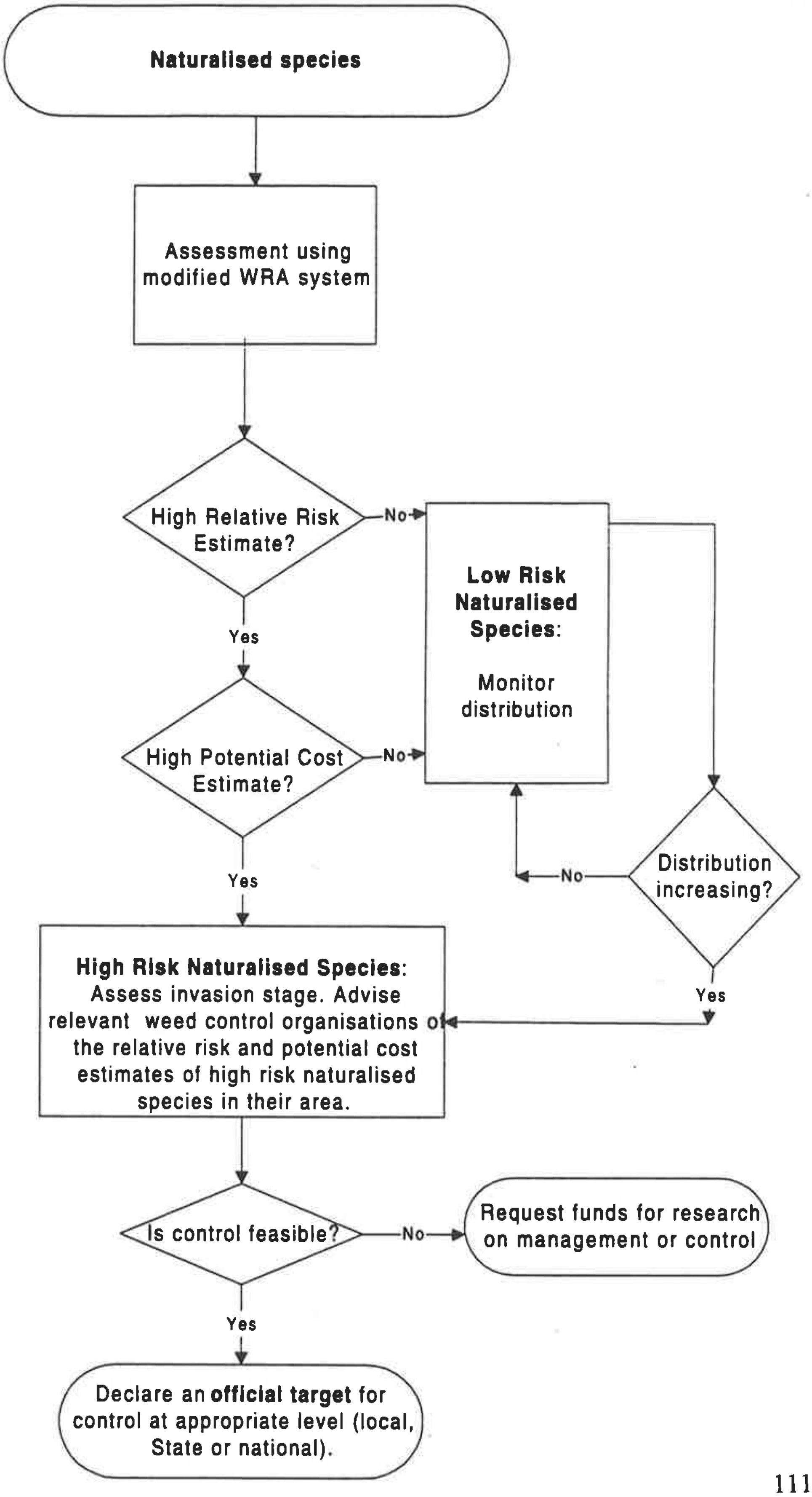
The potential per hectare costs of not controlling higher risk species could also be estimated and ranked using data on the current costs of controlling similar weeds:

Potential Cost Estimate = Mean cost per ha per species of controlling noxious weeds in the same family

The average cost of controlling a noxious weed in the same functional group (*sensu* Newsome and Noble 1986) could be substituted for mean cost per family in cases where there are no noxious weeds in the same family as the high risk naturalised species.

The second step in the process would consist of estimation of the date of first introduction and the invasion stage that each higher risk species had attained, and then alerting appropriate organisations of high risk naturalised species growing in their area.

Fig. 6.1 A system for assigning control priorities to naturalised species



The invasion stages could be defined as:

I Few, small, localised and apparently stable populations.

II Populations steadily increasing in number or area.

III Population at or near its maximum distribution (determined using climate-matching software).

Clearly, the most cost-effective control programs will be those for high risk plants in the early stages of invasion. However, some indication of the feasibility of control is needed in order to make sound decisions on resource allocation for control, monitoring and research. In the absence of any agreed method of measuring relative feasibility, it is perhaps advisable to rely on the knowledge and experience of organisations active in plant population monitoring and weed control. Scott and Panetta (1993) have shown that weed prediction accuracy is higher for plants with a longer history of naturalisation, so the length of time after introduction may be a useful weighting factor to use in assigning control priorities for species with otherwise similar apparent risks and control feasibilities. Landcare groups, regional Department of Agriculture offices, and regional parks and Shire Councils would be appropriate groups to consult on the feasibility of initiating official monitoring, eradication or control programs for naturalised species with high relative risk estimate and potential cost estimate scores in their local areas. State Departments of Agriculture and State parks and forestry services may be best placed to assess the feasibility of control of species with high relative risk estimate scores and potential cost estimate scores at invasion stage II. Those species thought to be controllable could become priorities for official control programs and noxious weed legislation. Those for which control is not thought to be feasible would be recommended to industry or research organisations as priority species for applied weed research projects. Most species with high relative risk estimate and potential cost estimate scores at invasion stage III would require a national effort to control, and the feasibility, desirability, strategies or alternatives for this would need to be discussed at a national level.

6.4 DOES THE WRA DETECT ENVIRONMENTAL WEEDS?

One requirement of the WRA is that the system 'be capable of identifying environmental weeds and identifying them as such' (Pheloung 1995). The questionnaire was therefore designed using the best information on environmental weeds available at the time. Nine questions on the questionnaire were identified (Pheloung 1995) as being primarily relevant to the identification of environmental weeds (these questions are listed in Table 6.1).

However, the predictive power of these questions for Australian environmental weeds was purely speculative when the WRA was devised. Scott and Panetta (1993) found no suitable predictors for non-agricultural (environmental) weeds when they developed a method of predicting agricultural weed status of southern African plants naturalised in Australia. The WRA questions targeting environmental weeds rely mainly on information from overseas situations, and their usefulness has not been verified for Australian ecosystems.

Table 6.1 WRA questions intended to target potential environmental weeds

(Pheloung 1995).

WRA Question	Points awarded for answer	
	Yes	No
3.04 Environmental weed	1 or 2	0
4.08 Creates a fire hazard in natural ecosystems	1	0
4.09 Is a shade tolerant plant at some stage of its life cycle	1	0
4.10 Grows on infertile soils	1	0
4.11 Climbing or smothering growth habit	1	0
5.01 Aquatic	5	0
5.03 Nitrogen fixing woody plant	1	-1
7.05 Propagules water dispersed	1	-1
7.06 Propagules bird dispersed	1	-1

When the WRA was tested before implementation, a clear positive relationship was shown between WRA score and the likelihood of a plant being an environmental weed (Pheloung 1995, Fig 3). In order to find whether this relationship holds after phylogeny is controlled for, I assigned environmental weeds and non-weeds of the species used by Pheloung (1995) to one of the following five categories: (i) naturalised non-weeds; (ii) weeds that pose a potential threat to one or more vegetation types; (iii) those that are a serious threat to one or more vegetation types; (iv) weeds that are a very serious threat to one or more vegetation types, and; (iv) declared noxious weeds (Carr *et al.* 1992, Parsons and Cuthbertson 1992, Csurhes and Edwards 1998). The WRA score data were then analysed using the CAIC methods described in Chapter 3 (section 3.5.1), and the importance of individual questions ascertained using the CAIC methods described in Chapter 4 (section 4.2). There was a significant correlation between WRA score and environmental weediness in the Asteridae ($r = 0.67$; $P<0.001$), Rosidae ($r = 0.45$; $P<0.001$) and Monocot groups ($r = 0.79$; $P<0.001$), (taxonomic groups are as defined by Chase 1993, page 551). Figure 6.2 shows the relationship between WRA score and the independent contrasts for plants in these taxonomic groups. These results suggest that the WRA can be used to identify an increased risk of a plant being an environmental weed in these groups in the data set.

There were insufficient data to analyse the correlation between environmental weediness and WRA score for the remaining taxonomic groups (these are the Ceratophyllaceae, gnetophytes, other conifers, Pinaceae, Ginko and cycads).

Many weeds of conservation areas, however, are also weeds of other land-use types. It is possible that the WRA is detecting traits common to weeds of other sectors and not identifying environmental weeds *per se*. Certainly, the ability of the WRA to identify environmental weeds is poorer if the plant is not also a weed of another sector (Table 6.2). When a plant is a weed of conservation areas only, the WRA rejects only about half of the environmental weeds.

Furthermore, when the questions in Table 6.1 are analysed using CAIC to see if the answers for environmental weeds are significantly different from those of non-weeds, all but one of the questions thought to target environmental weeds consistently fails to do so. It is quite plausible that the Australian environment will have different selective pressures from those at work in conservation areas on other continents. Responses to Question 3.04, 'Environmental weed elsewhere', were not consistently associated with those for any other question on the questionnaire (Chapter 4, section 4.2.1). CAIC analysis of the ECOFLORA data on seed weight and seed bank (Chapter 4 section 4.2.3) showed that these traits, too, can not be used to distinguish between environmental weeds and naturalised non-weeds in Victoria.

The WRA appears to work for environmental weeds as a group because it detects plant characters that are generally noxious in agricultural systems. We need much clearer ideas than we have at present on what characters make a plant noxious in natural ecosystems in Australia. The traits that contribute most to an exotic species diminishing or displacing native species are not clearly understood, nor is there an agreed method of measuring the impact of such processes (Parker *et al.* in press). The wide range of natural ecosystems present in Australia makes it highly unlikely that there are many, characters common to all environmental weeds (if any exist at all). However, it may be quite possible to identify risk factors at the scale of an ecosystem or park, in the way Tucker and Richardson (1995) have for potentially invasive alien plants in South African fynbos. Should this be done for individual Australian conservation areas, information from such studies could then be considered when the WRA is updated with a view to making the WRA conform to the requirement of being capable 'of identifying environmental weeds and identifying them as such' (Pheloung 1995).

Figure 6.2 The relationship between WRA score and environmental weed status for three major plant groups using the Pheloung (1995) data set.

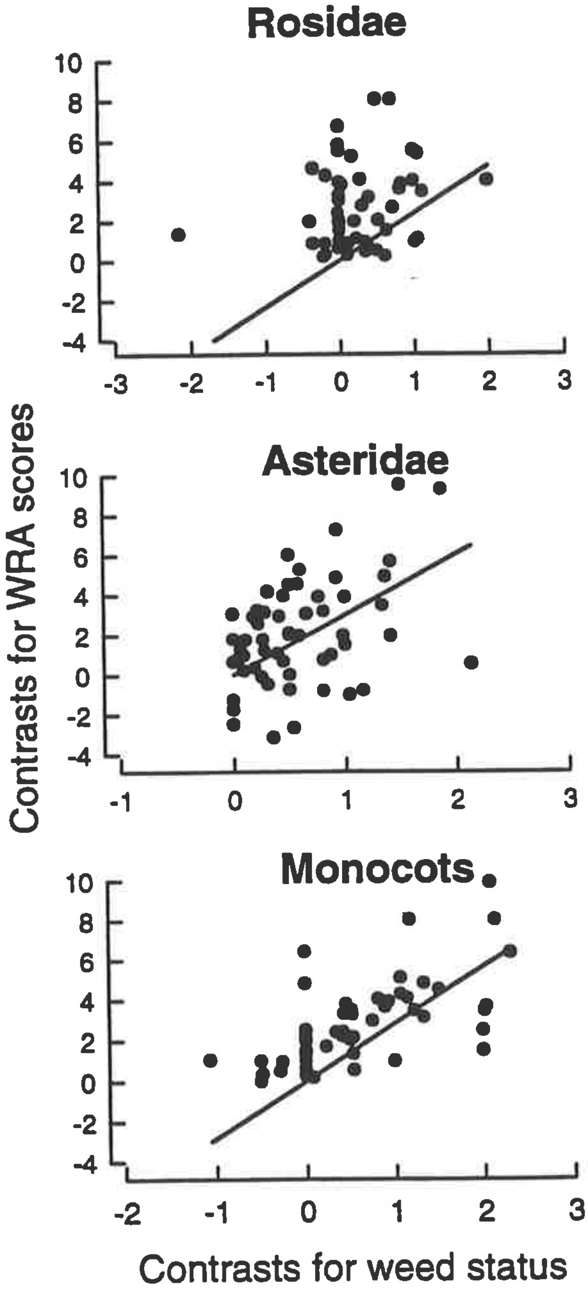


Table 6.2 WRA outcomes for environmental weeds vary with the number of other sectors affected (according to Parsons and Cuthbertson 1992, Carr *et al* 1992, Humphries *et al* 1991, Swarbrick 1983, Kleinschmidt and Johnson 1977, and Cowie and Werner 1987)

Sectors affected	Weeds rejected	Weeds not rejected	Total
Weeds of conservation areas only	45	41	86
Weeds of conservation areas and one or more other sectors	61	8	69
All environmental weeds	106	49	155

CHAPTER SEVEN: CONCLUDING REMARKS AND RECOMMENDATIONS

> *'Our knowledge of the way things work, in society or in nature, comes trailing clouds of vagueness. Vast ills have followed belief in certainty'*
>
> *Kenneth Arrow, Nobel laureate*

The WRA is an important component of the National Weeds Strategy. However, its position is made vulnerable by blindness to its true strengths and by claims, or expectations, of powers that it does not have.

7.1 WEAKNESSES OF THE WRA

In comparison to other areas of risk assessment, weed risk assessment is a relatively new field, and there is still much to learn. Perhaps it would be more accurate, and informative, to call the WRA a decision support system. It does not formulate risk assessments in the strict sense of the term because it does not estimate impact. Instead, it compares a plant species to two other groups of plants (a sample of known Australian weeds, and a sample of known non-weeds) and proceeds to identify it with the group it resembles the most. Risks can be ranked according to their damage estimates, WRA outcomes can not. There is a danger in calling the WRA a risk assessment system (instead of using some other term like hazard identification); for example, it can mislead one into assuming that plants with an 'evaluate further' outcome present a lower national risk than plants rejected by the WRA, when this is not the case.

The WRA is not a reliable tool for predicting weeds. Most of the species it identifies as potential weeds would probably not be if introduced. A more important quarantine issue is that the WRA is likely to accept applications to import potentially weedy species. The factors contributing to this, investigated in this thesis, are:

1. The circularity in the design of the tests originally used to evaluate the WRA and reported in Pheloung (1995). The weed status of the species used in tests was assigned by many of the same people who then answered the WRA questionnaires for those species. This lack of independence in building and testing a model is a fundamental flaw that will always impact on how generally the model may apply.

2. The absence of phylogenetic correction when determining accuracy or setting cut-off points for rejection. The WRA is not uniformly accurate across taxonomic groups (Table 3.6). Its accuracy when assessing plants in the Fabaceae, a continuing source of many importation applications, is about as good as one would get by tossing a coin.

3. The inability of the WRA to identify plants that are invasive principally in conservation areas (Chapter 6 section 6.4).

4. There seems to be a widespread misconception that the high accuracy rates reported in Pheloung (1995) will lead to the majority of future plant importation requests being correct. This is not necessarily the case. As Cardano, one of the founders of probability theory put it 'the probability of an outcome is the ratio of such outcomes to the total opportunity set' (Bernstein 1996). The test data set used to calculate the

accuracy of the WRA in Pheloung (1995) consisted of 84 non-weeds and 286 weeds and so cannot be regarded as a realistic 'total opportunity set'. The natural prevalence of potential weeds in the imported flora (the base-rate for weediness) is quite small, and may be as low, as 2% (*Panetta et al.* 1994). This means that the overall proportion of correct assessments (weeds rejected and non-weeds permitted entry) is mainly determined by the accuracy of assessing non-weeds, and this may be as low as 41% using the WRA (Table 3.3)

7.2 STRENGTHS OF THE WRA

The WRA is an essential part of the risk reduction process embodied in the National Weeds Strategy. It is in this role that it contributes the most, as it encourages importers to consider the national risk posed by introducing new plant species, and it prevents the entry of many species that resemble our present weed flora. Furthermore, it may be adapted to use in prioritising the control of species already naturalised, but not yet weedy, in Australia (Chapter 6, section 6.3). The function of the WRA and its role in the National Weeds Strategy should be strongly supported. It would be best supported by acknowledging its strengths and weaknesses allowing discussion, and encouraging research, in areas where high risks or incomplete information remain.

7.3 RESEARCH PRIORITIES

Weed risk assessment in Australia would benefit from research in the following areas:

1. In the absence of comprehensive data I have estimated of the base-rate probability of an exotic plant becoming naturalised in Australia by giving a range of values within which the probability may lie. I recommend that research resources be directed at constructing and maintaining a publicly accessible database on the purpose and the fate of future (and if possible, past) approved plant importations, so that base-rate probabilities for Australian weeds and for useful plant species can be calculated more precisely.
2. Studies of factors associated with weediness in well defined taxonomic or functional groups, and particular land use and climate types. For example, traits associated with woody and herbaceous legumes in temperate and tropical pastures.
3. Studies of 'at risk' environments in order to identify what drives or dampens invasion opportunities in these areas.
4. Studies on measures of the impact of plant invasions.
5. Studies on the early stages of invasion: what factors contribute to range expansion, and how it is best detected.

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GOALS AND OBJECTIVES OF THE NATIONAL WEEDS STRATEGY

GOAL 1: To prevent the development of new weed problems.

Objective 1.1	To prevent the introduction of new species with weed potential.
Objective 1.2	To ensure the early detection of, and rapid action against new weed problems.
Objective 1.3	To reduce weed spread to new areas in Australia.

GOAL 2: To reduce the impact of existing weed problems in Australia.

Objective 2.1	To facilitate the identification and consideration of weed problems of national significance.
Objective 2.2	To deal with established weed problems of national significance through integrated and cost effective weed management.

GOAL 3: To provide a framework and capacity for ongoing management of weed problems of national significance.

Objective 3.1	To strengthen the national research, education and training capacity to ensure ongoing cost effective, efficient and sustainable weed management.
Objective 3.2	To encourage the development of strategic plans for weed management at all levels
Objective 3.3	To establish institutional arrangements to ensure ongoing management of weed problems of national significance.

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WRA QUESTIONNAIRE

	A.	**Biogeography/ historical**	
C	1	*Domestication/ cultivation*	1.01 Is the species highly domesticated?
C			1.02 Has the species become naturalised where grown?
C			1.03 Does the species have weedy races?
-	2	*Climate and Distribution*	2.01 Species suited to Australian climates (0-low; 1-intermediate; 2-high)
-			2.02 Quality of climate match data (0-low; 1-intermediate; 2-high)
C			2.03 Broad climate suitability (environmental versatility)
C			2.04 Native or naturalised in regions with extended dry periods
-			2.05 Does the species have a history of repeated introductions outside its natural range?
C	3	*Weed Elsewhere (interacts with 2.01 to give a weighted score)*	3.01 Naturalised beyond native range
N			3.02 Garden/amenity/disturbance weed
A			3.03 Weed of agriculture
E			3.04 Environmental weed
C			3.05 Congeneric weed
-	**B.**	**Biology/Ecology**	
C	4	*Undesirable traits*	4.01 Produces spines, thorns or burrs
C			4.02 Allelopathic
C			4.03 Parasitic
A			4.04 Unpalatable to grazing animals
C			4.05 Toxic to animals
C			4.06 Host for recognised pests and pathogens
N			4.07 Causes allergies or is otherwise toxic to humans
E			4.08 Creates a fire hazard in natural ecosystems
E			4.09 Is a shade tolerant plant at some stage of its life cycle
E			4.10 Grows on infertile soils
E			4.11 Climbing or smothering growth habit
C			4.12 Forms dense thickets
E	5	*Plant type*	5.01 Aquatic
C			5.02 Grass
E			5.03 Nitrogen fixing woody plant
C			5.04 Geophyte
C	6	*Reproduction*	6.01 Evidence of substantial reproductive failure in native habitat
C			6.02 Produces viable seed.
A			6.03 Hybridises naturally
C			6.04 Self-compatible or apomictic
C			6.05 Requires specialist pollinators
A			6.06 Reproduction by vegetative fragmentation
C			6.07 Minimum generative time (years)
A	7	*Dispersal mechanisms*	7.01 Propagules likely to be dispersed unintentionally (plants growing in heavily trafficked areas)
C			7.02 Propagules dispersed intentionally by people
A			7.03 Propagules likely to disperse as a produce contaminant
C			7.04 Propagules adapted to wind dispersal
E			7.05 Propagules water dispersed
E			7.06 Propagules bird dispersed
C			7.07 Propagules dispersed by other animals (externally)
C			7.08 Propagules survive passage through the gut
C	8	*Persistance attributes*	8.01 Prolific seed production (>2000/m2)
C			8.02 Evidence that a persistent propagule bank is formed (>1 yr)
A			8.03 Well controlled by herbicides
A			8.04 Tolerates, or benefits from, mutilation or cultivation
C			8.05 Effective natural enemies present in Australia

A= agricultural, E= environmental, N= nuisance, C= combined