Session 1

Changing Worlds and Approaches

CHANGING WORLDS AND CHANGING WEEDS

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ABSTRACT

Whatever we predict about the future of weeds, the reality is likely to surprise us. The fact that weed problems, and the weeds themselves, evolve with such rapidity means that weed science is the prime field where evolution, environmental change and economic botany coincide. One of the problems of studying applied evolution is the lack of detailed baselines from which to assess the rate and direction of change. The pace of global change is faster now than ever, and these changes may produce their greatest effects by destabilising natural habitats and leading to new environmental weed problems. Examples are given of how weed problems may interact with anthropogenic habitat fragmentation and global climatic change (with elevated CO_2 levels). Dry evergreen tropical forest is suggested as a biome particularly vulnerable to a combination of global warming, increased fire frequency and the spread of weedy African fire-adapted grasses.

INTRODUCTION

If I had been giving a talk on "Weeds in the 20th century" in 1895, what would I have failed to predict? Probably the number of new weed species arising through allopolyploidy, and our increasing understanding of the process. Although *Spartina anglica* (Thompson, 1991) existed, as did its ancestor *Spartina* x *townsendii*, it was not well known and its origin was not understood. The concept of allopolyploidy did not exist: the chromosome had been discovered by Strasburger, but the subject of cytology was in its infancy, like molecular genetics today. Adaptation is another factor that was probably unseeable in 1895, when the role of natural selection was still being debated and before R.A. Fisher had demonstrated theoretically the enormous power of selection. The studies on weed adaptation to metalliferous soils and the rapid spread of herbicide resistance genes lay far in the future. Without knowing about the aeroplane, let alone mass intercontinental tourism, would I have foreseen air travel introducing a new order of magnitude to plant dispersal? The spread of germplasm, and the concomitant rapid spread of such weeds as *Salvinia molesta* and *Eichhornia* across the globe, would surely have surprised me.

So much for the spread of weeds. Turning to their eradication, would I have foreseen the development of chemical herbicides and sophisticated machines, and all the technological advances of weed control? It might have been difficult to predict the disappearance of cornfields red with poppies (*Papaver rhoeas*) and the complete disappearance of corncockles (*Agrostemma githago*). Perhaps the predictions that I would have made would have been quite wrong. I might have supposed that the emerging science of ecology should in the future century have been able to tailor crop practices, based on a knowledge of the behaviour of weeds, to outwit them. In some ways this has been a curious failure, and we are still, at the tail end of the 20th century, striving to develop effective integrated pest management (IPM). For many systems this is still a dream, dependent on much more knowledge of the interactions between organisms and between organisms and their environment.

My point here is that whatever we predict about the future of weeds, the reality is likely to surprise us. However, the fact that weed problems, and the weeds themselves, evolve with such rapidity means that weed science is the prime field where evolution, environmental change and economic botany coincide. It is an ideal arena for long term study. To follow changing weeds, no less than a changing world, baseline studies are essential, but the intractable question is: how do we know what baselines to establish, or what lines of research to pursue now, if we do not know what the future problems might be?

ENVIRONMENTAL WEEDS

One aspect of the weed problem which has frequently been left out of the weed literature in the past is the impact that weeds have on conservation. Land managers in many parts of the world face considerable problems in maintaining natural or semi-natural habitat of conservation importance in the face of massive invasion by weeds (often small trees or shrubs). This problem is one that Janice Fuller and I attempted to highlight in our book "Plant Invaders: the threat to natural ecosystems worldwide" (Cronk & Fuller, 1995), by drawing together the literature on this subject into a review and practical compendium for reserve managers. For our purposes we defined an "invasive plant" as: "an alien plant spreading naturally (without the direct assistance of humans) in natural or seminatural habitats, to produce a significant change in terms of composition, structure or ecosystem processes". Various patterns emerged from this survey which I will attempt to summarise here.

Although animal species invasions have a potentially serious impact on natural habitats, plant invasion is particularly serious as it hits at the primary production level of ecosystem function and the structure of the vegetation. Vertebrate invasions (particularly goats) can have equally catastrophic effects (Cronk, 1989) but are usually more straightforward to control. Invertebrate invasions are extremely difficult to control but rarely have the devastating effect in natural ecosystems that they have in agroecosystems. Plants are invading habitats of conservation importance on every continent except Antarctica. Antarctica is likely to be more at risk from invasions by bacteria and fungi, although the subantarctic island of South Georgia is under invasion by *Poa annua* with serious impacts on the ecosystem (Leader-Williams *et al.*, 1987).

<u>Conceptual model of invasion</u>

The conceptual model of invasion that emerges is that it is, foremost, an unpredictable process. This is because it is historically contingent and dependent on local specific conditions. We can either accept the primacy of this uncertainty and conclude that no predictions are possible, or, however tentatively, search for overarching generalisations. Of the latter, it can be concluded that the most important factor in invasion is, without doubt, <u>history</u>. All the most seriously invaded parts of the world (for instance Hawaii, Cape, Mauritius, SE Australia, and New Zealand) have a long history of germplasm import (e.g. Hawaii has some 9000 naturalized plants; Smith, 1989).

The next most important factor is <u>disturbance</u>. The very high reproductive potential of invasive shrubs is often associated with weediness, the ability to take advantage of high photosynthetically active radiation (PAR) to grow fast, and use high seed production to colonise bare areas as monospecific stands. Any disturbance therefore favours such plants, although in some cases, such as *Psidium cattleianum* in Mauritius, they may be tolerant of shade as well. Where invaders differ from usual gap colonists is in preventing regeneration of, and eventual gap infilling by, late successional trees.

After history and disturbance, the next most important factor is <u>biotic facilitation</u>. High reproductive capacity has already been stressed: but such high reproductive capacity will not be achievable or effective without suitable pollinators or dispersers. In cases where natural ecosystems have highly specialised pollinators and frugivores (which seems to be the case in Mauritius (Wyse Jackson *et al.*, 1988)), there may not be generalist animals present in sufficient abundance. However, where the cultural and socioeconomic conditions have been suitable for alien plant introduction there is also likely to have been animal introduction. In Mauritius these include pigs (*Sus scrofa*), bulbul (*Pycnonotus jocosus*) and macaques (*Macaca fascicularis*) as frugivores, and the honey bee (*Apis mellifera*) as a pollinator. Thus we should see invasive organisms not in isolation but as parts of "invasive complexes". In Puerto Rico pigs are present in the forest but in low numbers and appear to have no impacts on the ecosystem (F. Scatena, pers. comm.). They could potentially act as dispersal agents for invasives, however, as they do in Mauritius and Hawaii. Such invasions may in turn build up pig numbers by providing a very large new food reserve. Some naturalizations appear to be benign for many years before biotic facilitation enabled them to form an "invasive complex".

Following this factor there are some direct effects of <u>climate</u> on invasion at a global scale. Examination of the "worst" invasives in conservation terms (Cronk & Fuller, 1995) according to the temperature zones in which they are invasive, suggests that the tropical and temperate zones are under-represented and that the subtropical and warm temperate zones make up most of the sample. There are a multiplicity of different explanations for why subtropical and warm temperate zones are so invaded. Firstly, many of the regions which are badly invaded for historical reasons (e.g. Cape, New Zealand) happen to fall outside the tropics. Secondly, islands are often invaded and tend to have equable climates even when they are in the tropics by being swept by trade winds from cooler latitudes. Thirdly, lowland areas have often been heavily cleared and destroyed and so in some places the only areas of extensive forest for invasion are montane or submontane. Nevertheless there may be an underlying climatic factor, as indicated by the importance of <u>productivity</u>. Invasions are few and far between in both the <u>least</u> productive and diverse environments (arctic and desert environments) and the <u>most</u> productive and diverse environments (lowland tropical rain forests). If there is a climatic predisposition to invasion, then it is likely to be because subtropical and warm temperate regions tend to have moderately productive and diverse vegetation that is susceptible to invasion.

<u>Types of invasion</u>

So far we have spoken of invasion as being a homogeneous process: it is not. One first level classification of types of invasion (Cronk & Fuller, 1995) is into four categories: 1) Aquatic invaders 2) Forest invaders 3) Open habitat invaders and 4) Fire invaders. Forest invaders follow the pattern seen so abundantly in Mauritius (*Psidium cattleyanum*, *Ligustrum robustum* var. *walkeri*), Jamaica (*Pittosporum undulatum*) and Hawaii (*Myrica faya*, *Psidium cattleianum*, *Passiflora mollissima*). All these plants have animal dispersed fruits and have some shade tolerance. They all prevent the regeneration of native forest and the indigenous trees eventually die without replacement and a tall stature forest is replaced by a low stature forest.

Fire invasions, in contrast, have a very different environmental effect. Forest types that can withstand and are subject to the occasional burn are particularly vulnerable. Fire adapted species, either serotinous trees or grasses, can by accumulating dry matter, or by having volatile oils, increase the frequency and intensity of fires greatly. Their fast response to fire means that they can spread still more and soon the original forest ecosystem is completely changed, usually into fire-adapted scrub or fire grassland.

<u>The future</u>

What of the future? As humans continue to disrupt ecosystems, the problem of environmental weeds is sure to worsen. Many oceanic islands, colonised early and with large scale early introduction of plants, have an "invasion trajectory" that is already well advanced. Other areas, apparently little invaded, are merely in the early stages of what will become an appreciable problem. The spread of environmental weeds is thus a form of global change. For this reason increasing importance is being attached to the study of invasions. For the World Wide fund for Nature (WWF) it is a core theme in the WWF/Royal Botanic Gardens, Kew/UNESCO "People and Plants" programme. It is also a major programmatic theme in the International Union for the Conservation of Nature (IUCN) Species Survival Commission (SSC). An SSC "Invasive Species Specialist Group" has recently been set up.

WEEDS AS GLOBAL CHANGE

Global change comprises a huge array of factors including habitat fragmentation, land use change, human population increase, climate change, CO_2 increase, pollution, ozone depletion and weeds (Vitousek, 1992). Weeds are part of the equation because long distance transport by human agency has driven ecosystem change that is not natural. An example of this is the introduction of highly inflammable, fire-resistant species into ecosystems that rarely burn, thus altering the fire frequency and irretrievably changing the ecosystem (Vitousek, 1990, Vitousek *et al.*, 1987, D'Antonio & Vitousek, 1992, Hughes & Vitousek, 1993). This is happening on a global scale and is true global change. Other examples include plants forcing changes in hydrology, nutrient status (Vitousek, 1994) or salinity (Kloot, 1983, Vivrette & Muller, 1977).

This global change in turn interacts with parallel anthropogenic global change by habitat fragmentation in the forest landscape. Forest fragmentation by imposing an additional stress on forests and greater 'edge' is likely to exacerbate the effects of plant invasion. In Natal natural forest has a well developed and diversified forest margin flora (an essential element of the vegetation where forest and grassland intermingle so richly), but where new roads are cut through the forest the margin vegetation has no time to spread round to occupy the new edge, which is promptly taken over by bugweed (*Solanum mauritianum*) (B.L. Burtt, pers. com.). Aggressive weeds (mainly shrubs) can take advantage of any ecosystem dysfunction or low diversity to invade, so leading to largely irreversible changes in ecosystem structure, composition and processes (Cronk & Fuller, 1995). Thus alien organisms have been placed in an "evil quartet" of conservation threats, and are at the centre of many conservationists' concerns (Coblentz, 1990, Janzen, 1987, Soulé, 1990). However, unlike some other threats such as logging or pollution (which in theory can be stopped, allowing forest to recover naturally), alien invasions are self-sustaining once started and extremely difficult to reverse.

Alien invasions are frequently undetected until too late, as it is very difficult for even experienced scientists to appreciate the always surprising effects of exponential increase when faced with what are initially very small founding populations. Exponential increase is, of course, a feature of some natural populations, and has been detected palaeoecologically as a characteristic of the range changes of temperate trees in response to global climate change at the end of the last glaciation (Bennett, 1986). Exponential population growth was associated with the advancing front of the range, freed from density dependent effects. Indeed this exponential growth of "migrating" populations will be needed by all species whose ranges are coupled to climate if they are to keep up with the projected rates of climate change predicted by combinations of simple climate models and General Circulation Model (GCM) experiments (Hulme & Viner, 1995). An ecosystem subject to regular disturbance events may contain species which increase exponentially for short periods after such events. However, an alien species may reproduce exponentially until it has forced irreversible ecosystem change. However, where rapid exponential growth is prolonged and rapid, as in invasions by alien plants, the original system is always altered and in some cases destroyed entirely.

Weed invasion, considered as global change, will certainly interact with global climate change. It is possible that climate change may increase alien plant invasion, for instance by taking otherwise resistant forests over some threshold of invadability. The impact on those forests in terms of speed and magnitude of observed changes could be out of proportion to the observed climate changes, and it is therefore interesting to look carefully at what the interaction might be.

WEEDS AND GLOBAL CLIMATE CHANGE - THE INTERACTION

Of the many greenhouse gases that are thought to be driving global warming, CO_2 is one for which the year by year increase in recent times is well documented, and also one that has direct effects on plant growth. Weed growth is certain to be affected beneficially, as in the case of the water weed *Hydrilla verticillata* (Chen *et al.*, 1994). One possible direct effect that has to be considered is the certain influence of elevated CO_2 levels in increasing the shade tolerance of invasive forest shrubs, thereby reducing their dependence on disturbance and accelerating the establishment of a dense forest understorey to disrupt forest regeneration. However, it is likely that the effects of increased CO_2 at an ecosystem level will be transitory, as growth will soon fall back because of nutrient depletion. Apart from the direct effect of elevated CO_2, what can we predict about the likely effects of increased temperatures and altered patterns of rainfall, storms and lightning strikes?

The importance (indicated in a previous section) of history and biotic facilitation in the process of invasion means that invasion is historically and culturally contingent (rather than directly environmentally contingent). The occurrence of germplasm transfer and the introduction of feral mammals and birds is highly non-random. There are thus two elements of uncertainty to be considered in our thinking, both a) uncertainty due to assumptions of the model of invasion and b) uncertainty due to spatial heterogeneity. However, there is one component of our conceptual model which appears again and again and that is disturbance (taken here to mean removal of biomass), including an extreme form of disturbance - fire. The question of how climate change will affect disturbance therefore becomes highly pertinent.

A recent climate change scenario for the tropics (Hulme & Viner, 1995) suggests that some regions, notably South America, will experience drying of the climate, increase in dry season length and greater interannual rainfall variability. Thus severity of <u>drought</u>, likely to be greatly increased in some tropical forests, may be expected to lead to standing dead trees, death of limbs or accelerated leaf fall, leading to the opening up of the canopy and the admission of drought tolerant invaders. The recent massive programmes by some development agencies and institutions, notably the Oxford Forestry Institute (Hughes, 1988, Hughes & Styles, 1989) to promote fast growing, rapidly reproducing and highly drought-tolerant tree species for dissemination throughout the tropics may help to get invasives into susceptible areas. <u>Tropical cyclone</u> (TC) activity in a warmer world cannot be predicted with certainty but as invasions in Mauritius (Lorence & Sussman, 1986), Jamaica (Goodland, 1990) and Tahiti (currently being invaded strongly by *Miconia calvescens*) have been greatly helped by TC disturbance, any increase in TC frequency or intensity would be expected to favour invasion. <u>Fire</u> is an integral part of many invasions and thus any increase of fire-frequency or intensity brought about by drought would potentially have a dramatic effect - possibly leading to the widespread disappearance of forests in S.E. Asia and S. America, to be replaced by the invasion of (mainly African) fire-grasses. The likely effects of climate change will differ in according to the various processes and biomes. Biomes that have never burned before such as dry evergreen forests will be most at risk.

Disturbance by humans can provide an analogue. The dry coastal *Diospyros egrettarum* forests of Ile aux Aigrettes (Mauritius) are resistant to invasion in their intact state. However, where illegal woodcutters have disturbed the forest by removing biomass a massive invasion of *Flacourtia indica* has occurred, preventing regeneration of *Diospyros* and destroying the forest (Parnell *et al.*, 1989).

One possible direct effect of increased temperature may be to allow invasion of a naturalized species which is currently kept in check by climatic factors. An example is provided by *Hedychium gardnerianum* in Madeira. This species is limited in the uplands by temperature and in the lowlands by drought as indicated by the delayed leaf and flower production in the uplands and the restriction to riverside or wet sites in the lowlands. In the wetter Azores it is a very serious invader but Madeira has no climatic zone that is at present warm and wet enough for invasion by *Hedychium*.

It is unlikely, however, that these direct effects of single species will be of great significance. Instead, it is likely that effects will be more dramatic when climatic change acts on whole ecosystems than on single species. Invasions appear to have a disturbance threshold. Climatic change, by increasing ecosystem sensitivity, may push communities over this threshold. Invasion will then lead to <u>irreversible</u> changes. It is unlikely that increased wetness will cause a dramatic increase in disturbance (as removal of biomass), except in extreme habitats close to critical anoxic levels.

ADAPTATION AND GENETIC ENGINEERING

Gene flow in its various forms has always been central to the evolution of weeds, but hitherto it has been restricted to the inefficient and slow process of hybridization, followed by allopolyploidy or segregation and introgression to give new gene combinations. Human influence on this process has up until now been twofold: the bringing together of species that have previously been geographically separated, such as the introduction of the Oxford ragwort (*Senecio squalidus*) into Britain (see this book), and in environmental change resulting in what Anderson called "hybridization of the habitat" creating new niches for the persistence and spread of new genotypes.

<u>In situ evolution</u>

The introduction of *Senecio squalidus* to Britain allowed the independent origin twice of the allohexaploid *S. cambrensis* (Abbott, 1992), in man-made disturbed habitats in Flintshire and on the demolition sites of Leith near Edinburgh. The spread of *S. cambrensis* in response to demolition (engendered by the recession of the early1980's) was a transient phenomenon, and now most of the sites are built over again, *S. cambrensis* is extinct in Edinburgh (H.J. Noltie, R.J. Pankhurst & Q.C.B. Cronk, pers. obs. 1995). On the other hand, the radiate form of groundsel (*S. vulgaris*), which has evolved by introgression between that species and *S. squalidus*, appears to be spreading in Edinburgh and in many other sites. This example highlights the hit and miss nature of the process.

<u>Transgenic evolution</u>

A recent development promises to speed up certain aspects of weed evolution. This is the production of trangenic plants by the very simple procedure of biolistics. Single genes can be inserted into plasmids and cloned. The cloned plasmid DNA can then be coated onto gold microprojectiles ('bullets') and fired at naked protoplasts of the target plant at a pressure of about 1000 psi. The protoplasts are transferred to culture medium and grown into plantlets which may then be screened for the expression of the transgene. I do not wish to dwell on the ethics of introducing such transgenes to the environment. I believe that the political and economic forces for release are so strong that it is inevitable, whether we like it or not. We should therefore consider our practical scientific response to this phenomenon before the floodgates open, rather than lose any time on other considerations.

The phenomenon of lateral transfer of DNA between taxonomically widely separated organisms is known in nature as a rare but, in evolutionary terms, very important, phenomenon. Such laterally transferred genes are sometimes called xenologues, as they are xenologous (i.e. derived by lateral transfer, rather than descent (homologous)) with the "same" gene in the distant organism. We have the potential to unleash a greater amount of lateral transfer in the next few years than the biosphere has probably seen in its entire history.

Escape of transgenic genes into nature

That some of these genes will escape from the agroecosystem to the natural ecosystem is probably inevitable. Various experiments have been carried out to find mechanisms to limit transgene flow. In the main, these experiments, such as those in conjunction with the Calgene trials of genetically engineered rapeseed (*Brassica napus*) in California and Georgia, using trap crops and barren zones (Morris *et al.*, 1994), have just emphasized the limitations of our knowledge, and hence our models, of gene flow. Besides escaping in space, genes can escape in time, through a persistent seed bank (Linder & Schmitt, 1994). The whole process is complicated by the existence of closely related weedy relatives of many crop plants, which provide ideal vehicles for the escape of transgenes. An example is provided by sugar-beet (*Beta vulgaris*), and its closely associated weed beet, which has evolved from pollinations of cultivated beets by adventitious weed beets brought accidentally into seed production areas, with the cultivated beet as the maternal parent (Boudry *et al.*, 1993).

To get to grips with this problem we need more information on: 1) the nature, extent, and frequency of introgression rates, 2) the behaviour of transgenes in wild populations and 3) the nature and consequences of transgene expression in the wild (Darmency, 1994). Expression patterns can be complicated by modifying genes and epistatic factors, and so the behaviour of transgenes may not be obvious. A recent study of trangenic rapeseed (*Brassica napus*), transformed with resistance to the herbicide phosphinotricin, found that not all the cultivar-wilding hybrids that were shown to have the transgene by DNA amplification were, in fact, expressing it (Kerlan *et al.*, 1993).

DNA timeslices: setting baselines for the future

Whatever the future holds in this area, it is bound to throw up challenges for weed scientists. One thing that worries me is the present lack of genetic baselines against which to study the rate and direction of weed evolution. One way of addressing this would be to establish "DNA timeslices" of either extracted DNA or seeds, properly sampled from a defined weed population. Extracted frozen DNA does not appreciably denature: there appears to be no evidence of denaturation during storage at -80°C. A natural DNA timeslice may exist in the seed bank, but this is difficult to date and the timeslicing is coarse. With the progress of global environmental change and transgene releases, it seems certain that at some time in the future we will need to know what the frequency of particular genes was in the past - and the past is now.

BRAVE NEW WORLD, BRAVE NEW WEEDS

If habitat fragmentation and degradation lead us further into an ecological mess, weeds (and particularly weedy multipurpose agroforestry shrubs), or weed genes, may be in increasing demand to service the ecosystem and agroecosystem needs of the human population. Indeed, in many degraded ecosystems, exotic weeds are all that remain. St Helena, like other vulnerable oceanic islands, is a good example. The introduction of the goat at the time of the island's discovery in 1502 led to the rapid destruction of the non-browsing-resistant vegetation and some two thirds of the island's topsoil was washed out to sea. These destroyed ecosystems have been replaced by robust ecosystems of cosmopolitan weeds. If weed invasion in natural habitats, by increasing the relative abundance of pioneers in forests, makes them more resistant to global climatic change, then they may save areas from irreversible loss of productivity by erosion. In a warmer world it is conceivable that invasive plants become essential to create robust new utilitarian ecosystems to meet human needs and prevent catastrophic degradation of ecosystems. However, these "brave new ecosystems" will have only a fraction of native diversity and can only be a council of despair.

Control of invasions

It is possible, although difficult, to keep the unintentional introductions under control. Solutions fall into four broad categories depending on the temporal point along the invasion trajectory that action is taken: 1) prevention, 2) prediction, 3) integrated pest management (IPM), 4) biological control (Cronk & Fuller, 1995). The simplest way to combat invasion is to prevent the naturalization of likely invaders. The characteristics of existing invasion can be used in a limited way to predict the most dangerous candidates. Thus *Passiflora mollissima*, so troublesome in Hawaii, should not be allowed to invade similar forests in South Africa (Macdonald, 1987). If the invasion has got going then it may be limited with an IPM strategy, usually involving minimizing disturbance, careful hygiene and quarantine to prevent further spread, total eradication (physical and chemical) at new sites to limit spread, and landscape management to ensure that conditions are least favourable for the invader. Biocontrol is the only resort when the invasion is "out of control" but it is expensive to develop a programme for a new weed, and it is not always possible or fully successful. On the other hand, there are examples where even moderate success of biocontrol agents can be useful in integrated pest control programmes (see Hoffmann, this book).

The importance of a database

Increased databasing of invasion can supply necessary information for prevention, prediction and the pooling of resources for developing biocontrol. A database would also function as a baseline for understanding patterns and change, and is a priority. Very often basic autecological facts are unknown for invaders and this is particularly true of ecological behaviour in the native range. Plant invasions present natural experiments which all too frequently have not been properly recorded. As more attention has been given to the subject in recent years, the prospects have become much less gloomy, and there is a good chance that actions taken now can go a long way towards minimizing the effects of climatic change on natural ecosystems as mediated by invasion. As Coblentz (1990) has noted: "Invasive organisms provide an opportunity to combine first-rate science with effective land management to create functioning conservation biology". This is a great challenge for the future. Indeed, we need much greater sophistication in our response to weeds, particularly now human-driven global change imbues the problem with greater and greater severity.

The past and the future

Weeds have always played a role in human affairs, and vice versa. Weeds have been waiting in the wings for their anthropogenic appearance centre-stage ever since the first angiosperm tree fell in the Cretaceous forest, allowing the evolution of rapid life-cycle early-successional flowering plants. Pliocene aridification and lightning fires played their part, as did Pleistocene glaciation. The appearance of anthropogenic fire 50,000 years ago, and the Neolithic agricultural revolution 10,000 years ago contributed their milestones on the long march of weediness. Even war has played its part in the story. An example is the introduction of *Tagetes minuta* into the Eastern Cape (Grahamstown) of South Africa during the Boer War, as a contaminant in South American fodder for cavalry and draught horses. What of the future? Can we envisage biological warfare by means of genetically engineered superweeds, with multiple herbicide resistance, dropped onto crops? Such a strategy might severely damage a regime economically, without inflicting physical injury on the population. A dust-like seed plume of super-*Striga* targeted through accurate knowledge of atmospheric currents may sound like science fiction, but are we sure that such a proposal isn't feasible? And are we sure that all weed scientists have the integrity to refuse to work on such a project.

The response of future scientists to the surprises that weeds generate will be marked by increasing (and to us almost unimaginable) sophistication, and I predict that social scientists will become important players too. Many environmental weeds involve an element of social conflict. Is *Lythrum salicaria* in North America an important honey source or a wetland pest? That depends on how many hives you have. Are *Prosopis* species in India excellent honey sources, good fuel-wood sources or unstoppable destroyers of grazing land? The resolution of social conflict will be integral to the weed control of the future. Is there one straightforward thing that we could do to start this increase in sophistication? I think there is. Most invasions that we study are late in their invasion trajectory, so they are obvious. There are few case studies of invasions as they start, so that ecological processes of early invasion and genetic pre- and post-adaptation have not been studied in real time. Of course we may end up studying some introductions that remain unimportant. However, if successful, we would harvest much new knowledge from weeds, and truly be able to say that as scientists:

"Thus may we gather honey from the weed,
And make a moral of the devil himself." (Henry V).

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APPENDIX - GLOSSARY

Brave new ecosystem - a robust, low diversity vegetation of weedy species (usually agroforestry shrubs) replacing native vegetation that has failed to survive, function, or to service human needs.

Continued Approaches II