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Potential Geographical Distribution of Alligator Weed and its Biological Control by *Agasicles hygrophila*

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ABSTRACT

Alligator weed is a South American species that has invaded all continents except Africa and Europe and is spreading in Australia where it grows in both aquatic and terrestrial habitats. A climate matching program, CLIMEX, and the known distribution of the weed in South and North America were used to infer areas suitable for its growth elsewhere in the world. Results indicated that most eastern and southern areas of continental Australia are suitable, as are areas of Africa and southern Europe. Classical biological control, using the alligator weed flea beetle *Agasicles hygrophila*, has been effective in controlling aquatic growth of the weed in many areas in USA. CLIMEX parameter values were also fitted for this beetle using the distribution of the beetle in its native range. The fitted values were validated using the known distribution of the beetle in USA and CLIMEX was then used to find other areas of the world climatically suitable for this insect. *A. hygrophila* controls alligator weed over part of the weed's range in USA. This information was used to determine a threshold value of the Ecoclimatic Index (EI) produced by CLIMEX, above which effective control was likely. The results indicated that control of alligator weed by the flea beetle would be restricted compared to areas at risk of invasion by the weed. Such predictions are being used in Australia to predict spread and efficacy of agents and to assist control planning and management of alligator weed.

Key words: Alternanthera, weed control, biological control, spread, temperature, insect.

INTRODUCTION

Alligator weed, (*Alternanthera philoxeroides* (Mart.) Griseb. (Amaranthaceae) originated in the Parana River region of South America (Maddox 1968, Vogt et al. 1979). It has spread to other areas of South America and to the continents of North America, Asia and Australia and some of the adjacent island countries. In some areas alligator weed chokes waterways while in others it invades pastoral and agricultural land (Coulson 1977, Julien and Bourne 1988, Julien and Broadbent 1980).

The weed is a perennial species which rarely sets seed, and seeds produced usually are not viable. Thus, the weed reproduces by vegetative means from apical stem buds and axillary stem and root buds. It is described by Vogt et al. (1979) as an amphibious plant because it grows in a range of habitats from dry terrestrial to aquatic, where it may be rooted into the bank or substrate beneath shallow water or may form independent free-floating mats. Aquatic growth has larger hollow stems, providing buoyancy. On land, the stems are smaller and solid to slightly hollow (Julien et al. 1992).

Alligator weed has reached its limits of spread in USA (Coulson 1977) and China (R. Wang pers comm. 1988) but is expanding its distribution in Australia where it is considered a serious potential threat (Julien and Bourne 1988). To alert land and water managers and assist planning for weed surveillance, quarantine and control, it would be useful to predict areas that would support growth of this weed in Australia and elsewhere in the world.

In the 1960s, biological control of alligator weed was undertaken in the USA. A flea beetle, *Agasicles hygrophila* Selman and Vogt (Coleoptera:Chrysomelidae), a moth, *Vogtia malloi* Pastrana (Lepidoptera:Pyralidae) and a thrips, *Amynothrips andersoni* O'Neill (Thysanoptera:Phloeothripidae), were introduced from South America (Spencer and Coulson 1976). Later, the beetle and moth were released in Australia, New Zealand and China (Julien 1992). Control of the weed, due mainly to damage caused by the beetle, was achieved where it grew in aquatic habitats in Australia (Julien 1981). Control in the southern portion of its range in USA was due to the flea beetle (Coulson 1977, Buckingham et al. 1983) and in more northern areas by a combination of the moth and flea beetle (Vogt et al 1992), while the northern most infestations were not controlled. The beetle destroyed tops but did not reduce the size of floating mats in New Zealand (Roberts and Sutherland 1989). The beetle, but not the moth, has established in parts of China though it is not yet providing significant control (Julien pers obs.). Attempts to establish another beetle, *Disonycha argentinensis* Jacoby (Coleoptera:Chrysomelidae), in Australia and New Zealand to control alligator weed growing in terrestrial habitats failed (Julien and Chan 1992, Roberts and Sutherland 1989).

Vogt et al. (1979) documented the native range of *A. hygrophila*. Coulson (1977), Cofrancesco (1988) and Vogt et al. (1992) documented areas in the USA where this flea beetle provided successful control and areas where control was not successful. Again, to assist with weed management it would be useful to use current knowledge to predict where this biological control agent could be successful.

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METHODS AND MATERIALS

Sources of Data. The following sources of information were used: Vogt et al. (1979) and Coulson (1977) for the distribution of the weed in South America and USA; Vogt et al. (1979), Coulson (1977), Cofrancesco (1988) and Buckingham et al. (1983) for the distribution of the flea beetle in South America and USA, and the latter three sources for the effectiveness of the flea beetle in different localities in USA. The information helped define and validate parameter values used in the climate matching computer program CLIMEX.

CLIMEX. CLIMEX is a computer program that uses long-term average meteorological data to derive weekly and annual population growth indices (GI) which describe the potential of the location concerned to support population growth of a nominated species during the favourable season. Annual stress indices (cold, hot, dry and wet) and stress interaction indices (hot-wet, hot-dry, cold-wet and cold-dry) describe the severity of the unfavourable season in terms of the probabilities of extinction of the population. These indices are then combined into an annual ecoclimatic index (EI) which describes the potential for the persistence and growth of the population (Maywald and Sutherst 1991). EI is scaled between 0 and 100, the number being indicative of the relative size of the population, and in the case of the flea beetle, of the potential for control. CLIMEX (version 4.2) runs on IBM-compatible personal computers, and includes a climatic database of over 2500 locations.

Predicting the Distribution of Alligator Weed and the Flea beetle. The CLIMEX parameter values for both alligator weed and the flea beetle were estimated using the known distributions of the species in South America (Vogt et al. 1979). The values were iteratively adjusted until there was a close visual match between the endemic and predicted distribution. The exotic ranges in North America were then used to fine-tune the parameter values for both species in a similar manner. Adjustments to the parameter values were aimed at producing values of EI above 10 for locations favourable to the growth of alligator weed, with locations between 0 and 10 being marginal. The final parameter values for alligator weed were then used to predict areas in Australia and other parts of the world likely to be suitable for the weed (Sutherst and Maywald 1985). Similarly, the final values for the flea beetle were used to predict areas where this insect could be expected to successfully control alligator weed.

The effect of climate change due to the enhanced greenhouse effect was also investigated. The greenhouse assumptions used provided an increase in temperatures of 0.1°C for each degree of latitude north or south and an increased in rainfall of 20% in summer and a decreased of 10% in winter (Pittock and Nix 1986).

RESULTS

Potential distribution of Alligator Weed. The CLIMEX parameter values that best describe the observed distribution are shown in Table 1. Note that the moisture stress indices were not used as the weed requires adequate water for growth such as that available in aquatic, swampy and high water table locations. However, the weed can grow in quite dry habitats, competing with crops and contaminating produce.

Figure 1A shows the locations in the Americas where alligator weed was predicted to be able to grow. The observed distributions are also shown including the native range in Argentina, south-eastern Brazil and adjacent countries and exotic range in southern USA. The area of the circles on the maps are proportional to the suitability of each location for growth of the weed.

Figures 1B, 1C and 1D show predictions for Australia, eastern Asia and Africa and Europe, and include known infestations. In China the weed is widely distributed south of the Yellow River (R. Wang pers comm. 1988).

Distribution of the Flea Beetle. The CLIMEX parameter values that best describe the observed distribution are shown in Table 1. Note that in order to obtain a satisfactory fit the day-

TABLE 1. CLIMEX PARAMETER VALUES FOR ALLIGATOR WEED, *A. PHILOXEROIDES* AND FOR THE FLEA BEETLE, *A. HYGROPHILA*. THESE VALUES WERE GENERATED BY ITERATION WITHIN CLIMEX AND WERE NOT OBTAINED THROUGH EXPERIMENTATION.

		Alligator Weed	Flea Beetle
Moisture parameters*			
SM0	Lower soil moisture threshold for population growth	0.0	0.0
SM1	Lower optimal soil moisture for population growth	0.01	0.3
SM2	Upper optimal soil moisture for population growth	5.0	2.0
SM3	Upper soil moisture threshold for population growth	10.0	5.0
Temperature parameters			
DV0	Lower temperature threshold for population growth	12.0C	10.0C
DV1	Lower optimal temperature for population growth	25.0C	22.0C
DV2	Upper optimal temperature for population growth	32.0C	28.0C
DV3	Upper threshold temperature for population growth	36.0C	32.0C
Stress indices			
TTCS	Threshold of cold stress	10.0C	10.0C
THCS	Rate of accumulation of cold stress	0.00035	0.0006
DTHS	Threshold of heat stress (day-degree)	not used	75.0 day-degrees
DHHS	Rate of accumulation of heat stress	not used	0.00003
TTHS	Threshold of heat stress (temperature)	33.0C	not used
THHS	Rate of accumulation of heat stress	0.0045	not used

*The moisture parameters in CLIMEX are based on a soil moisture balance model using rainfall and evaporation as inputs, rather than using rainfall or relative humidity.

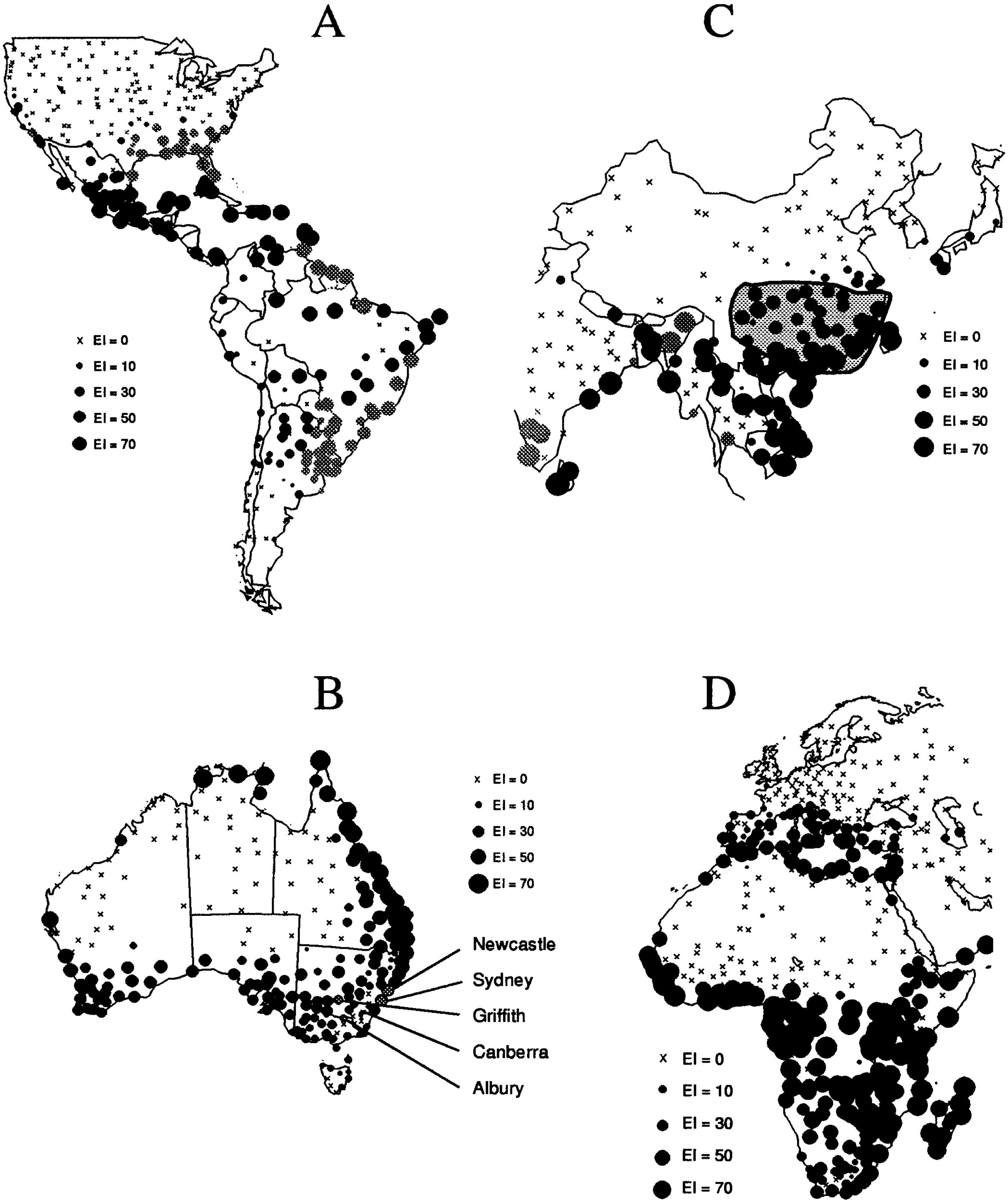

Figure 1. The predicted distributions of alligator weed in: A) The Americas, where locations that occur within the known distributions are hatched and the native range of the weed is considered to be around the Parana River system in north eastern Argentina; B) Australia, where Sydney, Newcastle, Albury and Griffith are hatched to indicate the current distribution; C) eastern Asia, where locations with alligator weed in India, Burma and Thailand are hatched while the southern region of China known to have alligator weed is hatched; and D) Africa and Europe. Crosses indicate unfavourable locations for growth and the areas of circles are proportional to the suitability of the location for the weed.

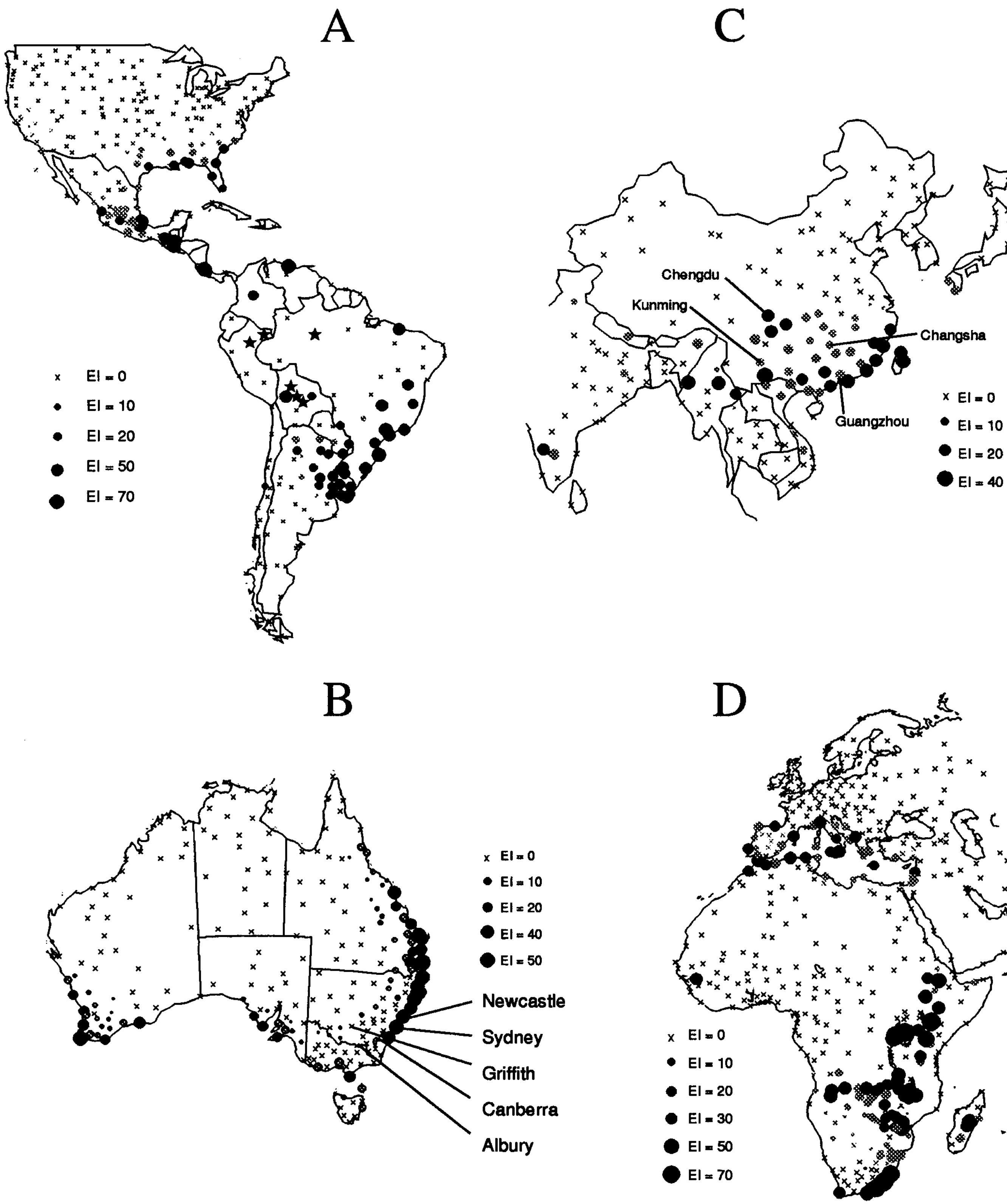

Figure 2. A) The native and introduced distributions of the flea beetle *Agasicles hygrophila* in South America and North America, respectively, and A) to D) predictions of the suitability of locations for the flea beetle in: A) Central America; B) Australia, where it is established near Sydney and Newcastle; C) eastern Asia, where it has been released in China at Kunming, Changsha and in Fujian Province and in Thailand in Bangkok; and D) Africa and Europe. Crosses indicate unfavourable locations and the areas of circles are proportional to the suitability of the location for the flea beetle. Hatched circles (EI<25) indicate locations were it is predicted that the flea beetle could establish but not control the weed. Dark circles indicate locations were control is predicted likely. Stars indicate sites were the flea beetle has been found but no CLIMEX location exists.

degree method had to be used for determining the heat stress. This method determined the heat stress by summing the total accumulated heat energy (day-degrees) above a threshold, in contrast to the alternative method where heat stress depends on the value of the maximum temperature (Maywald and Sutherst 1991).

The distribution of the flea beetle in its native range in South America, used to set the values for parameters to predict distributions in North America is shown in Figure 2A. Interrogation of the predictions and knowledge of localities where the flea beetle effectively controlled the weed in North America suggested that locations with an EI between 0 and 25 (hatched circles on Figures 2A, 2B, 2C and 2D) may support populations of the flea beetle, but the effects of climate will limit population increase and prevent control of the weed.

Since this flea beetle can only develop viable populations in aquatic habitats, these predictions show the potential for control of the weed in aquatic and not in terrestrial systems. Figures 2B, 2C and 2D show the predicted suitability of locations in Australia, eastern Asia and Africa and Europe for the flea beetle. Black circles indicate locations where the EI is above 25, that is, where it is predicted that populations of the flea beetle will control the weed.

DISCUSSION

Alligator Weed. Several locations known to have alligator weed were not included in the predictions. This was due to lack of available meteorological data near the location, for example, sites in Bolivia (Figure 1A), or to local conditions being more favourable than suggested by the meteorological data. For example, a small infestation was recently found, and eradicated, on Lake Ginninderra, Canberra (G. Sainty pers comm. 1994), a location predicted unsuitable for the weed (Figure 1B). CLIMEX predictions suggest likely distributions based on long term meteorological data averages, not on biological data, micro climate or other ecological factors. Consequently, anomalies, especially near the edges of the likely range of an organism, are inevitable. This should not devalue the use of CLIMEX as a predictive tool.

CLIMEX predicted with broad accuracy the locations in China where alligator weed grows (Figure 1C) and suggests that alligator weed has reached its geographical limits in that country. Further, the infestations in Australia occupy a very small proportion of the predicted distribution (Figure 1B) and large parts of Africa (Figure 1D), particularly the southern half where other water weeds have already caused serious problems, are at risk should alligator weed establish on that continent. It could also grow in the warmer southern parts of Europe.

Alligator weed is present in Puerto Rico and Java, India, Rangoon in Burma and Bangkok in Thailand and has been recorded from Singapore (Julien and Broadbent 1980). Other countries in Central America (Figure 1A) and Asia (Figure 1C) could also support its growth. However, in hot tropical regions, alligator weed does not present a serious threat. In Indonesia and Thailand the weed does not grow as vigorously as in more temperate areas. Even in polluted waterways in the tropics it fails to develop large monospecific stands or the high biomass that occurs in temperate regions (Julien pers. obs.). Similarly, at cooler, higher latitude regions that support growth of the weed, the problems it may cause are reduced. Growing seasons are shorter and frosts kill top growth and together these restrict biomass accumulation (Julien et al. 1992). Glasshouse studies indicated the optimum temperature for growth to be between 15 and 20°C (P. Sale and K. Bowmer, pers comm. 1992). Alligator weed grows best and is likely to cause most serious problems in sub tropical to cool, but not cold, temperate climates.

Should global climatic change occur as generally predicted, the distribution of organisms will alter as locations become more or less favourable for their existence. The effect of including the greenhouse scenario and rerunning the predictions for alligator weed reduced the suitability of inland areas and increase the suitability of southern locations in Australia. Asia generally became less favourable and Europe more favourable for growth of the weed. The west coast of the Americas became more favourable as did the east coast of USA and inland areas north of the current infestation.

Biological Control. If alligator weed were to spread in Australia as predicted (Figure 1B), the flea beetle is predicted to provide successful control only in areas close to the east coast that are south of central Queensland, along with portion of southern South Australia and the south western corner of Western Australia (Figure 2B). Biological control by this insect is unlikely to be effective in inland waterways including the major wetland and irrigation systems of the Murray and Darling Rivers. Here eradication of a large, recent outbreak of the weed near Griffith, New South Wales, is being attempted (G. McCorkelle pers comm. 1994). It is recognized that ongoing management of the weed at this location will probably be required but that biological control agents currently in Australia may not assist.

The flea beetle has been released in China at Kunming, Yunnan Province, in Fujian Province on the coast adjacent to Taiwan (H. Dayu. pers comm. 1992), at Changsha, Hunan Province and releases were planned for Chengdu, Sichuan Province (J. Balciunas pers comm. 1989). The predictions for China (Figure 2C) suggest that the flea beetle would be most successful if released in south-eastern coastal provinces. The beetle failed to establish at Kunming where the EI is low, but is established in Fujian where favourable EIs are indicated. Although the outcome of releases at the other sites is not known, CLIMEX suggests that the beetle could not establish at Changsha, whereas the EI is only marginally greater than 25 at Chengdu so the beetle should establish and may control the weed there. The flea beetle is established on alligator weed growing in eutrophic drains in Bangkok despite the CLIMEX prediction that Bangkok is unsuitable (Figure 2C).

A comparison of the potential distributions for alligator weed and the potential distributions for its control agent highlight important differences. The flea beetle has a more restricted distribution than the weed. The flea beetle is not adapted to hot tropical regions. The few suitable locations indicated at low latitudes are all at high altitudes. It is also less suited to cold conditions than the weed. An attempt to locate and establish a 'cold' biotype of the flea beetle to control alligator weed in its cooler range in USA was unsuccessful (Buckingham et al. 1983). This was likely due to the flea beetle, which does not undergo a winter diapause, being unable to survive in the absence of alligator weed tops which were destroyed by the winter conditions (Vogt et al 1992). In addition, much of southern and central Africa is favourable for growth of the weed but not the insect (Figures 1D and 2D).

General Comments. CLIMEX was developed to assist climate matching in biological projects. It provides broad predictions using macro-climatic data. Climate matching has been used in classical biological control for a long time (Doube et al. 1991, Wilson 1949, Julien 1981) though Leen (1991) found it difficult to determine its impact on the success of biological control projects. With the development of CLIMEX, assessments can be made quickly using large data bases with greater accuracy and consistency than was previously available. Consequently, CLIMEX is becoming widely used in the prediction of distributions for pests and beneficial organisms, for ecosystem management and for predicting the effects of climate change on distribution of organisms (Sutherst 1991), in biological control (Scott 1992) and quarantine planning and management (Sutherst and Maywald 1991).

CLIMEX can be applied to other pest control systems to predict spread of pests and efficacy of agents, especially those with a history of effective biological control. It can be used to match climates, assist planning of projects and alert authorities to the potential of exotic invaders to establish and become pests. Knowledge of the species in question is essential for interpretation of such predictions. For example, within climatically suitable locations the flea beetle requires alligator weed growing year round in an aquatic habitat to develop viable populations.

Crutwell McFadyen (1991) pointed out that predictions of the likely exotic distribution of an organism based solely on knowledge of its native range may be quite erroneous. In this paper we have used CLIMEX to make predictions for the distribution of a weed and its control agent, where both native and exotic ranges are known. In fact, both organisms had reached their geographical limits in at least part of their exotic range and this information was used to set the parameter values for predictions elsewhere. These predictions should be more reliable than any made using the native range only and are being used to assist planning future strategies for the management of alligator weed in Australia.

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