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PARTHENIUM WEED: A POTENTIAL MAJOR WEED FOR AGRO-ECOSYSTEMS IN PAKISTAN

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ABSTRACT

Parthenium weed (Parthenium hysterophorus L.) is a new and potentially major weed in Pakistan. This weed, originating from central America, is now a major weed in many regions of the world including Eastern Africa, India, parts of South East Asia and Australia. Presumably its recent arrival in Pakistan has been due to its movement from India, but this has yet to be established. In Australia it has been present for about 50 years, in which time it has spread from isolated infestations to establish core populations in central Queensland with scattered and isolated plants occurring south into New South Wales and north-west into the Northern Territory. Its spread in Pakistan is likely to be much more rapid, but lessons learnt in Australia will be of great value for weed managers in Pakistan. This annual herb has the potential to spread to all medium rainfall rangeland, dairy and summer cropping areas in Pakistan. In Australia its main effect is upon livestock production, but it is also causing health concerns in regional communities. However, in India it has also had a significant impact in cropping systems. To help coordinate actions on its management in Australia, a National Weeds Program has created a Parthenium Weed Management Group (PWMG) and under this group a Parthenium Weed Research Group (PWRG) has been formed. Funding coming from this national program and other sources has supported the PWRG to undertake a collaborative and technology exchange research program in two main areas: 1) biology and ecology and 2) management; while the PWMG has focused on community awareness and the production of various extension and management packages. Research in the area of biology and ecology has included studies on the evaluation of competitive plants to displace parthenium weed, the use of process-based simulation models to monitor and predict future spread and abundance under present and future climate conditions, the effect of the weed on human health and the ecology of its seed bank. Management research has focussed on the development of biological control approaches using plant-feeding insects and pathogens. The effectiveness of biological control is also being monitored through long term studies on seed bank size and dynamics. The use of fire as another potential management tool is also being evaluated. In addition to this important research, an effort has also been made to spread the most important findings and management outcomes to the wider community through an extension and education program driven by the PWMG. These developments within Australia, in parthenium weed management, will be of great help to Pakistan as its weed managers prepare to resist a potential invasion by this significant weed.

Key words: *Parthenium hysterophorus*, biological control, biology, ecology, management, Parthenium Weed Research Group, seed banks.

INTRODUCTION

Weed biology: Parthenium weed (*Parthenium hysterophorus* L.) is an herbaceous annual or ephemeral member of the Asteraceae, reaching a height of 2 m when growing in good soil and capable of flowering within 4 to 6 weeks of germination (Navie *et al*., 1996b). Large plants can produce more than 15 000 seeds which may be dispersed by wind, moving water, or in mud adhering to animals, clothing vehicles or machinery (Auld *et al*., 1983). It has been thought that most of the seeds germinate within 2 years if conditions are suitable (Butler, 1984), although a significant portion of buried seeds may remain viable for several years (Navie *et al*., 1998a). Parthenium weed grows best on alkaline to neutral clay soils (Dale, 1981), but will also grow less prolifically on a wide range of soil types. The water requirements of the plant are relatively high and both germination and growth are limited by poor rainfall (Williams and Groves, 1980).

Distribution: Parthenium weed occurs naturally throughout the tropical and subtropical Americas from the southern United States of America (USA) through to southern Brazil and northern Argentina (Dale, 1981). It was accidentally introduced into India around 1956 (Chandras and Vartak, 1970) and has since spread over most parts of the Indian sub-continent, including Pakistan. Parthenium weed has also spread to southern China, Taiwan and Vietnam in Asia (Nath, 1981), is present in several Pacific islands, and has invaded several African countries including Ethiopia, Kenya, Mozambique and South Africa (Njoroge, 1989; Tamado *et al*., 2002).

Parthenium weed was introduced into Australia from North America on at least two separate occasions. The most serious introduction occurred in 1958, where seed was brought in as a contaminant of pasture grass seed from Texas, USA (Haseler, 1976). This infestation originated in the Clermont area in central Queensland and did not spread very quickly until the early 1970's. However, rapid spread since this time has lead to 170 000 km^2 or 10% of Queensland being infested (Chippendale and Panetta, 1994). The other introduction was at Toogoolawah in south-eastern Queensland. It has been suggested that this introduction occurred during the 1940's and was due to the movement of aircraft and machinery parts from the USA (Parsons and Cuthbertson, 1992). This infestation has not spread nearly as extensively as the one at Clermont. There are now many new outbreaks reported in New South Wales each year and at least two infestations have been found in the Northern Territory (Figure 1).

The parthenium weed problem: Parthenium weed causes severe human health problems as well as agricultural losses. Parthenium weed and related genera contain sesquiterpene lactones (Picman and Towers, 1982) which induce severe allergic dermatitis and other symptoms. Agricultural losses can also be severe. In India, parthenium weed causes yield losses of up to 40% in several crops (Khosla and Sobti, 1979) and it is reported to reduce forage production by up to 90% (Nath, 1981). In

Australia, parthenium weed is a serious problem in perennial grasslands in central Queensland (for reviews see Adkins *et al*., 1996, 1997a, 2001; Navie *et al*., 1996a, 1997, 1998c), where it can reduce beef production by as much as AU$16.5 million annually (Chippendale and Panetta, 1994). Stock animals, especially horses, suffer from allergic skin reactions while grazing infested paddocks. Parthenium weed is generally unpalatable, but cattle and sheep will eat it when feed is scarce. Consumption of large amounts will produce taints in mutton (Tudor *et al*., 1982) or kill stock. In Pakistan the weed is likely to become a serious problem in perennial grasslands, wastelands around communities and summer crops.

Management: In most areas of the world the high costs of herbicides prohibit their use for parthenium weed management in perennial grasslands. Management can be achieved by maintaining a good pasture grass growth to maximise competition against the weed. When individual parthenium weed plants are found, or when the weed is a problem in certain crops, control can be achieved by using 2, 4-dichlorophenoxyacetic acid or residual herbicides such as atrazine (Holman, 1981). Biological control has been seen as a better alternative to herbicides in perennial grasslands and the search for natural control agents is on-going in Australia and other countries. Biological control, using a suite of agents, will presumably be a very useful core approach to management in Pakistan, since such approaches are showing promise in neighbouring India.

Scope: This paper will review recent advances in parthenium weed biology and management that have come about in Australia in the last 10 years. Earlier advances are summarised in an earlier publication (Adkins *et al*., 1997b). Research on parthenium weed management in Australia is currently being coordinated by the Parthenium Weed Research Group (PWRG). The PWRG was instigated by the Parthenium Weed Management Group (PWMG) to undertake a coordinated research program in the areas of biology, ecology and management of parthenium weed (Austin, 2005).

The participatory Parthenium Weed Research Group (PWRG) approach

Any functional weed management approaches should have an underpinning directed research program. In Australia this is achieved through the co-ordinated actions of the PWRG. The PWRG seeks to develop and implement cost-effective, environmentally friendly methods for the management of parthenium weed. The PWRG management program has three distinct sub-programs. The first sub-program is designed to improve the understanding of the biology and ecology of the weed. This includes work on seed biology, competitive ability, effects on human health, and predicting future weed spread and abundance. The second sub-program is designed to develop improved methods of biological control using insects and pathogens. This includes work on the assessment of agent efficacy under field conditions. The third sub-program is designed to develop ways to inform extension workers and farmers about the strengths of new management methods and how these methods might be integrated into present farming system approaches. This last sub-program is undertaken in conjunction with the PWMG and will not be reported on in this paper (see Austin, 2005).

Biology and ecology sub-program

The objective of this first sub-program is to undertake a comprehensive study of parthenium weed that will identify the life stages that are best targeted for biological control, competitive displacement with competitive plants, and other management methods. In addition, this sub-project will provide data for predicting the potential spread of the weed under present and future climatic conditions and for determining the field effectiveness of biological control agents.

Seed biology: Soil seed banks have been investigated and testing for seed longevity, seed dormancy, and the ability of parthenium weed to germinate under a wide range of temperature and moisture levels has also been undertaken.

Seed banks: In earlier studies the germinable soil seed bank was determined at two sites (Clermont and Moolayember Creek) in central Queensland on four separate occasions during a 2 year period in the mid-1990's (Navie *et al*., 2004). These sites were infested with parthenium weed and during this period, the seed bank varied between 3 282 and 5 094 seed per m^2 at the Clermont site, and between 20 599 and 44 639 seed m^2 at the Moolayember Creek site. Parthenium weed exhibited a very abundant and persistent seed bank at these sites, accounting for 47-73% of the total at Clermont and 65-87% of the total at Moolayember Creek, during this period (Navie *et al*., 2004). Parthenium weed seedlings were also found to emerge more rapidly from the soil samples than did those of most other species.

The species richness and species diversity of the seed bank, and the seed abundance of many other species, was lower at Moolayember Creek during spring (the time of year when the densest infestations of the weed are present). Further investigation of this data has shown that the diversity of these seed banks was lower in comparison with that observed in other grassland communities that were not dominated by an invasive weed species, such as parthenium weed (Navie *et al*., 2004). Hence, the prolonged presence of parthenium weed at this site may have substantially reduced the diversity of the seed bank, thereby reducing the ability of some of the native species to regenerate in the future. The domination of parthenium weed in the seed banks at this site suggests that the weed is having a substantial negative impact on the ecology of this plant community (Navie *et al*., 2004).

In recent studies collections of the soil seed bank were made at the same two sites in April 2000 and February 2001, to investigate any changes that may have occurred in the intervening period. It must be noted, however, that the numbers of seeds found on these more recent sampling dates should be slightly higher, due to the fact that the soil was sampled to a slightly greater depth on these two later occasions (Navie and Tamado, 2002).

The germinable soil seed bank at the Clermont site was found to be 5 508 seeds m^{-2} in April 2000 and 3 102 seeds m^{-2} in February 2001 (Navie and Tamado, 2002). As in previous samplings at this site (Navie *et al*., 1997; Navie *et al*., 2004) the seed bank was mostly dominated by parthenium weed (35-51%) and grass (28-56%) propagules. These two groups contributed 80-91% of the entire seed bank, but the proportion of grass propagules in the seed bank seemed to be higher than during the previous study period. The seed bank of parthenium weed on these two occasions was relatively low (1 955 and 1 584 seeds m^{-2}) compared with the average in the mid-1990's (2 415 seeds m^{-2}), but still higher than the value obtained on March 1995 (Navie and Tamado, 2002).

This pasture (i.e. the extant vegetation) was dominated by grasses during the later sampling periods, due to several years of good rainfall and some resting from grazing pressure. However, a very large seed bank of parthenium weed is still present and ready to emerge if the pasture condition deteriorates and/or when more appropriate growing conditions for the weed return. Hence, this more recent research suggests that such apparently healthy pastures remain susceptible to re-infestation from parthenium weed if conditions should change again in the future (eg. a return to less desirable pasture management practices brought about by a prolonged drought or a change in land ownership).

There have been much greater changes in the seed bank at Moolayember Creek since the original study period (Navie and Tamado, 2002). In the original study, the total seed bank averaged 34 054 seeds m^{-2}, and varied between 20 599 and 44 639 seeds m^{-2} (Navie *et al*., 2004). A total of 24 728 seeds m^{-2} were found in the seed bank at Moolayember Creek in April 2000 and only 13140 seeds m^{-2} during the February 2001 (Navie and Tamado, 2002). This latest value is much lower than any of those recorded on previous sampling occasions, especially considering the slightly deeper soil sampling method in the later collections.

Once again, parthenium weed was the most abundant species present and accounted for 26-41% of the total seed bank. The seed bank of parthenium weed varied between 17 579 and 33 904 seeds m^{-2} during the course of the original study (average: 26 436 seeds m^{-2}) and was reasonably constant until October 1996, when a significant decrease was detected (Navie *et al*., 2004). In the later studies the seed bank of parthenium weed was determined to be only 6 332 seeds m^{-2} in April 2000 and 5 433 seeds m^{-2} in February 2001 (Navie and Tamado, 2002). This equates to less than a third of the lowest value recorded during the original study, when it should be slightly higher due to the difference in sampling techniques.

Unlike at the Clermont site, a number of annual or short-lived perennial weeds were also very common in the seed bank, including *Conyza bonariensis*, *Lepidium bonariense*, *Sida* sp. and *Argemone ochroleuca*. These species contributed a combined total of 33% of the total seed bank in February 2001 (Navie and Tamado, 2002), which was less than the 43% they contributed in April 2000, but still much greater than any period during the original study (19% in March 1995 and 7% in March 1996). *Conyza bonariensis* is closely related to parthenium weed and quite similar in many respects. This introduced, but not highly invasive, species may be partially filling the gap in the vegetation that has been created at this site by the recent and continuing decline in importance of parthenium weed (Navie and Tamado, 2002).

The reduction in the parthenium weed seed bank at Moolayember Creek is most probably due to an increase in the activity of biological control agents at the site over the last 10 years. At the time of the original study only *Epiblema strenuana* was well established at the site, while outbreaks of *Zygogramma bicolorata* were becoming more numerous. The seed-feeding weevil *Smicronyx lutulentus* was first observed at this site in January 1996, and the arrival of this agent was suggested as a possible reason why the seed bank of parthenium weed dropped substantially in October 1996 (Navie *et al*., 2004). It is likely that the growing impact of these agents, along with favourable growing conditions for native grasses, has continued to decrease the dominance of this weed at the site during the last 10 years. The decrease in the seed bank of parthenium weed has also coincided with an increase in the seed bank of other annual weed species. These species may have moved in to fill that part of the niche in the ecology of this site previously occupied by parthenium weed that has not yet been filled by perennial grasses (Navie and Tamado, 2002).

While the changes in the vegetation at both sites are very noticeable, with much less parthenium weed being observed, a relatively large seed bank of this species still remains present in the soil at both sites (Navie and Tamado, 2002). By simply observing changes in the vegetation at these sites during the last 10 years, one may wrongly come to the conclusion that this weed is no longer a threat. However, the numerical size and longevity of the seed bank of this species means that it will remain a concern for many years after it has declined in the extant vegetation.

Seed Longevity: Long term burial studies have shown that after 2 years, 74% of the parthenium weed seed is still viable. The remainder either could not be recovered (18%) or did not germinate (8%). There was a log-linear decline in germinability of the buried seed over time which indicates a constant rate of seed loss, with a half life of about 6 years (Navie *et al*., 1998a). This indicates that buried parthenium weed seed can remain viable much longer than previously thought (Butler, 1984).

This has further implications for future management of parthenium weed, particularly in cultivated areas where seed burial occurs regularly. Recent field observations have backed up these past research findings. In one case parthenium weed seedlings were seen to readily germinate from a pile of soil and sunflower debris after it was moved. This pile had been left undisturbed for more than 10 years prior to this disturbance, and must have contained viable parthenium weed seeds when it was originally placed there.

Competitive ability: Parthenium weed is known to be allelopathic (Adkins and Sowerby, 1996) with root and shoot leachates capable of reducing growth and/or germination of numerous crops. The successful spread of the weed, in part, may be attributed to these allelopathic properties (Mersie and Singh, 1987). Several beneficial plants are known to behave similarly and/or be highly competitive with many weeds. Research has been under way to assess the competitive ability of such plants on the growth and development of parthenium weed.

The feasibility of managing parthenium weed through competitive displacement with beneficial plants has had little systematic investigation, especially under Australian environmental conditions. When studied in an additional series competition experiment Bisset bluegrass (*Bothriochloa insculpta*), Floren bluegrass (*Dichanthium aristatum*) and buffel grass (*Cenchrus ciliaris*) all out-competed parthenium weed (factors of 3.16, 1.49 and 1.11, respectively) (O'Donnell and Adkins, 2005). Among the legumes that were tested, butterfly pea (*Clitoria ternatea*) competed strongly, with one plant being competitively equal to 2.89 parthenium weed plants. The remaining legume species studied were all weaker competitors than parthenium weed with Peak Downs clover (*Glycine latifolia*), Burgundy bean (*Macroptilium bracheatum*) and Caatinga stylo (*Stylosanthes seabrana*) having competitive strengths relative to parthenium weed of 0.43, 0.38 and 0.38, respectively (O'Donnell and Adkins, 2005). These results, obtained using a wide range of potentially useful pasture plants, create a foundation on which future field-based studies can now be undertaken to identify a useful plant or plants that can competitively displace parthenium weed (O'Donnell and Adkins, 2005).

Potential spread: A generic pest/weed model has been used to predict the probability of parthenium weed invasion and occupation of a particular land area. These predictive models have been run using different climatic predictions and management regimes. The computer program CLIMEX is designed to predict the distribution of weeds based on environmental factors including temperature, soil moisture, light intensity and various stresses that may be important to a plant's growth. CLIMEX can produce environmental indices of growth and map them for hundreds of sites within Australia or around the globe (Figure 2). This analysis gives a good indication of where parthenium weed may be able to spread in the future. The analysis shows that many countries on the African continent are at risk as well as many countries in southern Asia (Navie, 2003).

A study investigated how several climate change variables may alter the present day distribution and abundance of parthenium weed. In general terms, the predicted climate change in Australia should advantage the weed as compared to the grasses in the northern rangeland where it is presently found. As parthenium weed is a C_3 plant, it will be able to benefit from the $C0_2$ enrichment; however, the C_4 tropical grasses will not (Navie *et al*., 2005). Parthenium weed may also benefit from the projected increases in the frequency of extreme climatic events such as flooding, which will facilitate its seed dispersal and provide bare ground which favours germination and seedling establishment. In a study designed to look at the effect of $C0_2$ enrichment on growth of parthenium weed, it was shown that the weed was stimulated when the atmospheric $C0_2$ level increased from 360 to 480 ppmv regardless of whether competition from buffel grass (*Cenchrus ciliaris*) was present or absent (Navie *et al*., 2005). Seventy days after sowing, a significant increase in the height, stem base diameter, above ground biomass and seed production was observed under the higher $C0_2$ concentration. In addition, these plants showed a more rapid phenological development, reaching maturity many days earlier than those plants growing under present day $C0_2$ concentrations (Navie *et al*., 2005). The conspicuous stimulation of growth and increased competitiveness of parthenium is an indication that this weed may become more aggressive in the future, especially in areas dominated by C_4 grass species such as the semi-arid, sub-tropical and tropical pastures of northern Australia.

Health issues: A survey undertaken in central Queensland demonstrated a relationship between positive allergy tests and contact with parthenium weed (Cheney, 1998). A more recent study investigated the relationship between allergy symptoms, sensitivity and health impacts for people living within the environment where the weed grows (Goldsworthy, 2005). The results indicated that there is an increased risk of developing allergy symptoms and sensitivity to the plant when living in contact with parthenium weed than when living away from the weed. This was indicated by an increased rate of allergy symptoms, which at 73%, was higher than would normally be expected in the general population. When testing for sensitivity to parthenium weed, a prevalence rate of 37% was found, also higher than would normally be expected in the general population. It was found that people who reported contact with parthenium weed at home had a 1.7 times increased likelihood of being classified as having allergic tendencies or being atopic to the weed.

The survey also found significant relationships between contact with parthenium weed in the home environment and females reporting allergy symptoms. Additionally, females reporting allergy symptoms were twice as likely to be sensitised to parthenium weed, in comparison with males. Individuals sensitised to parthenium weed were found to have a greater economic outlay to treat the effects of the allergy symptoms, than non-sensitised residents in the same area. In the 12 months prior to the study almost 77% of individuals sensitive to parthenium weed spent up to AU$40 per month for medication to help treat their allergy symptoms, considerably more than non-sensitised people in the study. This cost did not include consultation fees with medical practitioners, travel to the consultations, or time off work. Similarly, 37% of individuals sensitive to parthenium weed took up to 4 days a week off work when their allergy symptoms were severe. Health profiles of residents in the study area that were sensitised to parthenium weed had a comparatively lower state of health when compared with other health assessments in the wider area. More specifically, scores for mental health and feelings of well being for those with the allergy symptoms, and who were sensitised to parthenium weed, indicated decreases in energy levels with their usual daily activities suffering as a result. Many residents displayed an ignorance of the weed, its appearance, and its potential for causing allergic symptoms. Similarly, few residents knew how to deal with and dispose of the plant if it was found in their environment. Given the potential for spread of the plant, the cost of treating allergy symptoms, and the economic cost to individual and community, further studies are recommended to assess and identify allergy risk potential in other areas so that appropriate health programmes can be implemented. The recommendation may be more important when considering the health impact resulting from allergic reactions to parthenium weed.

Management sub-project

A biological control program involving the introduction of insects from the Americas was initiated in Australia in 1975 and is still in progress. By 2005, nine species of insects and two rust pathogens had been released. The rust pathogen *Puccinia abrupta* var. *parthenlicola* was released some time ago but drought conditions have hampered its establishment (Tomley and Evans, 1992). Some studies have been undertaken which indicate that for infection to occur this rust requires a significant number of dew days to moisten the leaf surface. It is believed that this rust will become more of an effective biological control agent as parthenium weed spreads into the cooler, moister regions of southern Queensland and northern New South Wales (Fauzi *et al*., 1996, 1999). All the insects that were introduced are now established in at least some areas, and evaluation of their impact on parthenium weed is now underway. Under a new Queensland Department of Natural Resources and Mines initiative, evaluation studies have now been completed for the impact of three insect species (i.e.*Epiblema strenuana*, *Zygogramma bicolorata*, and *Listronotus setosipennis*) upon parthenium weed survival, growth and seed production under controlled and field conditions. These studies complement glasshouse studies that were conducted at The University of Queensland to evaluate the impact of the moth *E. strenuana* on parthenium weed (Navie *et al*., 1998b). The results of this earlier study showed that this agent was most effective if it could attack the host early, particularly when the weed was in direct competition with pasture grasses.

Defoliation by leaf feeding insects: The leaf-feeding beetle *Zygogramma bicolorata* was introduced from Mexico into Australia in 1980 as a biocontrol agent for parthenium weed. It became noticeable in the field in 1990, and since 1992 there has been regular outbreaks resulting in the defoliation of parthenium weed in parts of central Queensland (Dhileepan *et al*., 1996).

The effect of this insect was observed under controlled greenhouse and field cage conditions.*Zygogramma bicolorata* was found to cause damage to parthenium weed meristems, resulting in shorter and more branched plants. In well watered plants, defoliation caused height to be reduced by 13-56% and flower production to be reduced by 25-45% (Dhileepan *et al*., 2000a). These reductions were more significant when the defoliation took place at an early stage of plant growth (Raghu and Dhileepan, 2005). However, there was no reduction in leaf production and plant biomass in the defoliated plants, irrespective of the plant stage at which defoliation was imposed. Under water stress, defoliation had less of an effect on plant height (reduced by 10-31%), flower production (reduced by 31-75%), leaf production reduced by 23-51%), and plant biomass (reduced by 2-9%) (Dhileepan *et al*., 2000a). In water-stressed plants, the negative effects of defoliation on flower production, leaf production, and plant biomass were more significant when defoliated at flowering stage than at early stages of plant growth. Flower production and root and shoot biomass declined with increase in the duration of defoliation. Defoliation for 74 days without water stress reduced flower production by 99%, shoot biomass by 67%, and root biomass by 80%. In cages placed in the field, *Z. bicolorata* caused 92% defoliation in about 90 days and reduction in plant height by 27%, root length by 56%, root biomass by 69%, shoot biomass by 81%, flower production by 83%, and soil seed-bank by 73% (Dhileepan *et al*., 2000a).

In a related field study the impact of defoliation by *Z. bicolorata* on parthenium weed was observed from 1996 to 1998 (Dhileepan *et al*., 2000b). *Zygogramma bicolorata* caused 91-100% defoliation in the field, resulting in reductions in weed density by 32-93%, plant height by 18-65%, plant biomass by 55-89%, flower production by 75-100%, soil seed bank by 13-86% and seedling emergence in the following season by 73-90%. At sites with continued outbreaks of *Z. bicolorata*, it is expected that the existing soil seed bank will be minimised, possibly resulting in reduced density of parthenium weed in 6 to 7 years (Dhileepan *et al*., 2000b).

Damage by stem-galling insects: The effects of gall damage by the introduced moth *E*. *strenuana* on different growth stages of parthenium weed was evaluated using potted plants with no competition and in a naturally occurring population experiencing competition (Dhileepan and McFadyen, 2001). Gall damage in the early stages of plant growth reduced the net photosynthesis, transpiration and leaf water potential (Florentine *et al*., 2005), resulting in reduced plant height, flower production, leaf production, and shoot and root biomass. All galled, potted plants with no competition produced flowers irrespective of the growth stage at which the plants were affected by galling, but to a lesser degree than un-galled plants (Dhileepan and McFadyen, 2001). Gall induction during early growth stages in field plants experiencing competition prevented 30% of the plants reaching flowering. However, 6% of the field plants escaped gall damage, as their main stems were less vigorous and unable to sustain the development of galls. Flower production per unit total plant biomass was lower in galled plants than in un-galled plants, and the reduction was more intense when gall damage was initiated during the early stages of plant growth (Dhileepan and McFadyen, 2001). In potted plants with no competition, the number of galls increased with the plant vigour, as the gall insects preferred more vigorous plants. But in field plants there were no relationship between gall abundance and plant vigour, as intraspecific competition enhanced the negative effects of galling by reducing the vigour of the weed (Dhileepan and McFadyen, 2001).

In another study the applicability of plant vigour and resource regulation hypotheses in explaining the interactions between parthenium weed and its stem-galling moth, *E*. *strenuana*, was investigated (Dhileepan, 2004). Parthenium weed plants exposed to galling were sampled at three sites in northern Queensland, over a 2 year period, and the relationship between gall abundance and plant vigour (i.e. plant height, biomass, flowers per plant, and branches per plant) was studied. To test the predictions of the plant vigour hypothesis (PVH) and resource regulation hypothesis (RRH), the vigour of parthenium plants protected from galling using insecticides was compared to galled plants and plants that escaped from galling. The vigour of un-galled plants was less than the vigour of galled plants (Dhileepan, 2004). The higher plant vigour in galled plants was not due to galling, as was evident from insecticide exclusion trials. The insect seemed to preferentially gall the more vigorous plants. These findings support the predictions of the PVH and are contrary to those of the RRH. Since gall abundance is linked to plant vigour, galling may have only a limited impact on the vigour of parthenium weed. This may explain the paucity of successes against biocontrol of annual weeds using gall insects (Dhileepan, 2004).

The stem-galling weevil *Conotrachelus albocinereus* from Argentina has also been released to regulate populations of parthenium weed. A study was conducted on the tissue and metabolic responses in parthenium weed in the context of the biology and feeding behaviour of the weevil (Florentine *et al*., 2002). *Conotrachelus albocinereus* induces elliptical galls often on the main shoot axes and rarely on the terminal and axillary meristems of the host plant. The host plant shows re-direction of its vital metabolites to the gall, and to the metaplasied cells of nutrition in particular (Florentine *et al*., 2002). Larval feeding also fractures the vertical continuity of vascular tissues, which affects the host plant's overall metabolism. As the larva tunnels the shoot column, it places the frass at the fissured vascular sites. That activity initiates necrosis and eventual death of the living cells of the vascular tissue complex. Such a development induces water-logging stress in the gall and the evapo-transpirational system displays contrasting responses (Florentine *et al*., 2002). Permanently closed stomatal apertures and abnormally inflated substomatal chambers indicate that parthenium weed suffers moisture-stress with cecidogenesis. The larval performance triggers moisture inundation in the galled shoot and this appears to be an advantage in using this weevil in the control of parthenium weed (Florentine *et al*., 2002).

***Damage by stem-boring insects*:** The effects of the stem-boring weevil *Listronotus setosipennis* on different growth stages of parthenium weed plants was evaluated in glasshouse and field trials, and its field prevalence in Queensland also assessed. In the glasshouse, *L. setosipennis* reduced the plant height by 51%, number of leaves by 78%, flower production by 63% and plant biomass by 54% in plants at the rosette stage of development (Dhileepan, 2003a). Damage in the field, at the same stage was less, with the primary stem height reduced by 26% and flower production by 38%, with the impact on total plant height, basal stem width, root length, number of branches, root biomass and total plant biomass was not significant (Dhileepan, 2003a). In both the glasshouse and the field, the impact of *L. setosipennis* on the pre-flowering and flowering stages of parthenium was not significant. The weevil was recorded at 48% of the 132 parthenium weed-infested sites studied with 16% of the sites showing a high to very high levels of incidence. The weevil favoured alluvial and black soils sites and was less present on clay and sandy soils. It is considered to be a promising biocontrol agent for infested regions with prolonged dry periods and erratic rainfall patterns (Dhileepan, 2003a).

Exclusion studies: Variation in the effectiveness of biocontrol agents on parthenium weed was evaluated at two properties (Mount Panorama and Plain Creek) in Queensland, Australia for four years (1996-2000) using a pesticide exclusion experiment (Dhileepan, 2003b). Parthenium weed-infested plots with and without biocontrol insects were sampled at monthly intervals and the impact of biocontrol insects on parthenium weed at individual plant and whole population levels monitored (Dhileepan, 2001).

Biocontrol insects were more effective at Mount Panorama (central Queensland) than at Plain Creek (northern Queensland). At Mount Panorama, higher levels of defoliation by the leaf-feeding beetle *Z*. *bicolorata*and galling by the moth *E*. *strenuana* Walker in 1996-97 coincided with an above average summer rainfall, but in the following 3 years with below average summer rainfall the defoliation and galling levels were significantly lower. Exclusion of biocontrol insects resulted in a 52% increase in seedling emergence and a seven-fold increase in the soil seed bank in the following season (Dhileepan, 2001). However, biocontrol had significant negative impact on the weed only in 1996-97 with no major impact in the following 3 years (Dhileepan, 2003b). At Plain Creek, galling by *E. strenuana* was evident in all the 4 years, but varied significantly between years due to non-synchrony between parthenium weed germination and *E. strenuana* emergence. Biocontrol had limited impact on the weed at this site in 1996-97 and 1997-98, with no significant impact in the following 2 years (Dhileepan, 2003b). Effectiveness of *Z. bicolorata* and *E. strenuana* was dependent on weather conditions and as a result had only limited impact on the weed in 3 out of 4 years (Dhileepan, 2003b). However, exclusion of biocontrol insects during 1996-1997 resulted in an eight-fold increase in the soil seed bank in the following season. Over the entire 4-year period, defoliation and galling resulted in 70% reduction in the soil seed bank at Mount Panorama, but the reduction in the soil seed bank at Plain Creek due to galling was not significant.

Parasitism of insect biocontrol agents: The significance of natural enemies in the failure or reduced effectiveness of weed biological control agents remains largely unknown. Larval and pupal parasitism, by native insects on the introduced stem-galling moth *E. strenuana*, was studied in northern Queensland 4 (1986-87) and 16 (1998-99) years after the introduction of *E. strenuana* as a biocontrol agent for parthenium weed (Dhileepan *et al*., 2005). There was no increase in the parasitoid species assemblage over the years. In 1986-87,*Antrocephalus* sp. and *Bracon* sp. were the most predominant species. The combined larval and pupal parasitism was low (2.6%) and there was no seasonal difference in the parasitism levels. In 1998-99 *Bracon* sp. was the most prevalent species. Parasitism by *Bracon* sp. in 1998-99 was several times higher (22.9%) than the combined larval and pupal parasitism in 1986-87. However, parasitism by *Bracon* sp. remained low (6.5-8.2%) at the beginning of the parthenium weed-growing season, and reached peak levels (49-53%) only at the end of the season. Parasitism by *Bracon* sp. was also significantly lower in rosettes (7.2%) than in flowering plants (22.8%). Galling can have a negative impact on the weed only when initiated at the rosette stage. In 1998-99 lower levels of parasitism early in the season when most plants are in the rosette stage suggest that the impact of parasitism on the effectiveness of the gall insect may not be significant (Dhileepan *et al*., 2005).

Summer rust. A major project funded by the Meat Research Corporation identified a summer-active fungal pathogen from Mexico, *Puccinia melampodii*, as a potential biological control agent for parthenium weed. Approval to release the summer rust was obtained in June 1999 on the basis of host specificity tests conducted at CAB Biosciences in UK. Field releases were commenced in the 1999-2000 summer season, and the rust became established in several sites in the same year. However, dry summer seasons over the subsequent years resulted in low levels of rust incidence in the field, culminating in negligible impact on the weed. Future research will focus spreading the rust with support from community groups in years with favourable weather conditions.

Fire and management of parthenium weed: A study of the role of fire in the management of parthenium weed, with and without simulated grazing pressure, has shown that fire does not significantly reduce the germinable soil seed bank of parthenium weed (at least on black cracking clay soils in central Queensland). Smoke and heat did not significantly stimulate parthenium weed germination. Fire did, however, result in one-off increases in parthenium weed densities, which after subsequent fires rapidly declined (Vogler *et al*., 2002). In other studies smoke has been shown to stimulate parthenium weed seed germination and in some cases seedling emergence (Adkins *et al*., 2000; 2001; 2003).

This study has also demonstrated that removal of grazing animals for extended periods (as with the control treatments) delivers similar reductions in the presence of parthenium weed to that of burning or mowing the pasture (Vogler *et al*., 2002). This indicates that managing grazing to maintain cover/biomass and desirable pasture composition is potentially the most important factor influencing the amount of parthenium present in native pastures in central Queensland. Therefore landholders should refrain from using fire where necessary as a cost effective management tool for pasture species manipulation or woody weed control. Rather, it appears that post fire pasture/grazing management is a more significant factor in determining the level of subsequent parthenium infestations than the use of fire (Vogler *et al*., 2002).

Best practice management on roadsides: Parthenium weed infestations along roadsides are the major sources of weed spread and hence a project to evaluate different herbicide management strategies for infestations in such locations was initiated in 2002 (Anon., 2005). Results so far from this ongoing trail, suggests the need to use one of a number pre-emergent herbicides in combination with an approach that promotes the growth of competitive plants. One of the primary means of weed management for small, local populations is the use of Atrazine, or an Atrazine plus 2,4-D mix, or Dicamba, or Hexazinone, or Metsulfuron or a Picloram plus 2,4-D mix. Any one of these treatments could give good results depending upon the situation in which the weed was present.

CONCLUSIONS

By bringing together scientists from around Queensland, together with Landcare groups and interested graziers, the PWRG is able to investigate many aspects of the ecology and management of this important weed. Out of this joint effort have a number of new improved management methods which can be applied throughout its present and potential range. The history of the weeds invasion in Australia, and the ongoing improvement of its management program, will be a very useful platform for Pakistan to appreciate the potential problems of this weed and the development of a future weed management program. The linking of the Australian management effort with that of Pakistan, through an international collaborative research project, would be a very beneficial step for both countries.

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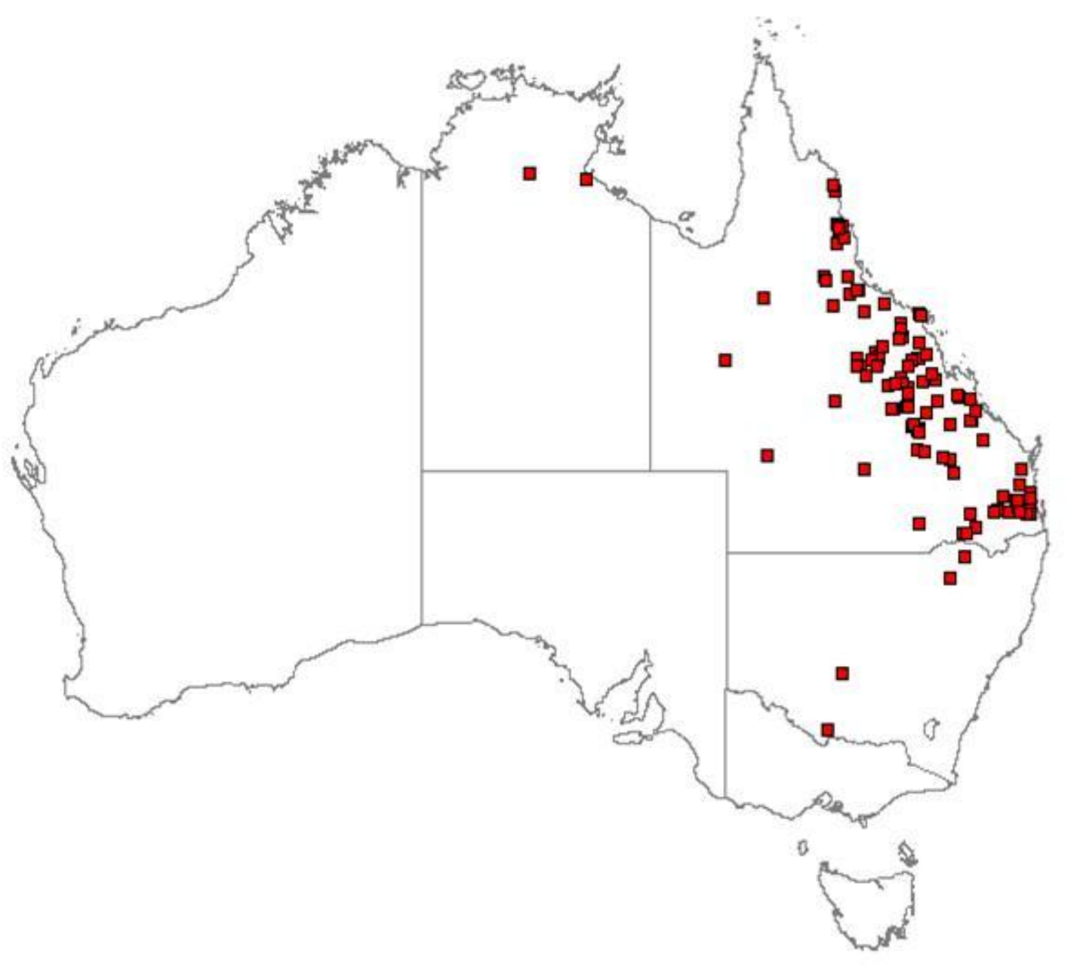
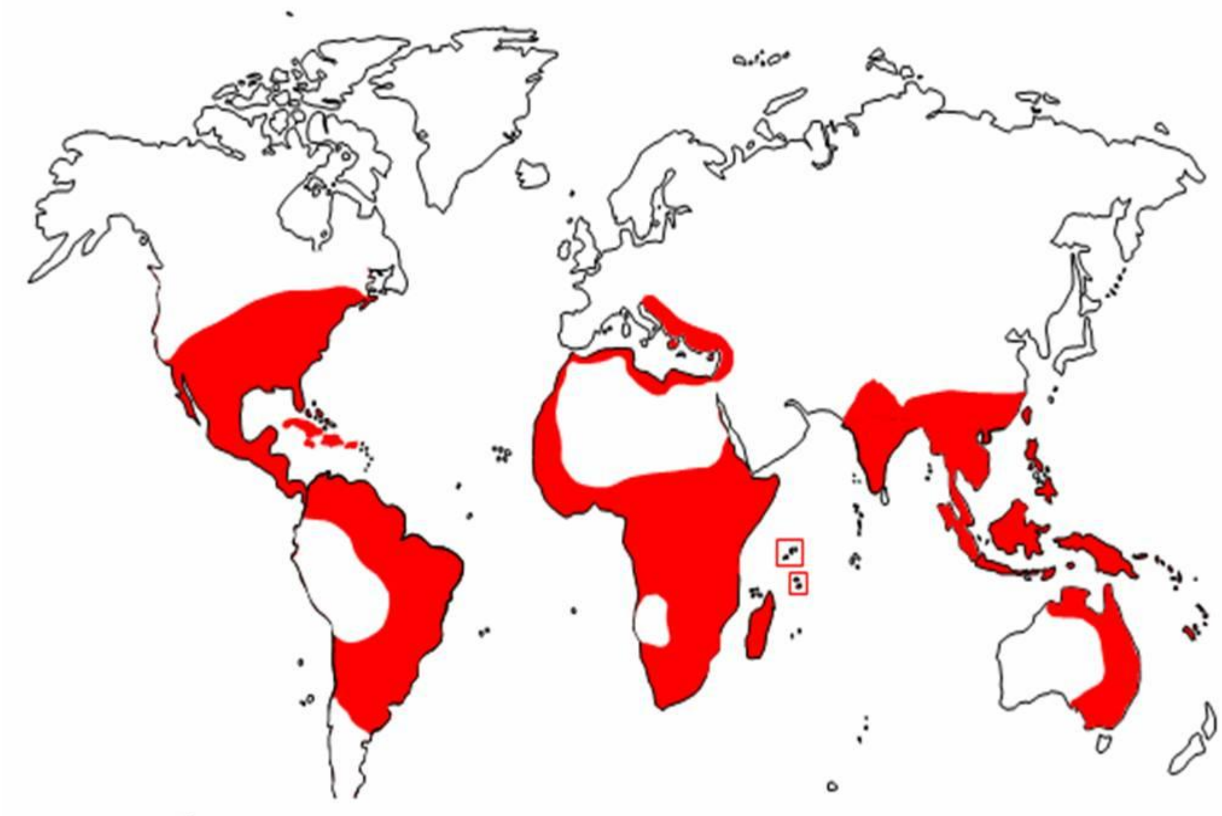


Figure 1. Map of the distribution of parthenium weed (*Parthenium hysterophorus*) in Australia, based on herbarium records. Map sourced from Australia's Virtual Herbarium, 28th October 2005.



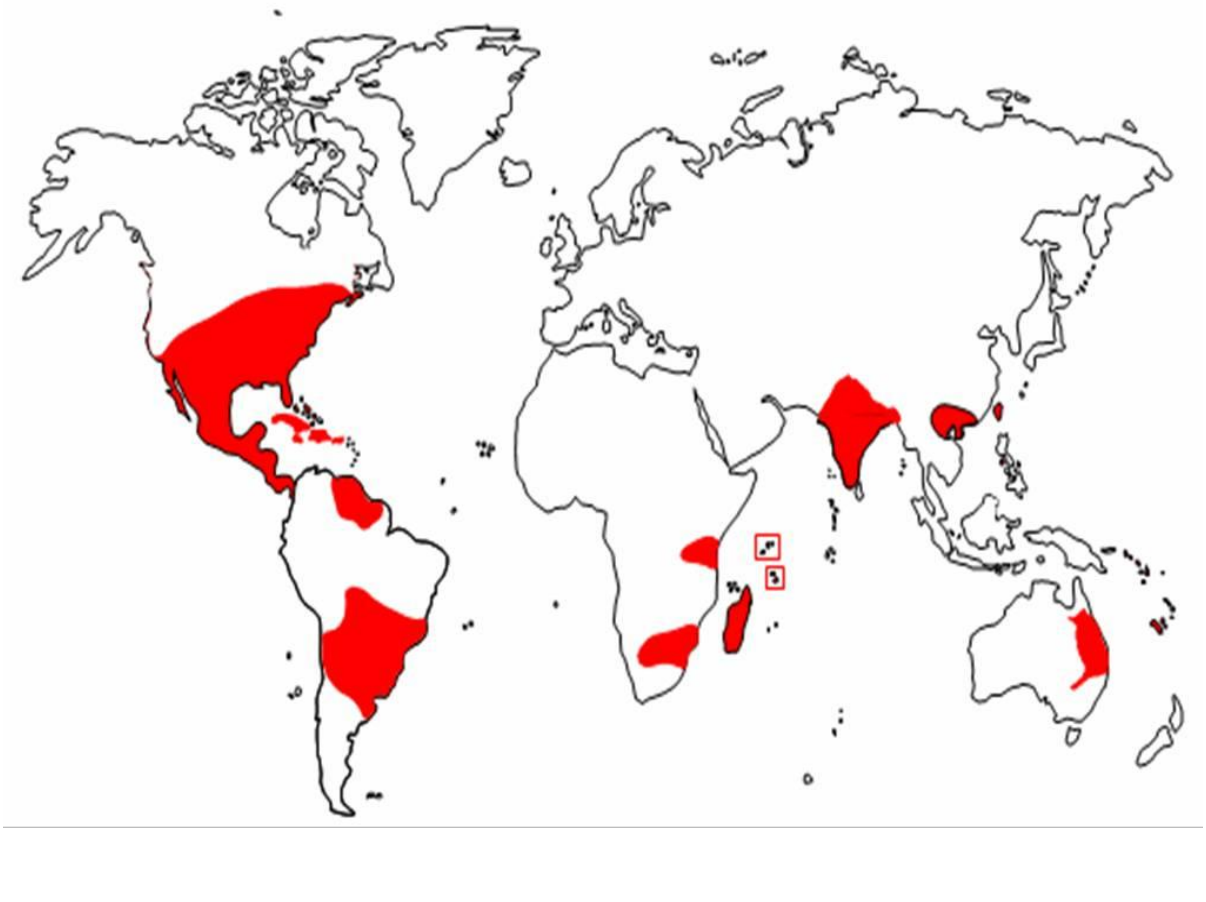


Figure 2. A map of the predicted potential distribution of Parthenium weed (*Parthenium hysterophorus*) around the world using CLIMEX (upper diagram) and its approximate actual distribution in 1994 (lower diagram).

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