INTRODUCTION

From its native range in tropical America (Haseler, 1976), *Parthenium hysterophorus* has aggressively spread across the globe and is now listed as an invasive weed in many countries. It was first observed in India and Australia in the mid-1950's, where it has since become particularly problematic (Pandey & Dubey, 1991; Navie *et al.*, 1996). Lack of adequate control measures has seen this weed continue to spread, having a detrimental effect on crop production, biodiversity, animal husbandry and human health (Navie *et al.*, 1996). Although the weed was first recorded in South Africa over 100 years ago, it has only become troublesome in the last two decades (Henderson, undated). In South Africa, *P. hysterophorus* has been declared a "Category 1" weed which according to legislation implies that: 'These are prohibited plants that will no longer be tolerated, neither in rural nor urban areas, except with the written permission of the executive officer or in an approved biocontrol reserve. These plants may no longer be planted or propagated, and all trade in their seeds, cuttings or other propagative material is prohibited. They may not be transported or be allowed to disperse' (Conservation of Agricultural Resources Act, 1983; Act No 43 of 1983).

The plant characteristic of allelopathy – broadly defined as chemical interactions between plants – is believed to be an important attribute contributing to the successful spread of *P. hysterophorus* in non-native ranges. Scientists of diverse disciplines have conducted chemical studies and bioassays to better understand *P. hysterophorus* allelopathy (Kanchan & Jayachandra, 1979; Mersie & Singh, 1987, 1988; Adkins & Sowerby, 1996; Kraus, 2003; Reinhardt *et al.*, 2004; Belz *et al.*, 2006). However, our knowledge and understanding of the effect of allelochemicals from *P. hysterophorus* on other plant species under natural conditions could be regarded as juvenile. This is largely due to the complexity of allelopathy research, with 'myriad biological, chemical and physical factors' interacting at every step, from allelochemical production, transport to and receptivity of target species, to fate of the compound in the environment (Reinhardt *et al.*, 1999). Inderjit & Weiner (2001) emphasize the importance of the effects of plant secondary metabolites on soil factors, such as soil ecology and nutrient availability on plant community structure.

The purpose of this study was to promote understanding of the allelopathic potential of *P. hysterophorus*, and the reliance of this invader plant on allelopathic interference in displacing natural vegetation and/or preventing natural succession. Limited success in discovering adequate insect or pathogen biological control agents for controlling this weed necessitates the need to discover other means of control, for example through employment of antagonistic plant species. Plants that can adequately interfere with parthenium are also useful in restoring areas previously infested with this weed.

Collaboration between the University of Pretoria and the University of Hohenheim in Stuttgart, Germany, was first initiated in 2000, with Kruger National Park Scientific Services subsequently joining. The collaboration is particularly efficient as it allows for relevant field work to be conducted in South Africa, while first-rate allelochemistry studies can be conducted in Germany. To date, some findings by the team have been reported by Kraus (2003), Reinhardt *et al*. (2004), and Belz *et al*. (2006). In a continuation of research by the team, the objectives of the current study were to investigate: (a) interference between *P. hysterophorus* and indigenous grass species, (b) the production dynamics of parthenin during the life-cycle of *P. hysterophorus*, and, (c) the degradation of parthenin in soil. Aspect (a) involved a field trial in the Kruger National Park, and bioassays done under controlled conditions at the University of Pretoria. Aspects (b) and (c) were both conducted at the University of Hohenheim as part of a study visit.

CHAPTER I – LITERATURE REVIEW

1.1 Alien invasive plants

An exponential increase in the movement of plant species across the world has been observed as a result of globalization. In some cases these species have become established in areas far from their native ranges, and under favourable conditions and in the absence of natural enemies have spread prolifically, often becoming a threat to biodiversity in these regions. Secondary effects on the structure and function of ecosystems can also be highly detrimental (Clout & De Poorter, 2005). Furthermore, these species can have adverse economic impacts by reducing crop yields or grazing land quality (Goslee *et al*., 2001) Recognizing this threat, the United Nations Convention on Biological Diversity calls on contracting parties [Article 8(h)] to ‘prevent the introduction of, control or eradicate those alien species which threaten ecosystems, habitats and species’ (Clout & De Poorter, 2005).

The introduction of one or more natural enemies to biologically control an invasive species has been a successful strategy in some instances. According to Fowler *et al*. (2000), however, ‘complete success of biocontrol, where no other control methods are required, accounts for approximately one-third of all successfully completed biological control programmes’. Other control measures are therefore often required for incorporation into an integrated control programme.

For South Africa, Nel *et al*. (2004) listed 117 major invaders – well-established species that already have a significant impact on natural and semi-natural ecosystems- and 84 emerging invaders – species with the attributes to potentially spread over the next few decades. According to Foxcroft & Richardson (2003), surveys revealed that by the end of 2001, 366 alien plant taxa were known to occur in the Kruger National Park. Invasive weeds present a very real threat in South Africa, and control measures have been unsatisfactory, with lack of resources being a major factor (Kluge & Erasmus, 1991; Goodall & Naudé, 1998).

1.2 Allelopathy

1.2.1 Definition and brief history

Allelopathy involves direct and indirect chemical interactions between plants as well as micro-organisms and was first termed by Molisch, an Austrian plant physiologist, in 1937. The term is derived from the Greek words ‘allelon’- meaning mutual - and ‘pathos’ - meaning harm or affection. Weston & Duke (2003) further define it ‘as an important mechanism of plant interference mediated by the addition of plant-produced secondary products to the rhizosphere’. Chemical interactions between plants were recorded thousands of years ago. The effect of *Cicer arietinum* (chickpea) on other plants was recorded in 300 BC, and the effects of several harmful plants on croplands were mentioned by Pliny in 1 AD. Pliny also observed the effects of the walnut tree (*Juglans nigra* and *J. regia*), which is one of the most widely known examples of an allelopathic plant today.

A vast diversity of secondary compounds is produced by plants, from simple hydrocarbons to complex polycyclic aromatics (Weston & Duke, 2003). Effects of allelochemicals in the field, as summarized by Inderjit & Weiner (2001), can be due to (i) direct effects of allelochemicals from donor plants, (ii) effects of transformed or degraded products from released allelochemicals, (iii) effect of allelochemicals released on chemical, physical or biological soil factors, and (iv) chemical induction of release of allelochemicals by a third species. Although allelopathy has been extensively studied under controlled conditions and our knowledge of growth inhibition mechanisms and allelochemical modes of action has been greatly enhanced (Inderjit & Weston, 2000), less is known on the fate of allelochemicals in the environment and their effect on soil ecology. Inderjit & Weiner (2001) propose that vegetation behaviour can be better understood ‘in terms of allelochemical interactions with soil ecological processes rather than the classical concept of direct plant-plant allelopathic interference’; and ‘researchers have now started to appreciate the ecological importance of allelochemicals on the ecosystem-level processes’ (Wardle *et al.*, 1998; Inderjit & Weiner, 2001). Allelopathic research has become inter-disciplinary, involving collaborative work by plant scientists, weed scientists, soil scientists, ecologists and others.

1.2.2 Modes of action of allelochemicals

Allelochemicals are able to effect both the germination and growth of plants. This is achieved by influencing a wide variety of metabolic processes. The exact modes of action of these chemicals is often very difficult to determine with any certainty, and of the vast quantity of allelochemicals that have been identified, modes of action have only been ascertained for a very small number of these (Einhellig, 1995). There is no single established method for determining the mode of action for these chemicals (Einhellig, 1995). Observations made during dose-response experiments can often be used to narrow down the possibilities of the site of action (Vyvyan, 2002), but these observations should not be over-interpreted. The mitotic index can be measured to determine an allelochemical's effect on root cell division; and chlorophyll concentration, fluorescence and carbon dioxide exchange can all be used to determine the agent's effect on photosynthetic efficiency of a particular plant (Vyvyan, 2002). Conductivity measurements can be used to determine whether allelochemicals disrupt cell membranes, and can additionally be used to assess whether the mode of action is light dependent. Careful study of the molecule's structure and the use of structure-activity databases can be helpful in determining modes of action. Macías *et al*. (1992) reported that various spatial arrangements which the molecule can adopt play an important role in activity.

Plant processes which have been found to be influenced by allelochemicals that have so far been identified include: mineral uptake, cell division and elongation, action of plant growth regulators, respiration, photosynthesis, stomatal opening, protein synthesis, haemoglobin synthesis, lipid and organic acid metabolism, membrane permeability and action of certain enzymes (Retig *et al*., 1972; Rice, 1974; Harper & Balke, 1981).

1.2.3 Allelopathy and agriculture

Weeds can interfere with crop growth and reduce yields, deteriorate crop quality, clog waterways and cause health problems; with eradication costs being massive (Singh *et al*., 2003). An estimated 240 weeds have been reported to have allelopathic potential (Qasem & Foy, 2001), although many of these species have been tested with unrealistic bioassays (Inderjit & Keating, 1999). In turn, allelopathic crops that are able to chemically interfere with weed growth have also been identified, such as *Secale cereale* (rye), *Triticum aestivum* (wheat), *Sorghum bicolour* (sorghum), *Oryza sativa* (rice), and *Helianthus annuus* (sunflower). In addition to beneficial chemical interference of crops with weed growth, there is potential for the advantageous use of allelopathy for practices such as crop rotation, cover and smother crops and retention of crop residues (Singh *et al*., 2003). According to Duke *et al*. (2002), two approaches for improving the utilization of allelopathy in crops to increase weed suppression are possible: (i) to enhance the existing allelopathic potential of a particular crop, and (ii) to introduce allelopathic potential through the insertion of foreign genes encoding for allelochemicals. This can be achieved through employing conventional breeding techniques as well as genetic modification techniques. With increased environmental awareness and public pressures, less detrimental means of weed control are continually being sought. One such approach is to consider allelochemicals as new sources of herbicides. This approach may be beneficial as natural plant products have advantages over synthetic herbicides, including: (i) allelochemicals often possess complex structures and exhibit structural diversity, making them valuable lead compounds, (ii) the compounds have high molecular weight with little or no halogens or heavy atoms, (iii) allelochemicals have little environmental impact as they degrade rapidly in the environment, and (iv) allelochemicals have novel target sites very often different to those of synthetics (Dayan *et al*., 1999; Duke *et al*., 2002; Singh *et al*., 2003).

1.2.4 Allelopathy and biodiversity

The end result of invasive plant spread is often a massive loss of biodiversity. Maintaining diversity is important as it enhances resource utilization efficiency (Foy & Inderjit, 2001), acts as a buffer against large ecosystem shifts, and maintains highly valued crop and wild plant genetic diversity (Chou, 1999). Allelopathy may play an important role in plant community structure and researchers have begun to recognize the ecological significance of allelochemicals on ecosystem-level processes (Wardle *et al*., 1998). Allelopathic potential may be an important attribute of certain successful invader plant species in displacing natural vegetation, and according to Hardin (1960), may be an explanation for the ability of invasive weeds to endure beyond early stages of secondary succession.

1.3 *Parthenium hysterophorus*

Parthenium hysterophorus L. belongs to the Heliantheae tribe, a member of the Asteraceae family. Within the Parthenium genus there are 15 species all of which are native to the Americas (Navie *et al*., 1996). *P. hysterophorus* specifically originates from tropical America from the areas surrounding the Gulf of Mexico (Haseler, 1976). The recent appearance of *P. hysterophorus* in many parts of the world has resulted in several common names for the plant, including: parthenium and Demoina weed (South Africa), carrot weed and congress weed (India), ragweed parthenium (USA), and parthenium weed (Australia).

1.3.1 Botanical description

Unless otherwise stated, the following description was obtained from Navie *et al*. (1996) and personal observation. Parthenium is an upright, herbaceous plant often displaying prolific branching. It displays highly vigorous growth in suitable climates and can reach a height of two metres. Following emergence the plant has two hairless cotyledons with short petioles. A rosette is formed by the young plant with dark green leaves that are up to 20cm in length and 4-8 cm broad. The leaves are pale green in colour and lobed. Leaves borne higher on the stem are smaller and narrower than the basal leaves. Leaves are borne alternatively on the stem. The stems and upper and lower leaves are covered in trichomes, including uniseriate macrohairs, uniseriate trichomes, monoiliform trichomes, capitate-sessile trichomes and capitate-stalked trichomes (Reinhardt *et al*., 2004). The stem is longitudinally grooved and the plant has a deep tap root system. Capitula are 3-5 mm in diameter and formed by many flower heads which are formed by five fertile ray florets and about 40 male disc florets and are white in colour. The first capitula are formed in the terminal leaf axil of the plant, after which the capitula are borne successively down the stem on lateral branches. Williams & Groves (1980) noted that temperature is a factor controlling the vegetative growth period before flowering and that no specific day-length was required for flowering. The cypsela has two sterile florets which adhere as ‘wings’ and is commonly termed as an achene. Achenes are 2-3 mm in length and 2 mm wide. The two sterile florets act as air sacs and assist with seed dispersal. The achene is flattened and narrows towards the base and is crowned by a pappus of orbicular scales. The seed is grey to black, flattened and spatulate in shape. Navie *et al*. (1998) reported that 73.7% of seeds remained viable after being buried for two years and estimated the half-life of the seeds to be about six years. Reports on seed dormancy have been contradictory but the germination of fresh seed has been observed. Although fresh parthenium seed has been noted to germinate immediately, the achene complex is known to contain germination inhibiting autotoxins (Picman & Picman, 1984; Reinhardt *et al*., 2004). Joshi (1991a) suggests that this imposed dormancy is removed through the natural course of weathering. Gupta & Chanda (1991) calculated that 9600 pollen grains per staminate flower were released and Lewis *et al*. (1988) observed that pollen is not transported over great distances but tends to remain airborne in substantial quantities around the plant source.

1.3.2 Distribution and habitat

From its natural occurrence in tropical America, parthenium has spread beyond its natural range in the Americas (Navie *et al*., 1996) and to many parts of the world, often becoming an invasive threat. Its spread has often been the result of the movement of military machinery and via contaminated produce and crop seed, and the plant has successfully become established in moderate and warm climates all over the world. Amongst others, *P. hysterophorus* has been reported in the following countries: South Africa, Bangladesh, Madagascar, Kenya, Mozambique, Ethiopia, Mauritius, Rodriguez, the Seychelles, Israel, India, Nepal, China, Vietnam, Taiwan, many South Pacific Islands, and India and Australia, where it may be having the greatest impact (Navie *et al*., 1996). In South Africa, although observed in the area formerly known as Natal as early as the 1880's, parthenium only became notorious in the 1980's (Henderson, undated), and its spread is believed to be linked to the cyclone Demoina which moved across the eastern coast of the country in 1986.

P. hysterophorus is quick to invade disturbed areas such as along roadsides and railways, cleared areas and croplands, and mismanaged rangelands. From these areas it often establishes a foothold for progressive, peripheral invasion, often at the expense of natural vegetation. McFadyen (1992) reported high incidence of the weed in areas that are regularly flooded, because grass cover is killed as a result of the submersion, leaving the weed with no competition. Parthenium is known to grow on a wide range of soil types and over a wide variety of different climates. Experiments and field observations conducted by Tamado *et al*. (2002b) suggested that the germination of *P. hysterophorus* was not affected by a variety of climatic conditions, although the seeds did have a high moisture requirement. Several cohorts of parthenium seedlings have been observed to emerge in a single growing season and plants can complete their life-cycle in a shorter period of time in less favourable conditions. An optimum day/night temperature regime of 33/22ºC for biomass production was determined by Williams & Groves (1980).

1.3.3 *P. hysterophorus* allelopathy

1.3.3.1 Allellochemistry

Broadly defined, allelopathy is the chemical interaction between plants. An *et al*. (1993) define the allelopathic characteristic of an allelochemical as the biological property of the allelochemical as opposed to its physical or chemical properties. In parthenium, phenolics and sesquiterpene lactones have been identified as the two major groups of allelochemicals.

Over 3000 sesquiterpene structures are known in nature (Harborne, 1999), and these structures are often associated with specialized secretary structures, such as glandular trichomes (Jordon-Thaden & Louda, 2003). Numerous sesquiterpene lactones have been isolated and identified in *P. hysterophorus*, including parthenin (Herz & Watanabe, 1959), coronopilin (Picman *et al*., 1980), damsin (Mabry, 1973), dihydroisoparthein and hysterin (Romo de Vivar *et al*., 1966), hymenin (Rodriguez, 1977), tetraneurin A (Picman & Towers, 1982) and others. Sequiterpene lactones that have thus far been discovered in nature have a wide variety of chemical structures, matched with a diversity of biological activities (Picman, 1986). Sesquiterpene lactones are known for their anti-inflammatory, analgesic, anticancer, cytotoxic, anti-malarial, anti-bacteria and anti-fungal properties (Picman, 1986; Lomniczi de Upton *et al*., 1999). Picman & Towers (1982) classified parthenium plants growing on several different continents in seven types according to sesquiterpene lactone content:

Type I : Parthenin, coronopolin and tetraneurin A
Type II : Parthenin, coronopolin
Type III : Coronopolin
Type IV : Hymenin, coronopolin and dihydrohymenin
Type V : Hymenin, coronopolin and hysterin
Type VI : Hymenin and hysterin
Type VII : Hymenin

Plants growing in South Africa were classified by Picman & Towers (1982) into the ‘parthenin race’ – plants containing parthenin, coronopolin and tetraneurin A. Rodriguez (1977) suggested that differences in secondary metabolite content may be a response to different environmental factors. Lomniczi de Upton *et al*. (1999) observed that the nature of the secondary metabolites in plants growing at the same location do not differ, only the percentages of these secondary lactones differ. De la Feunte *et al*. (2000) found differences in sesquiterpene lactone chemistry according to habitat in Argentina and Lomniczi de Upton *et al.* (1999) noted correlations between sesquiterpene lactone content and altitude.

Of these sesquiterpene lactones, parthenin is reported to be the most important and biologically active compound. Parthenin has been implicated for its phytotoxicity on a vast range of target species, autotoxicity (Picman & Picman, 1984; Kumari & Kohli, 1987), allergic reactions such as allergic eczematous contact dermatitis (Lewis *et al*., 1991; McFadyen, 1995), and live-stock poisoning (Narasimhan *et al*., 1984). The allelopathic potential of parthenium leaf extracts as well as pure parthenin has been reported in abundance (Pandey, 1994, 1996; Batish *et al*., 1997, 2002a, 2002b; Datta & Saxena, 2001; Belz *et al*., 2006). Parthenin has been observed to be released through leaching as well as through the decomposition of plant residual matter. The overall contribution of parthenin to the allelopathy of *P. hysterophorus* is still vague. Working with parthenium leaf extracts and comparable concentrations of pure parthenin in germination bioassays, Belz *et al*. (2006) observed that pure parthenin contributed between 16 and 100% of the relative potency of leaf extracts, and was highly dependent on the concentration of parthenin within extracts.

As mentioned, phenolics also constitute an important role in *P. hysterophorus* allelopathy. Caffeic, vanillic, p-coumaric, chlorogenic and ferulic acids have been identified in the plant (Kanchan & Jayachandra, 1980b). Phytotoxic effects of these phenolics have been investigated in numerous cases (Kanchan & Jayachandra, 1980b; Patterson, 1981; Williams & Hoagland, 1982; Mersie & Singh, 1988). According to Blum *et al*. (1999), phenolics are the most potent inhibitors among the water-soluble allelochemicals and can also affect nutrient availability through interference with decomposition, mineralization and humification (Van Andel, 2005).

1.3.3.2 Allelopathic effects

The allelopathic potential of *P. hysterophorus* is believed to play an important role in the ability of the plant to displace natural vegetation and interrupt natural succession. An abundance of literature exists on investigations into the allelopathic effects of leachates from various plant parts, as well as for compounds isolated from *P. hysterophorus*, on a plethora of test species. Phytotoxic effects of leachates or pure compounds from *P. hysterophorus* have been observed on important crops such as *Cicer arietinum* (chickpea), *Raphanus sativus* (radish), *Triticum aestivum* (wheat), *Zea mays* (maize), *Glycine max* (soybean), *Phaseolus vulgaris* (bean), *Lycopersicon esculentum* (tomato) (Kanchan & Jayachandra, 1979; Mersie & Singh, 1987, 1988; Batish *et al*., 2002a); aquatic plants such as *Salvinia molesta* (salvinia) and *Eichhornia crassipes* (water hyacinth) (Pandey *et al*., 1993; Pandey, 1994), grass species such as *Cenchrus ciliaris* (buffel grass), *Eragrostis curvula* (weeping love grass), *Eragrostis tef* (tef) and *Echinochloa crus-galli* (Adkins & Sowerby, 1996, Belz *et al*., 2006) and many other species including weeds species.

1.3.4 Importance of *P. hysterophorus*

1.3.4.1 Detrimental impacts

Impact on human health

The sesquiterpene lactone, parthenin, can cause allergic eczematous contact dermatitis in those who have continual contact with the weed, and hundreds of cases have been reported in India where it has been an epidemic (Subba Rao *et al*., 1977; Towers, 1981). Parthenium pollen has been observed to cause allergic rhinitis (hayfever) and allergic bronchitis (asthma) in humans (Navie *et al*., 1996).

Impact on rangelands and croplands

P. hysterophorus is a highly efficient interferer and can cause substantial yield losses. Yield losses of up to 40% were reported in India (Khosla & Sobti, 1981) and *P. hysterophorus* has been reported to negatively effect crop production in the Caribbean, Australia, Kenya, Ethiopia (up to 97% yield loss) (Tamado *et al*., 2002a), South Africa and most likely many other countries which it has invaded. Nath (1988) reported losses of forage production in grasslands by up to 90%. The weed is especially quick to infest mismanaged rangelands, and is particularly troublesome in Queensland, Australia, where by 1991 it was estimated to cover 170 000 km^2, which amounts to 10% of the entire state (Chippendale & Panetta, 1994). Due to the high seed production of *P. hysterophorus*, the marketing of produce such as grain can be adversely affected due to contamination risks.

Impact on livestock

P. hysterophorus can affect animal health and productivity and milk and meat quality. Although animals usually avoid the weed, it poses serious health hazards to the animals, and animals have been observed to eat vast quantities when dense stands do occur (Navie *et al*., 1996; Evans, 1997).

Impact on biodiversity

P. hysterophorus is notorious for its aggressive interference with other plant species and is often able to form pure, dense stands at the expense of the natural vegetation of the areas it has invaded. Total habitat alterations have been reported in grasslands, open woodlands, riverbanks and floodplains in Australia by McFadyen (1992) and Chippendale & Panetta (1994). Invasions of national wildlife parks in India (Evans, 1997) and South Africa pose a serious threat.

1.3.4.2 Beneficial attributes

South American Indians have been observed to use a boiled root decoction to cure dysentery (Uphof, 1959), and parthenin has been reported to be active against neuralgia and certain types of rheumatism (Dominguez & Sierra, 1970). It is applied externally on skin disorders and taken orally for a variety of ailments in the Carribean and central America, and even used as a flea-repellent for dogs and other animals in Jamaica (Dominguez & Sierra, 1970; Morton, 1981). The weed has also been reported as a good source of potash and oxalic acid, as well as a source of easily extractable protein for stockfeeds (Navie *et al*., 1996). Other promising properties of the sesquiterpene lactones, especially parthenin, such as anti-tumor activity, toxicity to insects, fungi and plants have high potential for future exploitation.

1.3.5 Control of *P. hysterophorus*

Attributes of high growth vigour, strong reproductive and regenerative potential, tolerance to many herbicides, and lack of effective bio-control agents makes the control of *P. hysterophorus* infestations very challenging. For these reasons, areas that are susceptible to *P. hysterophorus* infestation should receive special attention and management practices should focus on preventing the spread of *P. hysterophorus* as this is the most effective method of control. Furthermore, the tendency for *P. hysterophorus* to invade disturbed areas such as roadsides and old dumpsites often makes *P. hysterophorus* infestations uneconomical to control. The potential threat these infestations pose as propagule sources for further invasions should however not be underestimated. Preventive measures include: ensuring that *P. hysterophorus* seed is not introduced into an area via contaminated feed, pasture/crop seed, stock, machinery, vehicles or by any other means. Maintaining 'healthy, robust, diverse, competitive' pastures will increase resistance of the pastures to *P. hysterophorus* infestations (Parthenium Action Group, 2000). The land owner/manager must be aware of any isolated outbreaks and take immediate, suitable action before the situation worsens (Parthenium Action Group, 2000). Mechanical, chemical, and biological control methods are discussed below. The integrated use of these different practices often achieves the best results.

1.3.5.1 Mechanical control

Manual removal of *P. hysterophorus* is often not cost-effective and therefore used on a limited basis. Hand-pulling should ensure the removal of the entire crown to prevent regeneration from remaining lateral shoots. Protective clothing should be worn to prevent the possibility of allergic reaction (Gupta & Sharma, 1977). Slashing of *P. hysterophorus* is often not effective due to the plant's regenerative potential. Slashing may also stimulate denser branching and shorten the vegetative phase. Tillage, mowing or slashing should be performed before seed-set to reduce seedbank levels, since these practices can aid in the spread of achenes (Gupta & Sharma, 1977). Although burning has been successful in some instances, it is not generally accepted as a control practice as it may increase the vulnerability of the land to infestations by damaging native pastures, and because *P. hysterophorus* apparently does not burn well (Parthenium Action Group, 2000).

1.3.5.2 Chemical control

Selective herbicides can be used to control *P. hysterophorus* under most situations and several herbicides are registered for this purpose. As with mechanical control, chemical control of *P. hysterophorus* is often uneconomical in the short-term. Due to the high fecundity of *P. hysterophorus* newly emerged seedlings are often quick to appear after the successful control of mature plants. To a certain extent residual herbicides can solve this problem (Navie *et al*., 1996). Herbicides should be applied before seed set for most effective control and treated areas should be monitored for several seasons for any re-emergences. 2,4-D, picloram, dicamba, diuron, bromacil, karbutilate and atrazine (amongst many others) applied in high volume sprays can all be used for *P. hysterophorus* control (Navie *et al*., 1996). Parsons & Cuthbertson (1992) suggest spraying a mixture of atrazine and 2,4-D, with 2,4-D killing existing plants and atrazine having the residual activity to prevent re-emergences. Atrazine was recommended in Australia as the cheapest effective chemical for suitable long-term *P. hysterophorus* control, particularly along roadsides (Anon., 1978), while in India diquat, 2,4-D, linuron and bromacil provided quick and effective control (Gupta & Sharma, 1977).

1.3.5.3 Biological control

Abundant literature exists on the various natural enemies of *P. hysterophorus* that have been screened and/or introduced with varying degrees of success. Biological control would most likely offer the best and most effective solution to the *P. hysterophorus* weed problem (Haseler, 1976), but to date biological control of *P. hysterophorus* has only achieved limited control in Australia and India (McFadyen, 1992) and elsewhere in the world. Species that have successfully been introduced in Queensland, Australia include: *Zygogramma bicolorata*, a leaf-defoliating beetle; *Listronotus setosipennis*, a seed-feeding weevil; *Puccinia abrupta* var *partheniicola*, a winter rust; *Epiblema strenuana*, a stem-galling moth; *Conotrachelus* spp., a stem-galling weevil; *Platphalonidia mystica*, a stem-boring moth; *Carmenta nr ithacae*, a root-boring moth; and *Puccinia melampodii*, a summer rust (Parthenium Action Group, 2000). Many of the biological control agents' efficacy has been restrained by unsuitable climatic conditions. So far no immediate short term successes have been achieved in the biological control of *P. hysterophorus* and Evans (1997) describes the biological control programme in Australia as a 'costly failure'. The 'Parthenium Action Group' (2000) suggests the use of various biological control agents in combination for best results in reducing the competitive ability of *P. hysterophorus* and restoring the natural balance. Evans (1997) states that the long-term solution lies in releasing a number of agents that will attack as many plant organs as possible and so gradually reduce weed vigour over time.

In South Africa a parthenium biological control programme was started by the Agricultural Research Council Plant Protection Research Institute (ARC-PPRI) in 2003. A rust fungus, namely, *Puccinia melampodii* Dietel & Holw., and three insect species, namely *Zygogramma bicolorata* Pallister, *Epiblema strenuana* Walker and *Listronotus setosipennis* have been prioritised for the biocontrol programme. (Strathie *et al*., 2005).

In addition to the use of arthropods and pathogenic micro-organisms, the use of antagonistic plants appears to be a plausible method of biological control. One such biological control plant which has been identified is *Cassia uniflora* Mill., which has been shown to suppress parthenium growth, reduce seed production and dissemination, and phenolic leachates from *C. uniflora* have been demonstrated to inhibit parthenium seed germination significantly and also reduce seedling vigour (Joshi, 1991b). Joshi observed *C. uniflora* replacing *P. hysterophorus* through a centrifugal mode of expansion and states that complete replacement can occur on a site within three to five years.