Parthenium: Impacts and coping strategies in Central West Asia

Evidence Note (March 2019)

KNOWLEDGE FOR LIFE

This CABI evidence note may be referred to as:

CABI (2019) Parthenium: Impacts and coping strategies in Central West Asia.
CABI Evidence Note (March 2019). CAB International, Wallingford, UK, 43 pp.
DOI: https://dx.doi.org/10.1079/CABICOMM-62-8182

Acknowledgements

The authors gratefully acknowledge the financial support of the UK's Department for International Development (DFID) and the Netherlands' Directorate-General for International Cooperation (DGIS) for CABI's Action on Invasives Programme, as part of which this Evidence Note was produced. The views expressed in this document are those of the authors and do not necessarily reflect the views of DFID or DGIS.

Credits

Co-ordination: Julien Lamontagne-Godwin

Writing and analysis: Ivan Rwomushana, Julien Lamontagne-Godwin, Kate Constantine, Fernadis Makale, Winnie Nunda, Roger Day, Philip Weyl, Pablo Gonzalez-Moreno

Valuable contributions from: Fredrick Mbugua, Abdul Rehman, Kausar Khan

Executive summary

Background

Parthenium hysterophorus L. (Asteraceae) is an invasive weed thought to be native to the tropical and subtropical Americas, from where it has spread globally to 48 countries. The weed was first reported in Pakistan in the 1980s in the Gujarat District of Punjab Province. Over the last 10 years, parthenium has extended its range to most areas of the Punjab, Khyber Pakhtunkhwa (KP), the Federally Administrated Tribal Areas, Azad Jammu and Kashmir and more recently in Sind Province. The weed is spreading to agricultural farms, mainly through the extensive canal network that is used to irrigate the land. Many protected areas (national parks; reserves) have also been invaded, threatening the native plant diversity and environment. Several methods have been attempted to manage the weed, although no single approach can provide absolute control. This evidence note is therefore meant to provide information on the key facts about parthenium; to provide data on farmers' perception of the weed and how they are coping with it; to summarize the known control methods; and to make recommendations for the sustainable management of the weed for a wide range of stakeholders.

The economic importance of parthenium

Parthenium is typically a weed found in semi-arid, subtropical and tropical regions, with a preference for warmer temperate climates. It is commonly found in riparian zones; in disturbed areas such as roadsides, along railways and in pastures; and in seasonal floodplains, grasslands, open woodlands, waste areas, disturbed sites, lawns, gardens and croplands, and is particularly aggressive in degraded or disturbed pastures. The species is of particular global concern due to its aggressive and highly adaptable nature, establishing and expanding rapidly in a wide range of environmental and climatic conditions. Parthenium is extremely prolific, capable of producing up to 30,000 seeds per plant – a major attribute behind its invasive nature and a reason why it has spread and established in many parts of the world.

The dispersal mechanisms of parthenium

Parthenium seeds can be dispersed via wind, but this is very limited and only considered viable for shorter distances. The main modes of dispersion over longer distances include water, farm machinery, humans and animals. Accidental long-distance dispersal has mainly been facilitated by increased movement and trading grain for human and livestock consumption. In Pakistan, parthenium is believed to have spread from Islamabad with the movement of military vehicles to other regions of the country. At a local level, spread in Pakistan is attributed to contaminated potting mix/soil, contaminated soil from road construction and through the movement of ornamental plants. There is also a risk of the weed being present in fodder and floral bouquets. The lack of effective natural enemies enhances its ability to spread very quickly.

Known impacts of parthenium

Environment: in the introduced range, parthenium is an effective and aggressive colonizer, especially of disturbed landscapes, where it is capable of displacing native plant species and of reducing pasture carrying capacities by as much as 80% to 90%. Parthenium can also alter soil texture, pH, organic matter and N, K and P content. Parthenium has allelopathic properties, which likely contribute to the ability of the weed to displace native species. There is also some literature documenting the impact of parthenium on insects, amphibians and reptiles, birds, mammals, water systems and pollinators.

Human health: parthenium is poisonous, and regular contact has been known to cause serious allergenic reactions in humans. It is reported that, after exposure to parthenium for one to 10 years, 10% to 20% of the population will develop severe allergic reactions. Parthenium can also flower almost all year round, providing sugar meals for disease vectors such as mosquitoes, enabling females to accumulate substantial energy reserves and increase their longevity and malaria transmission rates within communities, negatively affecting national efforts targeted at malaria control.

Livestock production and health: parthenium invasions can displace palatable species in natural and improved pastures. In India, management cost of the weed to restore grazing lands cost about Indian rupees (INR) 300,000 m (US$ 6.7 bn) per annum. Parthenium also poses a serious hazard to livestock health. Farm animals can suffer from allergic reactions after spending time in fields infested by parthenium, and consumption of large quantities of parthenium taints meat quality and can even kill livestock. Up to 50% losses have been reported in milk quantity and quality due to this weed.

Crop yields: parthenium can impact crop yields through direct competition, as well as by inhibiting germination. Crop yield losses as high as 50% have been reported in different studies. In Ethiopia, sorghum grain yield was reduced from 40% to 97% due to parthenium invasions; in Pakistan, substantial yield losses in wheat and maize have been reported. A yield loss of 50% in maize was recorded at an infestation rate of 20 parthenium plants per square metre. Indirect impacts are as a result of the weeds ability to act as an alternative host to some important pests and pathogens. Usually crops mostly grown on marginal, less fertile and non-irrigated lands are the most affected with parthenium invasions.

The spread, distribution and environmental suitability of parthenium

Global: parthenium can grow and develop in a wide range of climatic conditions across the world, and is so far reported in 92 countries. The weed can thrive in arid areas due to its adaption to saline and low-moisture conditions. Parthenium also exhibits phenotypic plasticity in different climatic conditions without affecting germination or flowering, which has permitted its vast spread in introduced regions. Several published modelling scenarios suggest that the whole Mediterranean basin is at risk of parthenium invasion, as are the warm parts of Europe’s temperate regions. The highest risk exists in the southern part of the Mediterranean basin, but also in Spain. In Africa, large areas in western and central regions are highly suitable for parthenium, although they have not yet invaded. The more arid areas of the continent in southern Africa seem to be relatively less suitable. Most countries in Asia and Oceania with climates that are suitable for parthenium have already been invaded. In many Asian countries, parthenium is now considered to be an emerging weed with a very rapid spread. Considering climate change, the available models predict an increase in the potential area that could be invaded by parthenium globally. With continuous changes in land use and habitat modification, further spread is expected in areas that are currently suitable, such as West Africa.

Pakistan: in Pakistan, the current spread of parthenium seems to be facilitated by the road network and water canal systems for irrigation and flooding events. Areas with low climatic suitability such as the south of Punjab are affected by the weed, as are other areas such as Sind Province. Based on the likely expansion of parthenium following the irrigation network, the weed will likely spread towards the southwestern part of Punjab, threatening Pakistan’s cotton industry.

Farmers’ knowledge of parthenium in Pakistan

A household survey conducted in Pakistan in late 2018 investigated farmers’ knowledge about parthenium; how they control it and whether those methods are effective, safe and practical; and how much the control methods cost in relation to their overall crop yield and income. The study showed that 82% of respondents were aware of parthenium. For the farmers who had observed parthenium, it was most frequently observed in their fields (35%), in urban areas (29%), along roadsides and in water canals (22%), and on communal land (10%). Wheat and rice were the most affected crops. Over half of respondents (58%) reported that parthenium had increased in the five years prior to survey, although about 17% suggested that the cover had stayed the same, and a similar proportion thought it was rapidly spreading. In terms of management, 66% of farmers knew of hand-pulling only, hand-pulling coupled with chemical control (17%) and only using chemicals (14%). Negative effects due to parthenium were reported by a majority of farmers on their crops (72%), on human health (53%), on animals (28%) and on the environment (3%). Nearly 8% had experienced some health effects from parthenium including allergy, skin irritation, itching and inflammation of skin on the face, hands and feet. A small proportion of farmers (4%) reported negative effects of parthenium on animals, including tainted milk, mouth-watering and sickness.

Parthenium impact and control strategies

There were mixed feelings about the impact of parthenium on crop yield. Nearly 38% of farmers reported that the weed affected their yield, while 62% felt there was no effect on crop yield. The farmers who felt parthenium affected their wheat yield estimated a yield loss of 5% to 15%. We estimated that, on average, a farmer will spend Pakistani rupees (PKR) 7997 (US$ 94) per season to manage parthenium, largely spent on herbicide and labour. However, the weed caused other impacts that were harder to quantify, such as difficulties walking on the edges of fields and paved areas. Farmers responded to parthenium by either application of chemicals/herbicides (42%) and hand-weeding/pulling (39%), while 19% of farmers combined both hand-weeding and chemicals. Hand-weeding/pulling was considered the most successful method by 34% of farmers, followed by chemical spraying (19%). A modest proportion of farmers used personal protective equipment (PPE) when applying chemicals. About 43% used facemasks and 24% used gloves, with a smaller proportion of farmers using gum boots, helmets or overalls. At least 26% of farmers did not use any PPE. Overall, 56% of farmers reported experiencing side-effects due to the use of chemicals, including skin itching, headaches, dizziness and stomach ache.

Opportunities for the biological control of parthenium

The concept of biological control for the management of parthenium is still a largely alien concept to the majority of farmers in Pakistan. Only 24% of respondents were aware of biological control, mostly in relation to “beneficial insects”. Encouragingly, however, at least 60% were willing to use this approach to manage the parthenium problem. Indeed, 56% of the respondents were willing to use an alternative to a chemical if it worked. Interestingly, 51% of farmers were willing to pay more for an alternative to a chemical if it was as effective as the one they currently used, and if it had fewer health implications. Only 14% were not willing to pay more for biological control. At least 24% of farmers indicated they would be willing to pay 1% to 5% above their current expenditure on chemicals if the biological control solution had the same, or better, effect. In general, over 40% of respondents did not answer questions related to the willingness to pay, suggesting the need for increased awareness of biological control options and a better understanding of control economics regarding biological solutions.

Parthenium advice and information

Nearly 52% of farmers reported receiving information about parthenium, mainly from extension agents, fellow farmers, television and printed material. There is a noticeably low uptake of e-extension services using SMS and smartphones. CABI has launched a web-based parthenium portal (www.cabi.org/isc/parthenium) as an integral part of the open access Invasive Species Compendium. The portal includes a wide variety of information for farmers, policymakers, researchers and other stakeholders, collated from multiple sources.

Recommendations for the control of parthenium

Parthenium is currently considered a “superior weed” ranking in the top five weeds worldwide. As described earlier, it is extremely prolific, suggesting that any management approach will have to keep pace with its spread to limit its widespread impact on various facets of the economy and the social fabric of affected communities. The following recommendations are proposed to the wider range of stakeholders for the integrated management of parthenium under three different scenarios.

When parthenium has not yet arrived:

- to increase inspections of vehicles, livestock and seed and feed lots to manage parthenium seed movement through this pathway. Prevention of parthenium coming into a new area is much cheaper than eradication or control once it has invaded
- to create awareness at nurseries and floriculturists on weed identification, and to restrict the introduction of floral products from areas where the weed is present
- to co-ordinate effectively between working groups in different countries, to learn from each other and to create awareness about parthenium before it can arrive

When parthenium has just arrived:

- to help invaded countries develop and implement a parthenium management strategy to contain it and slow its further spread
- to communicate to communities regarding how to identify the weed, and to engage the community to eradicate it through chemical and mechanical means
- to implement legislative measures declaring parthenium to be a noxious plant, and to ensure public and political support through sufficient budget allocation to eradicate it
- to manually uproot parthenium, particularly before it flowers, and especially in small and isolated areas; protective clothing should be worn by workers to prevent allergic reactions
- to apply chemical control to parthenium along roadsides, in public parks or on private properties to eradicate the weed
- regulators should facilitate the registration and promotion of biological control agents through classical and augmentative biological control efforts to prevent the weed becoming widespread

When parthenium has already arrived and is firmly established:

- declare parthenium as a noxious plant and ensure public and political support through sufficient budget allocation to manage it
- cut and slash parthenium growing along roadsides; this should be destroyed immediately to destroy the seed
- plough and mulch while preparing land for planting with a crop or improved pasture, particularly at the vegetative stage before flowering occurs
- survey for natural enemies already present that can be used in the augmentative biological control of parthenium
- establish mass rearing facilities and undertake release efforts of natural enemies that feed on parthenium; regulators should facilitate the registration and promotion of biological control agents through classical and augmentative biological control efforts
- chemical control should be undertaken, but this may not be cost-effective over vast areas such as wastelands, rangelands, lower value field crops or within forests
- develop a technical guidance standard for herbicide use in parthenium management: procurement, risk reduction and resistance management
- establish the economic considerations for different control methods, including health and environmental impacts

Contents

List of tables

List of figures

Introduction

Parthenium (*Parthenium hysterophorus*) is a weed of particular global concern due to its aggressive and highly adaptable nature, establishing and expanding rapidly in a wide range of environmental and climatic conditions. In view of the threats posed by parthenium, this evidence note aims to provide evidence and recommendations for decision makers in Pakistan and the Central West Asia region, as well as for external organizations seeking to manage parthenium sustainably. This information will be useful for decision makers to prioritize investment and interventions in responding to the continuing threat posed by this invasive weed. This evidence note is structured into four sections.

- **Section 1** introduces the environmental and agricultural impacts of parthenium, highlighting its distribution across the globe and in Pakistan, followed by details of the weed's ecological and biological attributes that enable its rapid expansion and negative impacts
- **Section 2** synthesizes the results of household surveys conducted in Pakistan in 2018, highlighting farmers' knowledge and perceptions of parthenium and its impacts, the economic impact of the crop on wheat related incomes and the control measures currently used
- **Section 3** provides information on ongoing and recent research on control methods, highlighting significant new findings and existing information resources
- **Section 4** concludes with some recommendations for key stakeholder groups in Pakistan

1. Biology, impacts and spread

A detailed synthesis of the biology, impacts and spread of parthenium is provided in the CABI publication “Parthenium weed: biology, ecology and management” (Adkins et al., 2019). The book draws on examples from 48 countries invaded by this weed and covers aspects of (i) biology; (ii) ecology; (iii) genetics; (iv) introduction histories; (v) geographical distribution; (vi) the impact on agriculture, natural forests and the environment of protected areas; (vii) allelopathy; (viii) impacts on human and animal health; (ix) potential uses; and (x) management strategies, including chemical, cultural and biological control methods. This section, therefore, only provides a short summary of these aspects of parthenium.

1.1 Biology

Parthenium hysterophorus L. (Asteraceae) is an annual herbaceous plant that can reach a height of 1.5 m in its native range, but can grow up to 2.5 m where it is an invasive species (Navie et al., 1996). The plant possesses a deep taproot capable of exploiting significant below-ground water resources (Henderson, 2001). It is native to parts of tropical Central and South America and is currently a global invasive weed (Adkins and Shabbir, 2014; EPPO, 2018). It is typically found in semi-arid, subtropical and tropical regions, with a preference for warmer temperate climates, and is commonly found in riparian zones; in disturbed areas such as roadsides, along railways and in pastures; in seasonal floodplains, grasslands, open woodlands, waste areas, disturbed sites, lawns, gardens and croplands; and is particularly aggressive in degraded or disturbed pastures (Navie et al., 1996; McConnachie et al., 2011; Shabbir and Bajwa, 2006; Adkins and Shabbir, 2014; EPPO, 2018).

At germination, the younger plants start off as a rosette of leaves, maturing into branched taller plants that become woody as they age (Dhileepan and Strathie, 2009). The leaves are long, pale green with lower leaves that are deeply pinnately lobed, 80 mm to 200 mm long and covered with soft fine hairs. The flowers are creamy-white and form small (Figure 1), compact heads about 3 mm across with five corners each containing a black seed, forming multi-branched clusters (Henderson, 2001). The seeds are black and 2 mm long. The seedlings of parthenium emerge during warmer periods, but as long as conditions are favourable the plant can reproduce at any time during the year, producing up to five successive generations of seedlings (Navie et al., 1998).

Figure 1: Parthenium flower

***Source**: Bugwood*

The species is of particular global concern due to its aggressive, highly adaptable nature, establishing and expanding rapidly in a wide range of environmental and climatic conditions (Dhileepan and Strathie, 2009; McConnachie et al., 2011). Indeed, parthenium is a recognized and significant weed in many parts of Africa, Asia and Australasia (Bajwa et al., 2016), where it is found invading productive landscapes and posing serious threats to livelihoods and biodiversity. Parthenium has been officially declared a noxious weed through legislation and policy for management enacted by the governments of Australia, South Africa, Sri Lanka and India, and more recently within the East African region (for example, Kenya in 2010) (McConnachie et al., 2011; Dhileepan, 2009; EPPO, 2014, 2018; BioNET-EAFRINET, 2018; CABI, 2018).

Parthenium is extremely prolific, capable of producing up to 30,000 seeds per plant – a major attribute behind its invasive nature, and a reason why it has spread and established in many parts of the world (McFadyen, 1992; Navie et al., 1996, 2004; Adkins et al., 2005 in Strathie et al., 2011). The seeds are easily dispersed by wind, water, animals and even vehicles (Auld, 1983; Bajwa et al., 2014). The plant is also extremely durable: it germinates at a wide range of temperatures between 12°c to 27°c (Adkins and Shabbir, 2014). Parthenium can sustain highly viable seeds for long periods; up to 50% of the seeds are still viable after 26 months in the soil (Tamado et al., 2001). Field observations in Ethiopia correspond to what has been observed in Queensland and South Africa – parthenium germination is rainfall dependent. The seed bank in the soil requires adequate moisture to break dormancy, emerge and flower (Strathie et al., 2011; Adkins and Shabbir, 2014). Parthenium seeds germinate very fast, out-competing other plant species within the same seed bank to emerge and establish. For example, trials conducted in Ethiopian grazing lands to determine above-ground and seedbank species diversity in parthenium infested landscapes confirmed there is a negative relationship between parthenium and other grass species in both above-ground biomass and the seed bank (Nigatu et al., 2010).

In addition to these invasive properties, parthenium has developed other survival mechanisms for unfavourable conditions such as forming rosettes during poor climatic conditions that will subsequently bolt and flower easily when favourable conditions return (Kohli et al., 2006). Parthenium is also able to regenerate quickly from vegetative parts such as root stumps, petioles and midribs left in the soil (Kohli and Rani, 1994). In addition to its large and persistent soil seed bank that can undergo dormancy for long periods while remaining viable, parthenium also releases toxic chemicals (allelopathy) that prevent other plants from germinating in invaded landscapes. All these factors contribute to facilitating the weed's rapid spread across invaded landscapes (McConnachie et al., 2011; Rubaba et al., 2017).

Parthenium seeds can be dispersed via wind, but this is very limited and only considered important for shorter distances. For dispersion over longer distances, water, farm machinery, humans and animals are more effective (Navie et al., 1996). Accidental long-distance dispersal has mainly been facilitated by increased movement and trading grain for human and livestock consumption. For example, parthenium is believed to have been introduced to India in the mid-1950s as a contaminant of food grains from the US (Sushikumar and Varshney, 2010), and has subsequently spread over 35 m ha in the Indian subcontinent, where the weed has become naturalized and achieved major weed status (Manpreet et al., 2014; Sushikumar and Varshney, 2010).

Movement of machinery has been a major means of introduction for invasive species around the world, and parthenium spread has benefited from this in Asia and elsewhere (Blackmore and Johnson, 2009; Shabbir and Adkins, 2011). Records attribute the movement of aircraft and machinery from the US into Australia during the Second World War as the source of parthenium introduction (Parsons and Cuthbertson, 1992). In Pakistan, parthenium is believed to have spread from Islamabad with the movement of military vehicles to Chitral, Hango and Swat and a frontier region of Bannu.

At a local level, in Pakistan, parthenium can be spread as a contaminant of potting mix/soil, via contaminated soil from road construction and through the movement of ornamental plants (Shabbir et al., 2012). There are also unconfirmed reports of the weed's presence in fodder and the floral bouquet industry. The lack of natural enemies across the globe also enhances its ability to spread very quickly.

1.2 Impacts

Parthenium is responsible for the degradation of grasslands, peri-urban landscapes and wastelands, but also a reduction in yield in over 40 crops in various countries. Parthenium is usually among the top three most frequently found weeds within a few years after introduction in many of the countries it has invaded. Due to the many impacts of parthenium (see below), there is a fundamental need to focus increased effort and targeted strategies towards managing the global spread of this invasive weed, in addition to reducing further introductions.

Environment

In its introduced range, parthenium is an effective and aggressive colonizer, especially of disturbed landscapes, where it is capable of displacing native plant species and of reducing pasture carrying capacities by as much as 80% to 90% (Jayachandra, 1971; McFadyen, 1992). Parthenium's allelopathic properties significantly impact on biodiversity and the landscape (Pandey et al., 1993; Evans, 1997). In Australia, studies show that parthenium has transformed natural vegetation communities including grasslands, open woodlands, river banks and flood plains by inhibiting the growth of native species (McFadyen, 1992; Chippendale and Panetta, 1994). Parthenium can alter the soil texture, pH, organic matter and N, K and P content (Timsina et al., 2011). In India, parthenium is one of the weeds that affects structural composition and diversity dynamics of native vegetation (the other species including *Lantana* and *Ageratum*) (Kohli et al., 2006). In Ethiopia, a reduction in plant species diversity and community evenness was reported when parthenium densities increased (Nigatu et al., 2010; Ayele et al., 2013).

Human health

Parthenium is poisonous, and regular contact has been known to cause serious allergenic reactions in humans. It is reported that, after exposure to parthenium for one to 10 years, 10% to 20% of the population will have developed severe allergic reactions including hay fever, asthma, allergic rhinitis and skin allergies such as eczematous contact dermatitis (McFadyen, 1995; Evans, 1997; Fessehaie et al., 2005). Contact with parthenium can also worsen conditions for individuals suffering from chronic diseases such as HIV and tuberculosis (McConnachie et al., 2011). The ill effects associated with parthenium have real world impacts, such as mass abandonment of farms in India and other parts of the world due to the weed's direct and/or indirect impacts on people's livelihoods, particularly floristry workers (Witt, 2015). Parthenium can also flower almost all year round, providing sugar meals to disease vectors such as mosquitoes. This enables females to accumulate substantial energy reserves and increase their longevity and malaria transmission rates within communities (Nyasembe et al., 2012; Stone et al., 2018). Studies have also indicated that mosquitoes show preferences for particular plant species such as parthenium, *Tecoma stans, Ricinus communis* and *Senna didimobotrya* (Manda et al., 2007; Nyasembe et al., 2012), and the presence of the weed can negatively affect national efforts targeted at malaria control (Nyasembe et al., 2015).

Livestock

Studies in India and Australia show that parthenium invasions can displace palatable grazing species in natural and improved pastures. Sushilkumar and Varshney (2010) reported that approximately 35 m ha of land in India had been affected by parthenium and was costing INR 300,000 m (US$ 6.7 bn) per annum in management alone since introduction. In surveys carried out in Australia where parthenium was reported to have invaded over 17,000 km^2 of pastureland, it was predicted that at least 45,000 more cattle could have been marketed in the absence of the weed, which was equivalent to a net annual loss of revenue of AU$ 5 m to AU$ 17 m at the time of survey (McFadyen, 1992; Chippendale and Panetta, 1994).

Parthenium also poses a serious hazard to livestock health (Shrestha et al., 2015). Farm animals – especially horses, cattle, buffalo, sheep and even dogs – can suffer from allergic reactions after spending time in fields infested by parthenium (Dhileepan and Strathie, 2009; Narasimham et al., 1980).[1] Consumption of large quantities of parthenium taints mutton (Tudor et al., 1982) and can even kill livestock. In northern, central and eastern Ethiopia, parthenium is reported to reduce the quality of meat and milk products, with up to 50% losses reported in milk quantity and quality. This also poses a serious risk to the health of the children and adults who consume it, in addition to reduced income at market for tainted products (Ayele, 2007).

Crop yields

Parthenium can impact on crop yields through direct competition, as well as by inhibiting germination of a wide range of food and vegetable crops;[1] grasses such as Eleusine sp. and Eragrostis spp.; and important agroforestry tree species such as Acacia, Casuarina, Eucalyptus and Leucaena (Evans, 1997). Studies conducted using parthenium residues on

---

[1] Affected crops include wheat, barley, maize, sorghum, chick pea, mungbean, soybean, sunflower, ground nut, cotton, cabbage and potato.

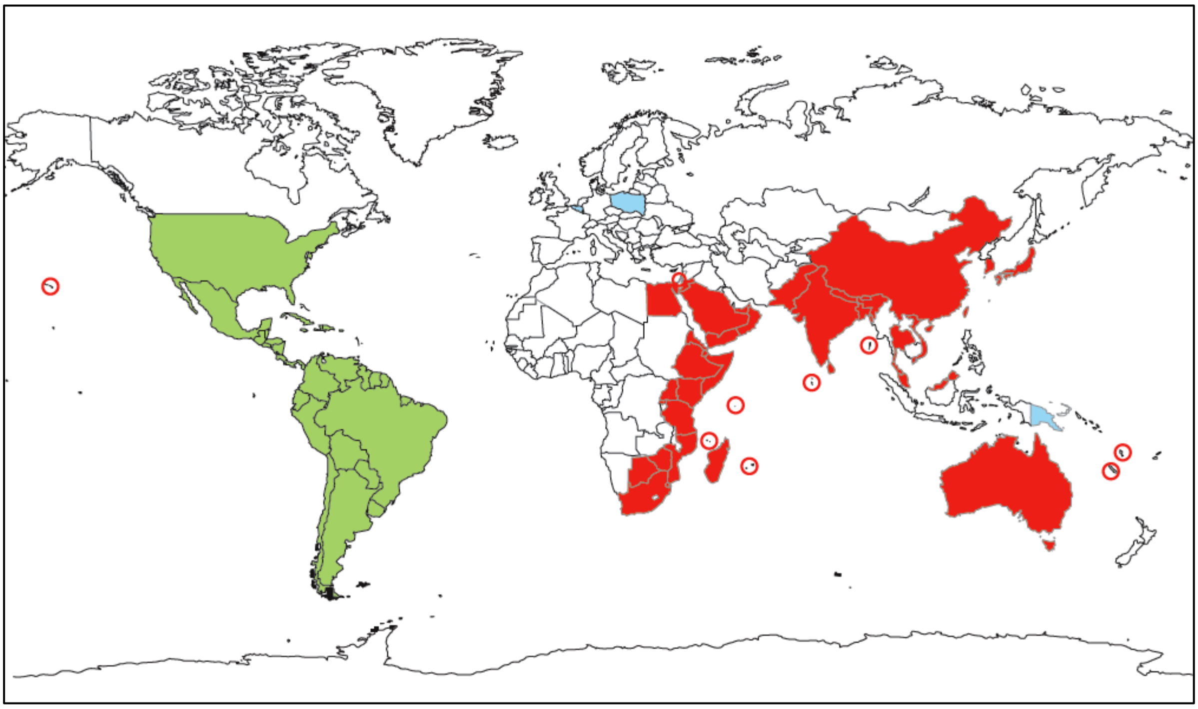
the growth of chickpea and radish plants found that both burned and unburned residues had toxic effects on seedling germination and dry weight, with the unburned residue more toxic when compared to the burned residue (Singh et. al., 2003). Crop yield losses as high as 50% have been reported in different studies (Netsere, 2015). In Ethiopia, sorghum grain yield was reduced from 40% to 97% due to parthenium invasions on croplands (Tamado, 2001; Tamado et al., 2002). In addition, at least 70% of farmers indicated that parthenium caused crop yield losses as high as 50%, and 73% of farmers thought that it affected soil fertility negatively and therefore reduced crop yield (Beyene et al., 2013). In Pakistan, substantial yield losses in wheat and maize have been reported (Khan et al., 2013). A yield loss of 50% was recorded at an infestation rate of 20 parthenium plants per square metre. Indirect impacts occur as a result of the weed's ability to act as an alternative host to some important pests and pathogens (Shabbir, 2013). Crops that are grown on marginal, less fertile and non-irrigated lands are usually the most affected by parthenium invasions.

1.3 Spread

1.3.1 Worldwide distribution

Parthenium is thought to be native to the tropical and subtropical Americas (Dale, 1981), but it has spread globally to reach a pan-tropical distribution, with a known presence in over 90 countries (Figure 22).

Figure 2: A worldwide map of Parthenium distribution



Note: *Red: invaded countries; blue: transient populations (present, but establishment is not expected to occur based on technical evaluation); green: countries in native range (Source: Shabbir et al., 2018)*

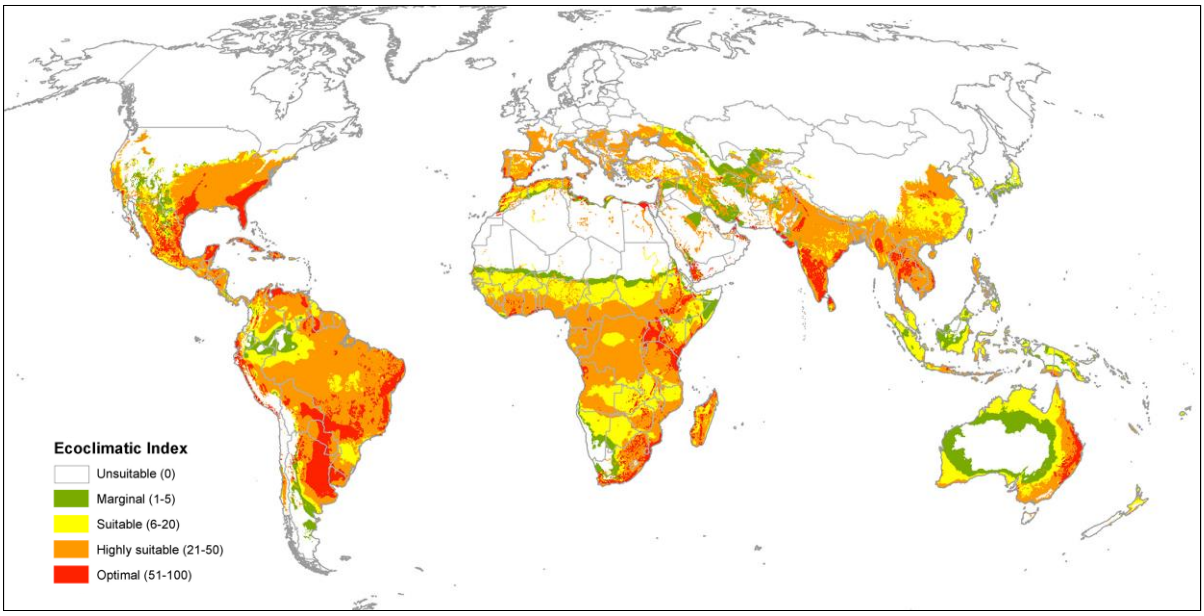
Parthenium has been found to grow and develop in a wide range of climatic conditions across the world. The weed's survival could potentially be limited in areas with an annual rainfall lower than 500 mm, but it might also be able to thrive in some of these arid areas due to its adaption to saline and low-moisture conditions (Khurshid et al., 2012), in addition to its association with irrigated agricultural areas (Kriticos et al., 2015). Parthenium has also been found to exhibit phenotypic plasticity in different climatic conditions (Kaur et al., 2017) without affecting germination or flowering, which likely explains the acclimatization potential of the weed, which has permitted its vast spread in introduced regions. Based on this wide environmental range and according to several published modelling scenarios, parthenium could still spread to large areas that are currently unoccupied (Figure 33; McConnachie et al., 2011; Shabbir, 2012; Mainali et al., 2015; Kriticos et al., 2015).

- Mediterranean and Europe: the whole Mediterranean basin is at risk of parthenium invasion, as are the warm parts of the temperate regions in France, Hungary, Moldova, Russia and Ukraine (Shabbir, 2012, Kriticos et al., 2015). Of these areas, the projections found that the highest risk exists in the southern part of the Mediterranean basin (Algeria, Israel, Jordan, Morocco, Tunisia and Egypt), but also in Spain (Mainali et al., 2015; Kriticos et al., 2015)
- Africa: large areas in West and Central Africa are highly suitable for parthenium, but not yet invaded, particularly the coastal areas around the Gulf of Guinea (eg Ghana, Togo, Benin, Nigeria, Congo and Guinea), but also large areas in Democratic Republic of

Congo and northern Angola (Shabbir, 2012, Kriticos et al 2015). In contrast, more arid areas such as Zimbabwe, Botswana, Namibia and Zambia seem to be relatively less suitable (McConnachie et al., 2011)

- Asia and Oceania: most countries with suitable climates for parthenium have already been invaded. In some countries, such as Pakistan, Nepal and Bangladesh, parthenium is now considered to be an emerging weed with very rapid spread (Shabbir et al., 2018, Shrestha et al., 2015)

Figure 3: Climate suitability for Parthenium establishment



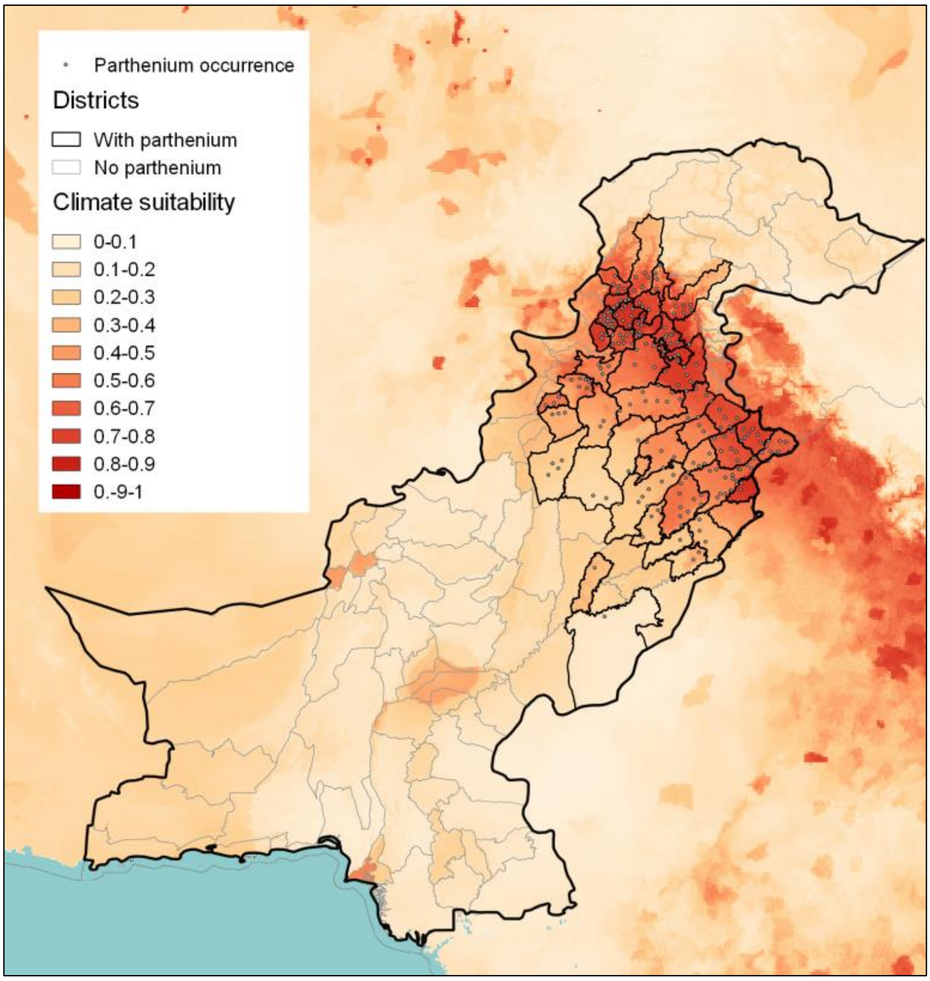
Note: M*odelled using CLIMEX and including the effect of irrigation (Kriticos et al., 2015)*

Considering climate change, the available models predict an increase in the potential area that could be invaded globally by parthenium (Shabbir et al., 2018), particularly when irrigation is included (Kriticos et al., 2015). Large areas in temperate Europe, the northern US and the south of Arabian Peninsula (mainly Yemen) are climatically suitable (Kriticos et al., 2015; Brunel et al., 2014). Furthermore, with continuous changes in land use and habitat modification, further spread is expected in areas that are currently considered suitable, such as West Africa. It is important that, with knowledge of future parthenium spread, authorities in the respective countries initiate early preventive mechanisms against this weed.

1.3.2 Distribution in Pakistan

The current spread of parthenium seems to be facilitated by the road network and water canal systems for irrigation and flooding events (Shabbir et al., 2012). Interestingly, areas with low climatic suitability – such as the south of Punjab – are currently occupied (Figure 44). The mean summer temperature in these areas is 34°c (May–June), with daily maximum readings often up to 50°c, with only 250 mm of annual rainfall (Shabbir et al., 2018), which should be beyond the arid tolerance of this species. The presence of parthenium in these drier areas could be explained by the influence of irrigated agriculture, which provides extra soil moisture (Shabbir et al., 2018, Kriticos et al., 2015). This was confirmed when parthenium was detected in the irrigated area of Khairpur District in Sind Province in 2012 (Shabbir et al., 2018).

Figure 4: Parthenium distribution in Pakistan



Note: *Dots indicate occurrences identified in the field. Districts with black line borders have parthenium occurrence according to data in Shabbir et al. (2012) (Punjab) and Khan et al. (2014). The red colour gradient indicates climate suitability according to Mainali et al. (2015) (no irrigation scenario)*

In the central districts of Punjab, parthenium is the most dominant weed growing in wastelands, along roadsides and water channels, and in abandoned fields and crops such as maize, wheat and various vegetable and floriculture crops (Anwar et al., 2012; Shabbir et al., 2012). Based on the likely expansion of parthenium following the irrigation network and the influence of climate change on the weed's spread across all its ranges, the weed might spread towards the southwestern part of Punjab, causing a significant threat to Pakistan's cotton industry (Shabbir et al., 2018).

2. Impacts of the household survey results

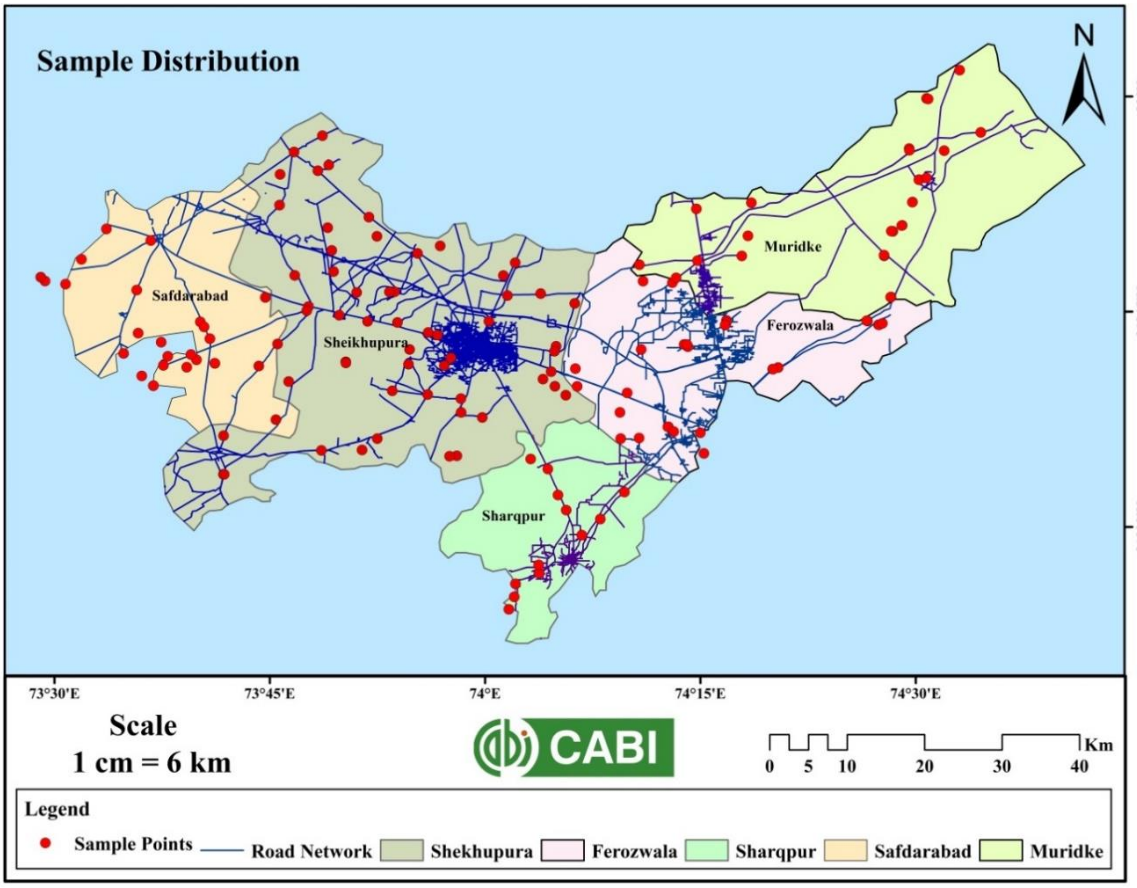
There is at present very little information on parthenium's proportion of cost to rural households in relation to the household's income over a season (Nuñes and Pauchard, 2010). In order to encourage governments to act locally as well as regionally, they must become aware of the impact this weed has on local economies. Many research institutes, including some in Pakistan, have focused their research on the control of parthenium, but there is a paucity of information about what farmers know about this plant and how they control it. Are their control methods effective, safe and practical? How much do they cost in relation to their overall crop yield income? The following section presents results from a rural household survey in Sheikhupura District in Punjab Province, specifically focusing on parthenium impacts and control measures at the household level.

2.1 Methodology

Survey methodology

In order to understand the impacts of parthenium on wheat yields and farmers' livelihoods, household surveys were conducted in Punjab Province in the Sheikhupura District using a "Google form" data collection tool on tablets. Sheikhupura was chosen to combine results with ongoing awareness campaigns on the subject of parthenium. The surveys were conducted by CABI staff. Household heads were interviewed face-to-face, and the survey tool captured information on household composition and farming activities, perceptions of impacts of parthenium on yield and control practices employed and information resources. The sample consisted of 185 farm households, selected through stratified random sampling in the Sheikhupura District (Figure 55), that had grown wheat during the 2016/17 and 2017/18 cropping season. Data was collected during December 2018. The survey targeted the household head or spouse, or any family member who was responsible for making farming decisions.

Figure 5: Mapping the respondents to the survey in Sheikhupura District



Many farmers did not respond to specific questions in this survey, either through lack of knowledge on the subject matter or because they were not in a position to answer, culturally or professionally. In future surveys, more attention must be given to the sections that did not yield many responses.

2.2 Results

Demographics

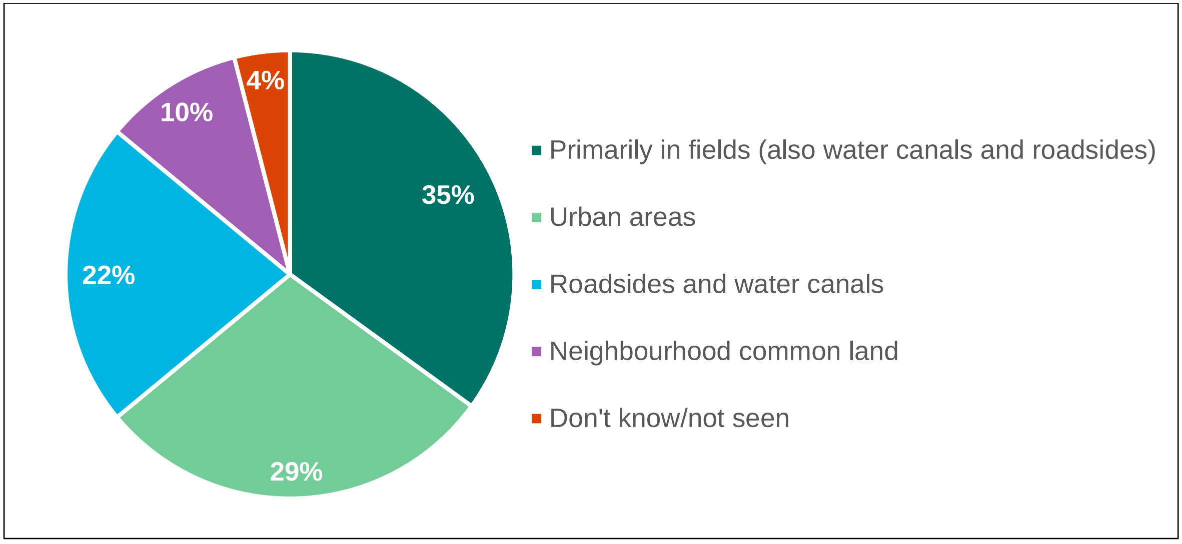
The majority of respondents were from tehsil Sheikhupura (40%), followed by Muridke (22%), Safdarabad (13%), Ferozewala (13%) and Sharqpur (12%). Of those interviewed, 77% were male and 23% female. In terms of age, 34% of respondents were over 50, 27% were aged 40 to 50, 23% were aged 30 to 40 and 11% were aged 20 to 30 (5% did not answer). A high level of respondents did not disclose their education level (62%), but for those that answered, 19% had no education and 10%, 5% and 4% had a primary, secondary or tertiary level education respectively. Almost all respondents lived in rural areas (98%).

The majority of respondents (80%) were household heads. Farming was the primary activity and main source of income for the majority of respondents. The average land holding size was 26.9 acres.

Parthenium knowledge and perceptions

Most respondents (82%) were aware of parthenium. Farmers who had noticed parthenium most frequently reported having first seen it in their fields (35%), many of them also stating that parthenium was also present along roadsides and in water channels. A number of farmers stated parthenium to be present in urban areas (29%), specifically along roadsides and in water canals (22%), and on neighbourhood common land (10%) (Figure 66).

Figure 6: Where farmers first noticed parthenium



Wheat and rice were the most affected crops. Wheat and rice were the most affected crops. Over 90% of farmers who responded stated that parthenium affected a very minor part of their field, and 8% a minor part 10–40%) with 48% of farmers not commenting.

Just over half of respondents (52%) reported that they had received information about parthenium this season (since April 2018). The majority of them had received information from extension agents, but they also mentioned receiving information from fellow farmers, television and printed material.

Those who had received information, along with the majority of those who had not, reported parthenium to have negative effects.

Over half of respondents (58%) reported the cover of parthenium to have increased in five years before survey. A similar proportion reported that the spread had occurred gradually, while 17% stated that the cover had stayed the same (the same proportion of farmers reported parthenium to be rapidly spreading).

For those respondents who had received information on parthenium in the past year, 74% could remember one method of control, primarily hand-pulling (66%), followed by hand-pulling in addition to chemical control (17%), and then solely using chemicals (14%).

Of the 118 farmers who reported negative effects (some reporting more than one effect) due to parthenium, the most frequently reported negative effects were on crops (72%). The weed was also reported to be harmful to human health (53%), in addition to being poisonous to animals and a problem to the environment (28% and 3% of responses respectively). For those farmers who had experienced health effects due to parthenium (8%), these included allergies, skin irritation, itching and inflammation of skin on the face, hands and feet. A small proportion of farmers (4%) reported negative effects of parthenium on animals, including tainted milk, mouth-watering and sickness.

Control

Of the 113 who managed parthenium, the application of chemicals/herbicides and hand-weeding/pulling were the most frequently used control methods (used by 42% and 39% of farmers respectively). Some farmers used a combined approach of both hand-weeding and applying chemicals (19%). A number of farmers (24%) stated that one method was more successful than another, but did not give further detail. However, for those who did provide details, hand-weeding/pulling was considered the most successful method (34%) followed by chemical spraying (19%), with farmers reporting that they would use both methods again.

For those using chemicals 43% used facemasks and 24% used gloves, with smaller proportions of farmers using gum boots, helmets or overalls, and 26% not using any protective gear at all. Overall, 56% of farmers reported experiencing side-effects due to the use of chemicals, including skin itching, headaches, dizziness and stomach ache.

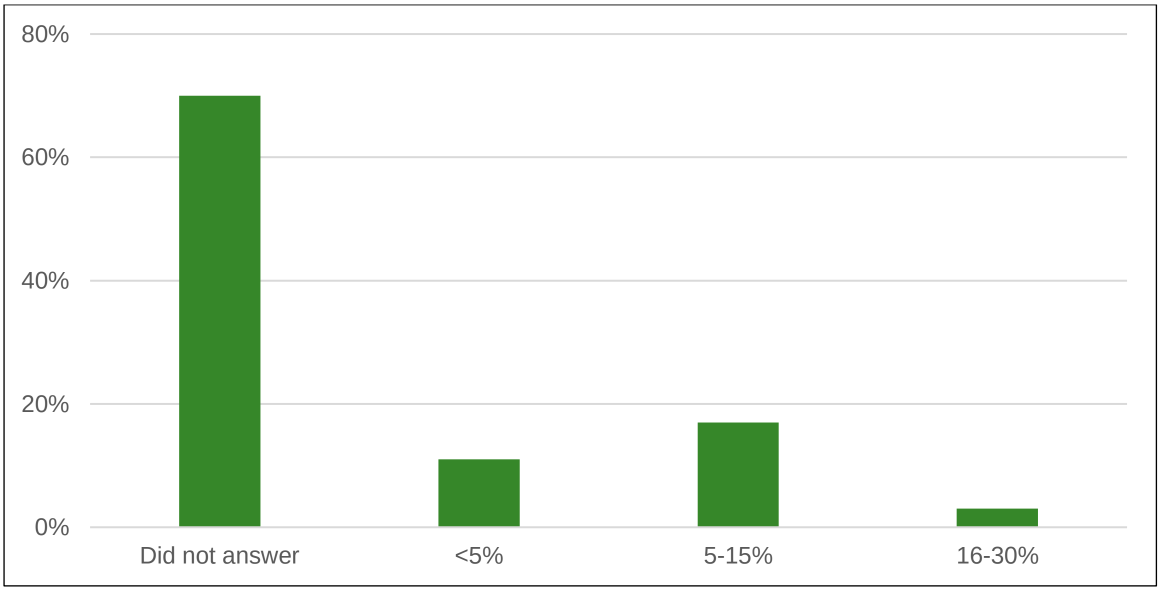
Farmer perceptions of impact

When asked whether parthenium affected their wheat yields, 38% and 62% of the farmers who responded to the question (n=128) reported that parthenium did/did not affected their yield respectively.

When those farmers who had reported that parthenium affected their wheat yield were asked by how much, those who responded (n=55) most frequently reported a yield reduction of 5% to 15% (Figure 7).

If parthenium had not been present on their land, 13% believed their yields would not have changed. However, 28% of respondents believed their yield could have increased by up to 1 maund, 13% by 1 maund to 3 maunds, and 33% believed their yield could have increased by 4 maunds to 6 maunds. A further 13% also believed their yield would increase by 6 maunds or more. While these numbers show that parthenium does affect yields, estimates of yield decrease proportions are hard to obtain due to the wide range of production per farm in the study. In addition to yield reduction, farmers reported that parthenium presence can result in difficulties walking on the edges of fields and paved areas.

Figure 7: Overall farmer reporting on wheat yield reductions due to parthenium



Economic impact of parthenium

The farmer survey attempted to measure the economic impact of parthenium on the livelihoods of wheat farmers. Of 185 interviews, 129 farmers responded to the cost of production questions, although not all datasets were complete. Of these, all were male, so a gendered analysis was not possible. Data was collected on the quantity and value of wheat harvested, the cost of inputs such as fertilizer and the cost of control, with the weighted means calculated and presented in Table 1.

Table 1: Data collected for economic analysis

	n	Mean (weighted)	Std Dev.	Min.	Max.
Farm size					
Farm area used to grow wheat (acre)	129	25	31	1	200
Wheat production					
Quantity harvested (maund per acre)	129	42.18	6	22	62
Total Quantity Harvested (maund)	129	1065	1284	35	9000
Price of wheat per Maund (rupees)	129	1179	173	120	1500
Total value of quantity harvested (rupees)	129	1,261,160	1,530,893	36,000	10,800,000
EXPENDITURE					
Inputs/fertilizer					
Number of urea bags bought (per acre)	123	1.60	0.62	0.5	3.5
Price per bag of urea (rupees)	124	1538	418	1250	4000
Cost of urea per acre (rupees)	123	2489	1360	700	11,100
A) Total cost of urea per season (rupees)	123	67,071	97,703	1400	595,000
Number of Di Ammonium Phosphate bags bought (per acre)	117	1.17	0.41	1	4
Price per bag of DAP (rupees)	117	2673	435	400	3800
Cost of DAP per acre (rupees)	117	3128	1171	400	10,400
B) Total cost of DAP season (rupees)	117	83,242	107,730	2000	567,000
C) Total cost of fertilizer A + B (rupees)	127	141,647	194,342	2800	1,043,000
Prevention/control					
Total cost of herbicide per season (rupees)	40	6684	13,289	550	55,000
Total cost of labour per season (rupees)	63	2565	4687.21	150	20,000
Weighted total cost of herbicide and labour per season (rupees)	78	7997			

In order to estimate parthenium economic impacts, the following assumptions were applied.

1. Wheat production: the total wheat harvest per farmer was calculated by multiplying farm size by harvest per acre. The total wheat harvested was then multiplied by the price of wheat per maund for each farmer and the weighted mean of the total calculated.
2. Inputs/fertilizers: the cost of inputs is the cost for the purchase of DAP and urea per season (price of DAP/urea per unit x number of acres) per farmer and total weighted average calculated.
3. Prevention/control costs: for herbicide and/or labour costs, responses were mainly not given per acre, so it was difficult to obtain the cost per acre for the two variables. For those farms where only herbicide and no labour was used, the total cost of control only included the cost of purchase of the herbicide and the spraying cost. Consequently, for those farms where the farmer only used labour, the total cost of control included only the

amount of money paid for labour. The weighted total cost of herbicides and labour was then calculated.

Methods for estimating the economic impacts of parthenium

Cost of inputs and control as a share of the value of wheat harvest

This considers the cost of herbicides (a) the cost of labour (b) and the cost of inputs/fertilizers (c) a farmer uses over a season to imply the impact of controlling parthenium (i). The proportion of impact to the value of crop is calculated by dividing the impact of controlling parthenium over the value of the average (weighted) quantity harvested and multiplying by 100 to give a proportion of the cost of control to the value of wheat production per farmer.

Where

$(a + b + c) / N$ = impact of parthenium (i)

Where the proportion of impact to value of crop is:

[(i / y) * 100] where "y" is the [average] value of quantity harvested by farmers

= proportion of impact to value of crop/number of famers = 11%

Cost of control as a share of the value of wheat harvest

The cost of herbicides (a) + cost of labour (b) per farmer over a season (cost of control of parthenium). The proportion of impact to the value of crop is then calculated by dividing the cost of control over the value of the average (weighted) quantity harvested and multiplied by 100 giving a proportion of the cost of control to the value of wheat production per a farmer.

Where

(a + b) / N = cost of control for parthenium (ix)

Where the proportion of impact to value of crop is:

[(ix / y) * 100] where "y" is the "[average] value of quantity harvested by farmers"

= proportion of impact (control) to value of crop/number of farmers = 1%

The first calculation indicates that, on average, approximately 11% of the value of the wheat crop is spent by farmers on inputs and control combined.

The second calculation considers only the cost of controlling parthenium in terms of herbicides and labour (ie without fertilizers), which results in an average of 1% of the value of the wheat crop being spent to control parthenium.

However, when interpreting these results, both the initial assumptions and the very small sample size (these results are based on the responses of only 24 farmers who provided enough economic information) must be considered.

In the farming context, controlling weeds in general is considered a necessity accepted by farmers, and in most instances, it is conducted by themselves and/or other family members. Importantly, these farmer/family labour costs have not been accounted for in this study. This is compounded by the fact that many rural activities undertaken by women in the household in Pakistan, which include weeding and other field activities, are not properly accounted for in economic terms, and that women even earn 25% less than men when employed as professional hired farm hands (Tsegaye et al., 2018). It is likely that, if the time and resources spent by farmers and their families on controlling parthenium in Pakistan are properly considered, the real impact of this weed will become apparent. Parthenium also has wider livelihood implications, such as education ramifications for school aged children, who are likely to assist with this task and will be taken out of school at key weeding periods. In addition, there are serious health implications resulting from contact with this allergenic weed, including respiratory and skin problems. We can therefore assert that, in reality, the actual social and economic cost of controlling parthenium is likely to be much higher than this rudimentary economic estimate suggests.

Awareness of biological control

Of the respondents who answered the question of whether they had heard of biological control (n=156), only 24% said they had heard of the term. Those that had heard of the term thought it referred to “beneficial insects”.

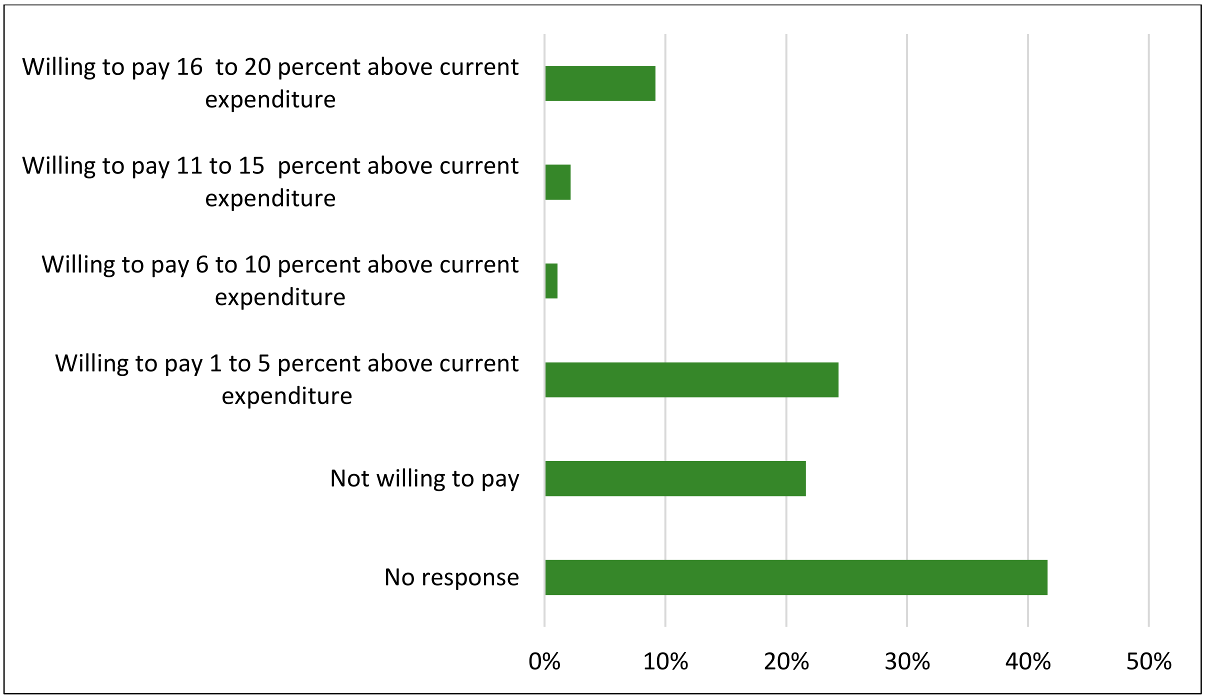
When farmers were asked whether they would be willing to use a biological control option to control parthenium if such an option were available, almost 60% stated they would be willing to use this approach, with only a small proportion (16%) stating they would not be willing (25% did not respond to the question).

Over half of the respondents (56%) stated they would be willing to use an alternative to a chemical if it worked, and only 11% would not use a chemical alternative (33% did not answer, either through lack of knowledge or because they did not want to).

In addition, 51% were willing to pay more for an alternative to a chemical that was just as effective as the one they used now if it had fewer health implications, with only 14% not willing to pay more (35% not responding). When asked how much they would be willing to pay, 24% said they would be willing to pay 1% to 5% above their current expenditure on chemicals (Figure 88).

It is worth noting that over 40% of respondents did not answer this particular question for a variety of reasons that would need to be investigated further. This possibly demonstrates the need for increased awareness of non-synthetic chemical options, as well as a better understanding of control economics regarding biopesticides.

Figure 8: Willingness to pay



Note: *The amount above current chemical expenditure farmers would be willing to pay for an alternative to a chemical just as effective as the one they currently use but with fewer health implications*

3. Parthenium management best practices

Having achieved the status of a major weed in different parts of world, parthenium poses a threat to natural and agricultural systems and impacts negatively on the wellbeing of humans and animals. As described above, parthenium has a long-lived seed bank, an innate ability to reach reproductive maturity rapidly and multiple methods of dispersal. Its management therefore has to be implemented on a regular and sustained basis to achieve a desired level of control, while making every attempt to limit the risk of reintroduction. Different management strategies have been employed in different countries, and these have been extensively highlighted in Adkins et al. (2019). This section therefore only briefly discusses the salient features for each control method.

3.1 Physical and cultural

Manual uprooting of parthenium has proven to be effective in reducing the weed's population and its impacts, especially when undertaken before flowering and/or seeding (Manpreet et al., 2014). This involves hand-weeding and hoeing before bloom in croplands (Getachew, 2017) and is commonly used in India as a first line management strategy. Indeed, the results from the survey in the previous section show its popularity: over a third of respondents used hand-weeding techniques, and it was considered the most effective methods of control. However, hand-weeding requires manual labour, and as farm workers become increasingly aware of the health risk involved in handling this weed, they are less likely to want to remove it (Gnanavel, 2013). Cutting and slashing of parthenium plants should be undertaken before flowering, as doing it after will further aid dispersal (Kumari, 2014), but this is laborious and time-consuming, and could prove costly. An economic study conducted to estimate the costs of managing parthenium in India has shown that it would cost INR 182 000 m per year, or approximately US $2 bn (Sushikumar and Varshney, 2010), to control parthenium using manual/physical means.

Burning has been used as a control strategy against parthenium in some countries, but the approach has been limited, making it ineffective. Vogler et al. (2006) have shown that fire was not an effective control technique in Australia, and could in fact make the problem worse. In addition, burning requires large quantities of fuel and destroys other economically important plants in the vicinity (Ray and Gour, 2012).

Manipulation of sowing time and the seed rate of crops is one cultural strategy that has been used to manage parthenium and its impacts (Getachew, 2017). Early sowing before the rains begin can give a head-start to the crop, allowing it to become established before the weed germinates. Conversely, when sowing is delayed, the emerged weed plants can be killed while preparing the land for sowing. Use of a higher crop seed rate will help increase competition through shading effect, or by reducing the space available for the weed. Land preparation practices also bring the buried seeds to the surface, further reducing the seed bank. Exposed seeds can additionally be destroyed by adverse conditions.

Mulching has been used in weed suppression in some countries, and Nishanthan et al. (2013) have shown that mulching with *Gliricidia sepium* leaves was able to supress the growth and development of parthenium and to increase yield in tomato plots in Sri Lanka. Apart from its role in weed suppression, mulch also conserves moisture, lowers surface temperature, fertilizes the soil, offers protection from soil erosion and improves soil quality.

Planting of other competitive plants (eg *Cenchrus ciliaris, Clitorea terneata* and *Digitaria milanjiana*) to suppress parthenium has been suggested by some researchers (O'Donnell and Adkins, 2005), but its practicability has been limited, since parthenium is mostly a wastelands weed.

3.2 Chemical control

This involves the use of herbicides in bringing down the population of parthenium. Different chemicals with different active ingredients and modes of action have been used in the control of parthenium (Abdulkerim-Ute and Legesse, 2016; Adkins and Shabbir, 2014; Manpreet et al., 2014; Mishra and Bhan, 1996; Sushilkumar, 2014; Vila-Aiub et al., 2008). Chemicals can be used when the main goal of the management strategy is the eradication and containment of parthenium. They have been used either as a pre- or as a post-emergent treatment. The herbicide approach is only financially feasible on high-value crops and in other circumstances, such as along roadsides, in public parks or on small areas (Adkins and Shabbir, 2014). Control over vast areas (eg wastelands, rangelands or within forests) has been found not to be cost-effective (Sushikumar and Varshney, 2010). The timing of herbicide application is critical for the method to be effective. Parthenium should be treated before flowering and seed-setting (Getachew, 2017). Paraquat, atrazine, glyphosate, flumioxazin, metribuzon, metsulfuron-methyl and diquat are the common chemicals used in parthenium control, and the efficacy of different dosing and application regimes has been reported for each chemical. In pasture and grasslands, selective herbicides that do not kill other species are recommended, as the competition from growing grasses is important to limit recolonization by parthenium (Adkins and Shabbir, 2014). Spraying of a solution of common salt (sodium chloride) at a 15% to 20% concentration in open wastelands, in non-cropped areas and along railway tracks and roadsides has been found to be effective (Gnanavel, 2013).

Other factors in addition to cost limit the adoption of using chemicals for parthenium control. Environmental (including persistence in the soil), human and animal health hazards top the list (Manpreet et al., 2014). The resistance of this weed to glyphosate has also been reported (Vila-Aiub et al., 2008).

3.3 Natural products

Some extracts, residues and essential oils of many allelopathic plant species (herbs, grasses and trees) can reduce the germination and/or growth of parthenium (Singh et al., 2003; Javaid et al., 2010). Similarly, the metabolites of many fungal species can also have herbicidal effects on the germination and growth of parthenium (Javaid et al., 2010). However, the commercialization or use of natural products on a large scale is not widespread. This is attributed to complexities in the structure of the allelochemicals, the lack of cost-effectiveness, mammalian toxicology, poor results in field trials, rapid degradation, short-lived effects and intellectual property rights issues (Singh et al., 2003).

3.4 Biological control

Parthenium has been a candidate for various biocontrol approaches for over 50 years, including the use of microbial pathogens and insects (Dhileepan et al., 2018; Manpreet et al., 2014; Ray and Gour, 2012). Two main strategies are employed in biocontrol: the classical approach (the introduction of host-specific natural enemies from the native range with the intention of producing self-sustaining populations that exert vegetative and/or reproductive suppression) and the augmentative approach (where the populations of already-present natural enemies are increased by mass rearing to promote their densities or dispersal capabilities). Both strategies have been used in the management of parthenium in different regions of the world. Several countries (Australia, South Africa, India, Tanzania, Ethiopia, Uganda and Sri Lanka) have released biological agents against parthenium, and others (Kenya, Pakistan, Nepal, China and Ethiopia) have agents that have unintentionally arrived there (Adkins and Shabbir, 2014; Javaid and Shabbir, 2006).

Biological control of parthenium was initiated in the 1970s. Since then, nine insect species and two rust species have been introduced in different parts of the world (Table 2) (Abdulkerim-Ute and Legesse, 2016; Dhileepan, 2009; Dhileepan et al., 2018; Evans, 1997;

Sushilkumar, 2014), where they have shown good potential to control the weed. Follow-up studies and assessments in Australia have shown that insects *Zygogramma bicolorata* (*Z. bicolorata*), *Epiblema strenuana* and the rust *Puccinia abrupta* (*P. abrupta*) var. *partheniicola* have established and are having a significant impact on parthenium, leading to an increase in the grass production (Dhileepan, 2007). Other agents with establishment but limited dispersal are *Listronotus setosipennis, Smicronyx lutulentus, Bucculatrix parthenica* and *Puccinia melampodii* (Dhileepan and McFadyen, 1997). The winter rust, *P. abrupta* var. *partheniicola*, has been found to cause a significant reduction in plant height, the number of leaves and branches and the total biomass of parthenium in Ethiopia (Taye et al., 2002).

The leaf-feeding beetle, *Z. bicolorata*, was introduced in India (Dhileepan, 2009) and has become established, with a population attaining damaging levels within three years. It is capable of causing a defoliation of 85% to 100%, resulting a reduction of up to 99.5% of parthenium in the Bangalore region (Jayanth and Visalakshy, 1994) and other areas. In South Africa, parthenium biocontrol initiatives were started in 2003 with similar agents, and have shown some level of success (Strathie et al, 2011). The biological control of parthenium can prove successful, especially when multiple agents are used in combination, as has been the case in Australia, where nine insect agents and two pathogens have been released (Dhileepan et al., 2018). Other countries where parthenium is invading should consider biological control as an important control strategy for management through release of a combination of agents.

Z. bicolorata was first recorded in Pakistan by Javaid and Shabbir (2007) in March 2006 during surveys in the Punjab region, specifically around Lahore and Changa Manga Forest. Based on minor feeding on sunflowers in India (Evans, 1997), Javaid and Shabbir (2007) suggest additional testing of this agent before mass releases in Pakistan are made. Feeding on sunflowers was ultimately rarely observed, and sporadic feeding mostly occurred on plants in very close proximity to parthenium, as reported by the Parthenium Fact-Finding Committee of the Indian Council of Agricultural Research (Gupta et al., 2004). Since 2006, however, both parthenium and *Z. bicolorata* have extended their range to Pakistan, and these additional tests are probably no longer warranted.

We can expect significant reductions, not only in biomass, plant height and density, but also in flower production and seed-set following the mass release of biocontrol agents in affected countries. In central Queensland, for example, *Z. bicolorata* inflicted defoliation of 91% to 100%, reducing weed density by 32% to 93%, plant height by 18% to 65%, plant biomass by 55% to 89%, flower production by 75% to 100%, the soil seed bank by 13% to 86% and seedling emergence in the following season by 73% to 90% (Dhileepan et al., 2000). Similar impacts have been observed in other areas in India (Kumar, 2000; Dhiman and Bhargava, 2005; Jaipal, 2008). The redistribution of *Z. bicolorata* into suitable climatic regions in the Punjab region where parthenium is present is warranted.

According to King (2008), *Z. bicolorata* requires relatively warm temperatures and high humidity to remain active. *Z. bicolorata* is present in the northeast and northwest districts of Punjab (Shabbir et al., 2012), as predicted by CLIMEX models (Dhileepan and Senaratne, 2009). Areas in the southern parts of Punjab Province also seem climatically suitable for *Z. bicolorata*, but the beetle has not been observed there as of 2012. A full survey of the study area in Punjab Province needs to be conducted to determine the extent of *Z. bicolorata* distribution and the distribution and density of parthenium.

3.5 Integrated parthenium management

Several countries have used different control strategies in the management of parthenium in an integrated manner, on the basis that one method alone is unlikely to be sufficient for sustainable control. Varied success rates/levels have been reported regarding this approach. For instance, a study in Australia to evaluate the combined effect on the management of parthenium of biological control using *Epiblema strenuana* with plant competition (using two competitive pasture plant species, butterfly pea and buffel grass) found that they were synergistically able to reduce the biomass of parthenium by between 62% and 69% in pasture lands increasing grass production (Shabbir et al., 2015; Shabbir et al., 2013). Kohli et al. (2006) report a successful integrated approach against parthenium in India involving community efforts and other land management strategies, which was more effective than using individual control approaches in isolation.

Regional working groups (eg the Parthenium Action Group in Australia) in the development of site-specific integrated management plans have shown good results when deployed against parthenium (Adkins and Shabbir, 2014). An online network (https://apwss.org/apwss-ipawn.htm) linking different working groups established at the University of Queensland in 2009, with members across 30 countries, has acted as a source of exchange of information on parthenium. Information has been provided on topics of new research, identification kits and best management practice guides for parthenium (Adkins and Shabbir, 2014)

Table 2: History and current status of parthenium biological control agent use

Biological control agents	Country of introduction	Source country	Year imported/ reported	Year release approved/commenced	Establishment status
Lepidoptera*: *Tortricidae					
Epiblema strenuana Walker	Australia	Mexico	1982	1982	Widespread and abundant
	India	Australia	1985	Not released	
	Sri Lanka	Australia	2003	2004	Unknown
	Papua New Guinea	Australia	2004	Colony failed	Localized
	Vanuatu	Unknown	2014	No deliberate release	
	South Africa	Australia	2010 and 2018	Testing in progress	
	China	Australia	1990	Released on ragweed	Established on parthenium in Guangxi Province
Platphalonidia mystica (Razowski and Becker)	Australia	Argentina	1991	1992	Localized
Lepidoptera*: *Sessidae					
Carmenta nr *ithacae* (Beutenmüller)	Australia	Mexico	1996	1998	Widespread and abundant
Lepidoptera*: *Bucculatricidae	South Africa	Australia	2014	Testing in progress	
Bucculatrix parthenica Bradley	Australia	Mexico	1983	1985	Widespread
Coleoptera*: *Chrysomelidae					
Zygogramma bicolorata Pallister	Australia	Mexico	1980	1981	Widespread and abundant
	India	Mexico	1983	1984	Widespread and abundant
	Pakistan	India	2003	No deliberate release	Widespread
	Nepal	India	2009	No deliberate release	Widespread and abundant
	South Africa	Australia	2005	2013	Localized establishment
	Ethiopia	South Africa	2007	2013	No establishment
	Tanzania	South Africa	2013	2013	No establishment
	Uganda	South Africa	2018	2018	Unknown
Coleoptera*: *Curculionidae					
Listronotus setosipennis Hustache	Australia	Argentina and Brazil	1981	1982	Abundant and widespread
	South Africa	Australia	2003	2013	Widespread establishment

	Ethiopia	South Africa	2007	2013	No large-scale releases
	Uganda	South Africa	2018	2018	Unknown
Smicronyx lutulentus Dietz	Australia	Mexico	1980	1981	Abundant and widespread
	India	Australia	1985 and 2018	Colony failed in 1985.	
	South Africa	Australia	2010	Testing in progress	Widespread establishment
	Ethiopia	South Africa	2015		
Conotrachelus albocinereus Fiedler	Australia	Argentina	1992	1995	Localized
Homoptera*: *Delphacidae					
Stobaera concinna (Stål)	Australia	Mexico	1982	1983	Localized
Basidiomycotina*: *Uredinales					
Puccinia abrupta partheniicola Parmelee	Australia	Mexico	1991	1991	Localized and abundant
	Ethiopia	Unknown	1997	No deliberate release	Widespread and abundant
	India	Unknown	1980	No deliberate release	Localized
	South Africa	Unknown	1995	No deliberate release	Localized
	Nepal	Unknown	2011	No deliberate release	Localized
	China	Unknown	2007	No deliberate release	Localized
Puccinia xanthii var. *parthenii-hysterophorae*	Australia	Mexico	1999	1999	Widespread
Seier, H.C. Evans and Á. Romero	Sri Lanka	Australia	2003	Unknown	Unknown
	South Africa	Australia	2004	2010	Localized

Source: *Dhileepan and Strathie, 2009; Dhileepan and McFadyen, 2012; K. Dhileepan, unpublished data; L. Strathie, unpublished data; S. Adkins, unpublished data; S. Tang, unpublished data. Table adapted from Dhileepan et al., 2018*

3.6 Public awareness campaigns

Public knowledge about parthenium and its environmental, health and ecological hazards currently remains limited around the world. Such knowledge can, however, be an important tool in the management of this weed. Successful management of invasive species involves the active participation of the local communities (Batish et al., 2004). Farmers, students and the general public should be taught about the basic biology and ecology of the weeds so that they can recognize them as seedlings, removing them at an early growth stage and putting the land to proper management practices. In Nepal, conscious efforts have been undertaken to create public awareness on parthenium and to bring members of the public on board to own and participate in parthenium control projects around different municipalities. A parthenium public awareness campaign was able to save a heavily-infested roadside (300 m by 11 m) in Chandigarh, India (Batish et al., 2004); after having been educated on the weed biology and impacts, the public was able to participate in the manual removal of the weed and in restoring the roadside with native grass. This served as a model for other cities.

It is also important to increase awareness of different, safer and more sustainable management strategies, such as biological control. In a recent survey in Pakistan, a quarter of respondents had heard of biological control, over half were willing to use an alternative to chemical control measures, and over a quarter were willing to pay more for such an alternative.

3.7 Legislative control

Early, effective and co-ordinated prevention of entry of parthenium in new ranges is the most cost-effective management strategy (Dhileepan, 2009). Addressing the pathways related to entry and spread (contaminated vehicles, machinery, livestock, grain and other products) of parthenium with legal instruments (laws) is a crucial aspect of the sustainable management of parthenium. A few countries have declared parthenium a noxious weed; trading, distributing and spreading it is prohibited. An example of this is the Australia Biosecurity Act 2014, which prohibits the sale, intentional movement or distribution of parthenium within Australia; for areas where parthenium is considered a high risk weed but where it has not become well established, the legislation focuses on reporting and eradicating outbreaks and preventing further introductions. Territories and landowners are also mandated to control it and/or report it to the relevant state authorities immediately after spotting it (Adkins and Shabbir, 2014). In Queensland, vehicles travelling from infested to parthenium-free areas are required to clean their vehicles at several “wash-down” facilities. It is also legally mandatory for suppliers of stock, machinery, soil, water or other products from areas known to be infested with parthenium to declare that the material they supply is parthenium-free (Dhileepan, 2009; Parsons and Cuthbertson, 1992).

Despite the widespread distribution of parthenium in India, it has only been declared a noxious weed in Karnataka state (Dhileepan, 2009) under the Karnataka Agricultural Pest And Disease Act, 1969 (Sushilkumar, 2014). Due to the lack of follow-through and co-ordination, however, the impact of this legislation on the management of parthenium in the region has been minimal. Parthenium has also been declared a noxious weed in South Africa and Sri Lanka, which have also strictly prohibited the movement of adult plants to areas that are currently parthenium-free (Dhileepan, 2009). It is nevertheless worth noting that, despite the widespread distribution of parthenium in the natural and agricultural systems of a variety of countries, little or no nationwide legislation exists in those countries to prevent the introduction and/or further spread of the weed. It is hoped that the known impacts in various countries will be a motivation for more countries to introduce preventative legislation against parthenium.

3.8 Recommendations for the control of parthenium

Parthenium is currently considered a “superior weed” ranking in the top five weeds worldwide. As described above, it is extremely prolific, which suggests that any management approach will have to keep up with the pace at which it is spreading to limit its widespread impact on various facets of the economy and the social fabric of affected communities.

The sooner parthenium is managed once a country has been invaded, the lower the impacts. What we have learned, however, is that any one management strategy alone is unlikely to solve the problem. One size does not fit all when it comes to the management of parthenium, and management strategies need to be adapted to local conditions and continuously adjusted based on information gathered during the management process. Based on the management strategies described above, the following recommendations are proposed to the wider range of stakeholders in Pakistan and Central West Asia for the integrated management of parthenium under three different scenarios.

When parthenium has not yet arrived:

- increase inspection of vehicles, livestock and seed and feed lots to manage parthenium seed movement through this pathway. Preventing parthenium from coming into a new area is much cheaper than eradication or control once it has invaded
- create awareness at nurseries and floriculturists regarding weed identification, and restrict the introduction of floral products from areas where the weed is present
- engage in effective co-ordination between working groups in different countries to learn from each other and to create awareness about parthenium before it can arrive

When parthenium has just arrived:

- invaded countries should develop and implement a parthenium management strategy to contain it and slow its further spread
- communities should be informed how to identify the weed, and the community should be engaged to eradicate it through chemical and mechanical means
- legislative measures should be enacted, for example declaring parthenium to be a noxious plant, to ensure public and political support for its eradication through sufficient budget allocation
- parthenium should be manually uprooted, particularly before it flowers and especially in small and isolated areas; workers should wear protective clothing to prevent allergic reactions
- chemical control of parthenium should be engaged in along roadsides, in public parks or on private properties to eradicate the weed
- regulators should facilitate the registration and promotion of biological control agents through classical and augmentative biological control efforts to prevent the weed becoming widespread

When parthenium has already arrived and is firmly established:

- declare parthenium to be a noxious plant and ensure public and political support for its management through sufficient budget allocation
- cut and slash parthenium growth along roadsides; this should be destroyed immediately to destroy the seed

- plough and mulch while preparing land for planting with a crop or improved pasture, particularly at the vegetative stage before flowering occurs
- survey for natural enemies that are already present and that can be used in the augmentative biological control of parthenium
- establish mass rearing facilities and undertake release efforts of natural enemies that feed on parthenium; regulators should facilitate the registration and promotion of biological control agents through classical and augmentative biological control efforts
- chemical control should be engaged in, although this may not be cost-effective over vast areas such as wastelands, rangelands and lower value field crops or within forests
- develop a technical guidance standard for herbicide use in parthenium management: procurement, risk reduction and resistance management

4. National and local management recommendations for Pakistan

Parthenium has firmly taken hold in Central West Asia, including vast areas of Pakistan, and although it has not yet reached its full potential in Pakistan (see section 1.3.2). As a country, Pakistan is in the process of taking action in the management of parthenium to mitigate the impacts of the weed at a social, economic and environmental level. For the moment, the management of the weed relies almost exclusively on hazardous chemical inputs and costly labour to manually remove it from the fields and roadsides in rural and urban areas. Awareness should be raised regarding the dangers of the weed and of the indiscriminate use of herbicides regarding the environment and human health. To avoid side-effects from the intensive use of herbicides and to lower the risk of resistance, sustainable integrated pest management (IPM) strategies of the kind that are already widely utilized in Australasia and Southern Africa need to be promoted in Central West Asia, based on biological control whenever possible.

Based on the information available, as well as on feedback from stakeholder workshops, we have developed a set of recommendations and an action plan for the management of parthenium in the short, medium and long term, specific to Pakistan and Central West Asia. Recommendations include the following.

Short-term aims:

- to gather systematic baseline data on socioeconomic- and human health-related impacts
- to understand the knowledge and perceptions of biological control
- to understand the floral industry's value chain, identified as a crucial stakeholder involved in the spread and establishment of parthenium across the country
- to concentrate on the development of containment strategies, focusing on households and provincial quarantine guidelines
- to continue the country's valuable strategy of sensitizing decision makers in various sectors to raise awareness of the issue of parthenium and other invasive species

Medium-term aims:

- to build on existing biological control protocols and finalize a state-of-the-art quarantine testing facility to research the impacts biological control agents may have on parthenium growth
- to implement the large-scale release of an existing biological control agent to measure its impact on the weed, as well as corresponding crop yields and income impacts
- to tackle the spread of parthenium by stepping up efforts to regulate the spread of this noxious weed through tougher legislation and more targeted policies regarding quarantine and pathways
- to engage the floral industry to discuss standards of practice, and to conduct an in-depth review of Pakistan's Animal and Plant Quarantine Act to understand how to engage more on multisectoral issues such as invasive species
- to develop a definitive and practical guide to IPM parthenium control, explaining the importance of preventive and sustainable measures to reduce the economic and environmental cost of control
- to develop and run a community of practice to strengthen communication and ownership of invasive species issues

- to raise awareness of the parthenium issue in urban and rural environments, and to run targeted campaigns within schools and universities (either through curricular or simple awareness-raising on campus)

Long-term aims:

- to focus on biological control releases as part of a dedicated IPM strategy to reduce the impact of parthenium
- to engage and enforce changes within the floral industry's value chain regarding the use of parthenium
- to develop a parthenium special issue in a recognized Pakistani academic journal, and to develop a "centre of excellence" on invasive species dedicated to the research and implementation of invasive species projects

Table 3: Parthenium management Action Plan

Version 2 (November 2018)

COMPREHENSIVE ACTION PLAN FOR THE MANAGEMENT OF PARTHENIUM IN PAKISTAN – November 2018			
Collaborators involved: MNS-University of Agriculture, Multan; Ayub Research, Faisalabad; Pest Warning Punjab, Lahore; CABI; Young Professional for Agricultural Research Development; Department of Agricultural Extension, KPK; National Agricultural Research Centre; Pakistan Agricultural Research Centre; Nuclear Institute for Food and Agriculture; University of Agriculture Faisalabad; Ministry of Climate Change; Punjab University, Lahore; Pakistan Natural History Museum			
SHORT-TERM ACTIVITIES			
List as accomplished so far: to understand chemical control registration processes for parthenium in Pakistan to develop a Weed Management Decision Guide for parthenium in Pakistan to develop and initiate a communication strategy to generate awareness of parthenium at different levels and to detect its presence across the country to initiate development of risk assessment documents for the import of further biological control agents for research trials			
#	Activity	Timeline	Monitoring activities and evaluation of impacts
1	Gather evidence of parthenium's socioeconomic and human health impacts from a gendered perspective	June 2019	Baseline figures obtained through field surveys; report written (through evidence note); compare future results to current baseline
2	Understand stakeholder perceptions of biological control and the willingness to pay for biological pesticides to control invasive plants from a gendered perspective	June 2019	Baseline figures obtained through field surveys; report written (through evidence note); compare future results to current baseline
3	Understand parthenium's pathways of spread and establishment across the country	June 2019	Analysis of pathways conducted to serve as a baseline for reporting over time for impact
4	Investigate florists' use of parthenium and the market processes behind it	June 2019	Market research and value chain analysis; report written; compare future results to baseline processes for impact

5	Develop a containment strategy through official guidelines and protocols to prevent spread from a domestic quarantine aspect	June 2019	Strategy written at household and provincial level
6	Sensitize high level heads of various sectors, including human health and education	June 2019	High level awareness-raising campaign and discussions through meetings and lobbying
MEDIUM-TERM ACTIVITIES			
List as accomplished so far: to develop protocols to mass rear and investigate the effect of multiple biological control agents on parthenium control			
7	Instigate discussions with the chemical industry about the registration of safe and effective herbicides, utilizing “willingness-to-pay” study’s findings	End 2019	Continued discussions with regulator and private sector stakeholders; willingness to pay studies to be conducted contributing to debate
8	Research crop yield changes in relation to parthenium infestations with and without natural enemies (*Z. bicolorata* trial)	End 2019	Field trials conducted; evaluation in the field over multiple seasons
9	Conduct national awareness campaign focusing on key messages regarding spread and effective control practices in urban and rural environments, as well as private arenas (ie the floral industry)	End 2019	Awareness-raising campaign conducted; determine change in knowledge and behaviour through follow-up surveys
10	Initiate in-depth review of Pakistan’s Animal and Plant Quarantine Acts to understand what needs to be amended	End 2019	Review to be conducted, with consultancy to determine possible changes; contribute to debate and legislative changes
11	Discuss the process needed with appropriate parties to amend acts from the legislation and policy side	End 2019	Discussions on legislative changes conducted; contribute to act of change
12	Discuss possible amendments to industry standards with floral industry stakeholders for the use of parthenium	End 2019	Discussions with floral industry stakeholder conducted; contribute to amendments to industry standards
13	Instigate the process for legislative and policy amendments, as well as voluntary industry sector standards and agreements	End 2019	Discussions with floral industry stakeholder conducted; contribute to amendments to industry standards

14	Draw up a definitive guide to IPM parthenium control practices and their effectiveness in the field	End 2019	Guide produced and disseminated to relevant stakeholders in various formats along the value chain; contribute to a change of behaviour and knowledge (surveys conducted to establish change)
15	Link parthenium data collection to traditional and innovative monitoring activities ("remote sensing, crop reporting services, etc.)	End 2019	Parthenium data collected can feed into larger monitoring initiatives; impacts of parthenium management plan can be monitored
16	Process established to gather long-term socioeconomic impacts of weeds	End 2019	Discussions with collaborators ongoing and data collated from various activities to capture socioeconomic impact of weeds
17	Create community of practice and data sharing platform guidelines	End 2019	Develop knowledge-sharing mechanism among action plan collaborators; collate anecdotal evidence to explain how this has increased awareness and activities over time
18	Research the integration of invasive species awareness and biodiversity resilience into the school/higher education curricula or extracurricular activities in Pakistan	End 2019	Discussions with universities to integrate invasive species related modules into their curriculum; contribute to more awareness of multisectoral issues around invasive species
19	Build and use a mass rearing facility for two biological control agents for parthenium and other invasive weeds in collaboration with the public and private sector	End 2019	Quarantine facility built; contribute to development and research of greater biocontrol practices for invasive species
20	Implement large-scale release of biological control agents in areas affected by parthenium	End 2019	Release conducted and report written; impact on yield and incomes to be researched over time
21	Create a steering committee to review planned activities, measure progress, review funding situations for invasive species management, etc.	End 2019	Steering committee formed with key stakeholders to deliberate on invasive species; meetings minuted and reports

			developed; impact on decision making at a high level through anecdotal evidence
LONG-TERM ACTIVITIES			
22	Investigate changes in the actions of the floral industry regarding the use of parthenium, and the resulting impacts	End 2020	
23	Investigate the effect of multiple biological control agents on parthenium control in Pakistan	End 2020	
24	Create a parthenium special issue in a Pakistani publication	End 2020	
25	Suggest legislative and policy amendments to fit into Pakistani legislation	End 2020	
26	Develop case studies and other communication materials for various stakeholders to disseminate lessons learned	End 2020	
27	Initiate the development of a centre of excellence on invasive species	End 2020	
28	Utilize innovations in the large-scale monitoring of weeds and associated biological control agents	End 2020	
29	Review awareness campaign successes and failures regarding parthenium	End 2020	
30	Build academic modules centred around awareness of invasive species and biodiversity resilience	End 2020	
31	Develop in-depth communication tools to produce a two-way information system for collecting data on parthenium and invasive species spread, as well as for the delivery of management advice (citizen science; app development; mass extension)	End 2020	

References

Abdulkerim-Ute, J. and Legesse, B. (2016). *Parthenium hysterophorus* L.: distribution, impact, and possible mitigation measures In Ethiopia. *Tropical and Subtropical Agroecosystems, 19*, 61-72.

Adkins, S. and Shabbir, A. (2014). Biology, ecology and management of the invasive parthenium weed (*Parthenium hysterophorus* L.). Pest Management Science, *70*(7), 1023-1029. https://doi.org/10.1002/ps.3708

Adkins, S. W., Shabbir, A. and Dhileepan, K. (2019). *Parthenium Weed: Biology, Ecology and Management*. CABI. doi: 10.1079/9781780645254.0000

Anwar, W., Khan, S.N., Tahira, J.J. and Suliman, R. (2012). *Parthenium hysterophorus*: an emerging threat for *Curcuma longa* fields of Kasur District, Punjab, Pakistan. *Pakistan Journal of Weed Science Research*, *18*, 91-97.

Ayele, S. (2007). The impact of parthenium. MSc Thesis, Haramaya University, Ethiopia.

Ayele, S., Nigatu, L., Tana, T. and Adkins, S. W. (2013). Impact of parthenium weed (*Parthenium hysterophorus* L.) on the above-ground and soil seed bank communities of rangelands in Southeast Ethiopia. *International Research Journal of Agricultural Science and Soil Science*, *3*(7), 262-274.

Bajwa, A. A., Chauhan, B. S., Farooq, M., Shabbir, A. and Adkins, S. W. (2016). What do we really know about alien plant invasion? A review of the invasion mechanism of one of the world’s worst weeds. *Planta, 244*(1), 39-57.

Batish, D. R., Singh, H. P., Kohli, R. K., Johar, V. and Yadav, S. (2004). Management of invasive exotic weeds requires community participation. *Weed Technology*, *18*(sp1), 1445-1449.

Beyene, H., Gebrehiwot, L., Nigatu, L., Zewdie, K. and Regassa, S. (2013) Impacts of parthenium (*Parthenium hysterophorus*) on the life of Ethiopian farmers. *Ethiopian Journal of Weed Management*, *6*, 1-14.

BioNet-Eafrinet (2018). Invasive plants key and fact sheets. Retrieved from http://keys.lucidcentral.org/keys/v3/eafrinet/index.htm

Blackmore, P. J. and Johnson, S. B. (2010). Continuing successful eradication of parthenium weed (Parthenium hysterophorus) from New South Wales, Australia. In: *Proceedings of the 17th Australian Weeds Conference*. Christchurch, NZ: New Zealand Plant Protection Society (pp. 382-385).

Brunel, S., Panetta, D., Fried, G., Kriticos, D., Prasad, R. et al. (2014). Preventing a new invasive alien plant from entering and spreading in the Euro-Mediterranean region: The case study of Parthenium hysterophorus. *EPPO Bulletin*, *44*(3), 479-489. https://doi.org/10.1111/epp.12169

CABI, 2018. *Parthenium hysterophous*. In: *Invasive Species Compendium*. Wallingford, UK: CAB. Retrieved from www.cabi.org/isc

Chippendale, J. F. and Panetta, F. D. (1994). The cost of parthenium weed to the Queensland cattle industry. *Plant Protection Quarterly*, *9*(2), 73-76.

Dale, I.J. (1981). Parthenium weed in the Americas. *Australian Weeds*, *1*, 8-14.

Dhileepan, K. (2007). Biological control of Parthenium (*Parthenium hysterophorus*) in Australian Rangeland translates to improved grass production. *Weed Science*, *55*(05), 497-501. https://doi.org/10.1614/WS-07-045.1

Dhileepan, K. (2009). Managing parthenium weed across diverse landscapes: prospects and limitations. In *Management of Invasive weeds*. Dordrecht: Springer (pp. 227-259).

Dhileepan, K., McFadyen, R., Strathie, L. and Khan, N. (2018). Biological control. In: Adkins, S., Shabbir, A. and Dhileepan, K. eds. *Parthenium Weed: Biology, Ecology and Management*. CABI, UK (pp. 131-156).

Dhileepan, K. and Strathie, L. (2009). *Parthenium hysterophorus* L. (Asteraceae). In: Muniappan, R., Reddy, G. and Raman, A. eds. *Biological control of tropical weeds using arthropods*. Cambridge: Cambridge University Press (pp. 274-318).

Dhileepan, K. and McFadyen, R. E. (1997). Biological control of parthenium in Australia: progress and prospects. In: *Proceedings of the First International Conference on Parthenium Management*, vol. 1. University of Agricultural Sciences (pp. 40-44).

EPPO (2014). *Parthenium hysterophorus* L. *Asteraceae* – Parthenium weed. *EPPO Bulletin*, *44*(3), 474-478. https://doi.org/10.1111/epp.12168

EPPO (2018). PQR database. Paris: European and Mediterranean Plant Protection Organization. Retrieved from http://www.eppo.int/DATABASES/pqr/pqr.htm

Evans, H. C. (1997). *Parthenium hysterophorus*: a review of its weed status and the possibilities for biological control. *Biocontrol News and Information*, *18*, 89N-98N.

FAO and WHO (2014). *The International Code of Conduct on Pesticide Management*. Rome, Italy.

Fessehaie, R., Chichayibelu, M. and Hailegeorgis, M. (2005). Spread and ecological consequences of Parthenium hysterophorus in Ethiopia. *Arem (Ethiopia)*.

Getachew, M. (2017). Threats and Management Options of Parthenium (*Parthenium hysterophorus* L.) in Ethiopia. *Agricultural Research and Technology*, *10*(5). https://doi.org/10.19080/ARTOAJ.2017.10.55579

Gupta, O. P. and Sharma, J. J. (1977). Parthenium menace in India and possible control measures. *FAO Plant Protection Bulletin*, *25*(3), 112-117.

Gnanavel, I. (2013) *Parthenium hysterophorus* L.: A major threat to natural and agro eco-systems in India. *Science International*, *1*, 186-193.

Henderson, L. (2001). *Alien Weeds and Invasive Plants (Plant Protection Research Institute Handbook No. 12)*. Pretoria: Agricultural Research Council.

Javaid, A., Shafique, S., Kanwal, Q. and Shafique, S. (2010). Herbicidal activity of flavonoids of mango leaves against *Parthenium hysterophorus* L. *Natural Product Research*, *24*(19), 1865-1875.

Jayachandra, J. (1971). Parthenium weed in Mysore State and its control. *Current Science*, *40*, 568-569.

Jayanth, K. P. and Visalakshy, P. N. G. (1994). Dispersal of the parthenium beetle *Zygogramma bicolorata* (Chrysomelidae) in India. *Biocontrol Science and Technology*, *4*(3), 363-365. https://doi.org/10.1080/09583159409355345

Kaur, M., Aggarwal, N. K., Kumar, V. and Dhiman, R. (2014). Effects and management of Parthenium hysterophorus: a weed of global significance. *International Scholarly Research Notices*.

Kaur, A., Batish, D. R., Kaur, S., Singh, H. P. and Kohli, R. K. (2017). Phenological behaviour of *Parthenium hysterophorus* in response to climatic variations according to the extended BBCH scale. *Annals of Applied Biology*, *171*(3), 316-326. https://doi.org/10.1111/aab.12374

Khan, H., Marwat, K. B., Hassan, G., Khan, M. A. and Hashim, S. (2014). Distribution of parthenium weed in Peshawar valley, Khyber Pakhtunkhwa, Pakistan. *Pakistan Journal of Botany 46*, 81-90

Khan, H., Marwat, K.B., Hassan, G. and Khan, M.A. (2013). Socio-economic impacts of parthenium (*Parthenium hysterophorus* L.) in Peshawar Valley, Pakistan. *Pakistani Journal of Weed Science Research*, *19*, 275-293.

King, H. (2008). Thermal physiology and predicted distribution of Zygogramma bicolorata (Chrysomelidae), a promising agent for the biological control of the invasive weed Parthenium hysterophorus in South Africa. PhD thesis, University of KwaZuluNatal.

Kohli, R. K., Batish, D. R., Singh, H. P. and Dogra, K. S. (2006). Status, invasiveness and environmental threats of three tropical American invasive weeds (*Parthenium hysterophorus* L., *Ageratum conyzoides* L, *Lantana camara* L) in India. *Biological Invasions*, *8*(7), 1501-1510. https://doi.org/10.1007/s10530-005-5842-1

Kohli, R. K. and Daizy, R. (1994). Parthenium hysterophorus: a review. *Research Bulletin of the Panjab University, Science*, *44*(1/4), 105-149.

Kriticos, D. J., Brunel, S., Ota, N., Fried, G., Lansink, A. G. O. et al. (2015). Downscaling pest risk analyses: Identifying current and future potentially suitable habitats for Parthenium hysterophorus with particular reference to Europe and North Africa. *PLoS One*, *10*(9), e0132807.

Khurshid, S. and Nasim, G. (2012). Growth responses of *Parthenium hysterophorus* L. growing under salt stress. *Pakistan Journal of Weed Science Research*, *18*(1).

Kumar, S. and Rohatgi, N. (1999). The role of invasive weeds in changing floristic diversity. *Annals of Forestry*, *7*(1), 147-150.

Kumari, M. (2014) *Parthenium hysterophorus* L.: a noxious and rapidly spreading weed of India. *Journal of Chemical, Biological and Physical Sciences*, *4*, 1620-1628.

Mainali, K. P., Warren, D. L., Dhileepan, K., McConnachie, A., Strathie, L. et al. (2015). Projecting future expansion of invasive species: comparing and improving methodologies for species distribution modeling. *Global Change Biology*, *21*(12), 4464-4480.

Manda, H., Gouagna, L. C., Nyandat, E., Kabiru, E. W., Jackson, R. R. et al. (2007). Discriminative feeding behaviour of *Anopheles gambiae* ss on endemic plants in western Kenya. *Medical and Veterinary Entomology*, *21*(1), 103-111.

McConnachie, A. J., Strathie, L. W., Mersie, W., Gebrehiwot, L., Zewdie, K. et al. (2011). Current and potential geographical distribution of the invasive plant *Parthenium hysterophorus* (Asteraceae) in eastern and southern Africa. *Weed Research*, *51*(1), 71-84.

McFadyen, R. C. (1992). Biological control against parthenium weed in Australia. *Crop Protection*, *11*(5), 400-407.

Mishra, J. S. and Bhan, V. M. (1996). Chemical control of carrot grass (*Parthenium hysterophorus*) and associated weeds in soybean (Glycine max). *Indian Journal of Agricultural Sciences*, *66*(9), 518-521.

Narasimhan, T. R., Ananth, M., Swamy, M. N., Babu, M. R., Mangala, A. and Subba Rao, P. V. (1980). Toxicity of *Parthenium hysterophorus* L. partheniosis in cattle and buffaloes. *Indian Journal of Animal Sciences*.

Navie, S. C., McFadyen, R. E., Panetta, F. D. and Adkins, S. W. (1996). The biology of Australian weeds. 27. *Parthenium hysterophorus* L. *Plant Protection Quarterly*, *11*(2), 76-88.

Navie, S. C., Panetta, F. D., McFadyen, R. E. and Adkins, S. W. (1998). Behaviour of buried and surface-sown seeds of *Parthenium hysterophorus*. *Weed Research (Oxford)*, *38*(5), 335-341.

Navie, S. C., Panetta, F. D., McFadyen, R. E. and Adkins, S. W. (2004). Germinable soil seedbanks of central Queensland rangelands invaded by the exotic weed *Parthenium hysterophorus* L. *Weed Biology and Management*, *4*(3), 154-167.

Netsere, A. (2015) Allelopathic effects of aqueous extracts of an invasive alien weed *Parthenium hysterophorus* L. on maize and sorghum seed germination and seedling growth. *Journal of Biology, Agriculture and Healthcare*, *5*, 120-124.

Nigatu, L., Hassen, A., Sharma, J. and Adkins, S. W. (2010). Impact of *Parthenium hysterophorus* on grazing land communities in north-eastern Ethiopia. *Weed Biology and Management*, *10*(3), 143-152. https://doi.org/10.1111/j.1445-6664.2010.00378.x

Nishanthan, K., Sivachandiran, S. and Marambe, B. (2013). Control of *Parthenium hysterophorus* L. and its Impact on Yield Performance of Tomato (*Solanum lycopersicum* L.) in the Northern Province of Sri Lanka. *Tropical Agricultural Research*, *25*(1), 56-68.

Nunez, M. A. and Pauchard, A. (2010). Biological invasions in developing and developed countries: does one model fit all? *Biological Invasions*, *12*(4), 707-714.

Nyasembe, V. O., Teal, P. E., Mukabana, W. R., Tumlinson, J. H. and Torto, B. (2012). Behavioural response of the malaria vector *Anopheles gambiae* to host plant volatiles and synthetic blends. *Parasites and Vectors*, *5*(1), 234.

Nyasembe, V. O., Cheseto, X., Kaplan, F., Foster, W. A., Teal, P. E. et al. (2015). The invasive American weed *Parthenium hysterophorus* can negatively impact malaria control in Africa. *PLoS One*, *10*(9), e0137836.

O'Donnell, C. and Adkins, S. W. (2005). Management of parthenium weed through competitive displacement with beneficial plants. *Weed Biology and Management*. https://doi.org/10.1111/j.1445-6664.2005.00160.x

Pandey, D. K., Kauraw, L. P. and Bhan, V. M. (1993). Inhibitory effect of parthenium (*Parthenium hysterophorus* L.) residue on growth of water hyacinth (*Eichhornia crassipes* mart solms.) I. Effect of leaf residue. *Journal of Chemical Ecology*, *19*(11), 2651-2662.

Parsons, W. T. and Cuthbertson, E. G. (1992). *Noxious Weeds of Australia*. Melbourne: Inkata Press.

Ray, P. and Gour, H. N. (2012). Integrated Management of *Parthenium hysterophorus* L. (Asteraceae): A weed of worldwide significance. *Reviews in Plant Pathology*, *5*, 605-632.

Shabbir, A. (2013). Parthenium invasion in Rawalpindi, Pakistan. *Indian Journal of Weed Science*, *45*(4), 263-266.

Shabbir, A. (2014). Ragweed emerging a major host for the cotton mealy bug in Pakistan. *Indian Journal of Weed Science*, *46*, 291-293.

Shabbir, A. and Adkins, S. W. eds. (2010). *International Parthenium News*, *2*, July 2010.

Shabbir, A. and Bajwa, R. (2006). Distribution of parthenium weed (*Parthenium hysterophorus* L.), an alien invasive weed species threatening the biodiversity of Islamabad. *Weed Biology and Management*, *6*(2), 89–95. https://doi.org/10.1111/j.1445-6664.2006.00202.x

Shabbir, A., Dhileepan, K. and Adkins, S. W. (2012). Spread of parthenium weed and its biological control agent in the Punjab, Pakistan. *Pakistan Journal of Weed Science Research*, *18*, 581-588.

Shabbir, A., Dhileepan, K., O'Donnell, C. and Adkins, S. W. (2013). Complementing biological control with plant suppression: Implications for improved management of parthenium weed (*Parthenium hysterophorus* L.). *Biological Control*, *64*(3), 270-275.

https://doi.org/10.1016/j.biocontrol.2012.11.014

Shabbir, A., Dhileepan, K., Zalucki, M. P., O'Donnell, C., Khan, N., Hanif, Z. and Adkins, S. W. (2015). The combined effect of biological control with plant competition on the management of Parthenium weed (*Parthenium hysterophorus* L.). *Pakistan Journal of Botany*, 47(Jan.), 157-159.

Shabbir, A., McConnachie, A. and Adkins, S.W. (2019). Spread. In: Adkins, S., Shabbir, A. and Dhileepan, K. eds. *Parthenium Weed: Biology, Ecology and Management*. CABI, UK (pp. 40-56).

Shrestha, B. B., Shabbir, A. and Adkins, S. W. (2015). *Parthenium hysterophorus* in Nepal: a review of its weed status and possibilities for management. *Weed Research*, *55*(2), 132-144. https://doi.org/10.1111/wre.12133

Singh, P.K., Dixit, A., Singh, V. P. and Gogoi, A.K. (2003). On farm evaluation of herbicide for the control of parthenium and Ipomoea species under none crop situation. In: *Abstracts: Proceedings National Seminar on Alien invasive weeds in India, 27-29 April 2003*. Jorhat, India (pp. 89-90).

Stone, C. M., Witt, A. B. R., Walsh, G. C., Foster, W. A. and Murphy, S. T. (2018). Would the control of invasive alien plants reduce malaria transmission? A review. *Parasites and Vectors*, *11*(1), 1-18. https://doi.org/10.1186/s13071-018-2644-8

Strathie, L. W., McConnachie, A. J. and Retief, E. (2011). Initiation of biological control against *Parthenium hysterophorus* L. (Asteraceae) in South Africa. *African Entomology*, *19*(1), 378-392.

Sushikumar, V.J. and Varshney, G. (2010). Parthenium infestation and its estimated cost management in India. *Indian Journal of Weed Science*, *42*, 73-77.

Sushilkumar (2014). Spread, menace and management of Parthenium. *Indian Journal of Weed Science*, *46*(3), 205-214.

Tamado, T. and Milberg, P. (2000). Weed flora in arable fields of eastern Ethiopia with emphasis on the occurrence of *Parthenium hysterophorus*. *Weed Research*, *40*(6), 507-521. https://doi.org/10.1046/j.1365-3180.2000.00208.x

Tamado, T. (2001). *Biology and management of parthenium weed (Parthenium hysterophorus L.) in Eastern Ethiopia* (No. 311). Sveriges Lantbruksuniversitet (Swedish University of Agricultural Sciences).

Tamado, T., Ohlander, L. and Milberg, P. (2002). Interference by the weed *Parthenium hysterophorus* L. with grain sorghum: influence of weed density and duration of competition. *International Journal of Pest Management*, *48*(3), 183-188.

Taye, T., Gossmann, M., Einhorn, G., Büttner, C., Metz, R. and Abate, D. (2002). The potential of pathogens as biological control of parthenium weed (*Parthenium hysterophorus* L.) in Ethiopia. *Mededelingen (Rijksuniversiteit te Gent. Fakulteit van de Landbouwkundige en Toegepaste Biologische Wetenschappen)*, *67*(3), 409-420.

Timsina, B., Shrestha, B. B., Rokaya, M. B. and Münzbergová, Z. (2011). Impact of *Parthenium hysterophorus* L. invasion on plant species composition and soil properties of grassland communities in Nepal. *Flora-Morphology, Distribution, Functional Ecology of Plants*, *206*(3), 233-240.

Tsegaye, M., Drucza, K. L. and Hailemariam, M. (2018). Gender norms agency and innovation in wheat-based systems and livelihoods: synthesis report of six community case studies in Pakistan. CIMMYT, Islamabad, Pakistan

Tudor, G. D., Ford, A. L., Armstrong, T. R. and Bromage, E. K. (1982). Taints in meat from sheep grazing Parthenium hysterophorus. *Australian Journal of Experimental Agriculture*, *22*(115), 43-46.

Vila-Aiub, M. M., Vidal, R. A., Balbi, M. C., Gundel, P. E., Trucco, F. and Ghersa, C. M. (2008). Glyphosate-resistant weeds of South American cropping systems: an overview. *Pest Management Science: formerly Pesticide Science*, *64*(4), 366-371.

Vogler, W., Navie, S., Adkins, S. and Setter, C. (2002). *Use of fire to control parthenium weed*. Rural Industries Research and Development Corporation, Australia, 41.

Witt, A. (2010). Impacts of invasive plants and their sustainable management in agro-ecosystems in Africa: a review. *CABI Africa, NRB*, 1102-1109.

CABI's Action on Invasives programme is supported by:

Ministry of Foreign Affairs of the Netherlands

UKaid from the British people

To find out more, please contact:

Roger Day, Programme Executive, Action on Invasives
T: +254 (0)20 2271000/20
E: r.day@cabi.org Roger Day,

www.cabi.org

CABI

KNOWLEDGE FOR LIFE