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REVIEW ARTICLE

Eco-Biology and Management of Alligator Weed [*Alternanthera philoxeroides*) (Mart.) Griseb.]: a Review

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Abstract

Exotic plant invasion, a global issue, has a tremendous impact on ecology, economy, human, and animal health. Alligator weed (the world's first aquatic weed) is a serious invasive weed in 32 different countries of South America, Australia, Asia, and North America. Recently, it has been recorded as a threat weed of rice, maize, soybean, vegetables, fruit trees, and pastures, causing 19–45% yield losses in these crops in addition to its infestation in canals, lakes, and ditches. Alligator weed has the potential to ruin agricultural and natural ecosystems and recreational areas. Ability to propagate via vegetative fragmentation, water-borne dispersal of vegetative propagules, and allelopathic potential contribute towards its success as an invasive weed species of terrestrial, semi-aquatic, and aquatic environments. Application of glyphosate, metsulfuron-methyl, dichlobenil, fluridone, hexazinone, triclopyr amine, dimethylamine, imazapyr, diuron, and amitrole herbicides have been found most effective in controlling this weed in different habitats. *Agasicles hygrophila, Vogtia malloi pastana, Amynothrips andersoni*, and *Nimbya alternanthera* have been reported as bio-agents for the control of alligator weed. We present a comprehensive review of the biology, interference, and management options of an extremely dangerous invasive weed species. Although management of alligator weed through chemical, biological, and mechanical means are often effective, there is need for well-planned, long-term field experiments to evaluate the role of different factors that are stated to be responsible for its increasing infestation and distribution (e.g., regeneration after damage caused by herbicides, high soil fertility levels, soil disturbances, shallow vs. deep ploughing and grazing management). It is recommended that future research should focus more on the integration of different management approaches in both aquatic and terrestrial ecosystems, and in various ecological regions.

Keywords Aquatic weed · Eradication · Herbicides · Invasiveness · Infestation · Weed control

Introduction

Alligator weed [*Alternanthera philoxeroides*) (Mart.) Griseb.] (Amaranthaceae) is an immersed aquatic or semi-aquatic clonal plant, probably originated in the Rio de la Plata basin of southern Paraguay and north-eastern Argentine (South America) (Buckingham 1996; Coventry et al. 2002; Sosa et al. 2008). It has the ability of extremely rapid growth, particularly in aquatic or semi-aquatic situations (Clements et al. 2011). Among all the species of *Alternanthera* genus, *A. philoxeroides* (alligator weed) is the most important weed distributed and studied worldwide. It has raised its status from an immersed aquatic plant to an aggressive invader in 32 different countries across the world (Barreto and Torres 1999; Garbari and Pedulla 2001; Chaman et al. 2002; Erwin et al. 2013; USDA-ARS 2016). The aquatic form of the plant has the potential to become a serious threat to rivers, waterways, wetlands and irrigation systems. The terrestrial type forms dense mats with a massive underground rhizomatous root system (ISSG 2016). In Australia, it is usually considered as the largest threat to moist and terrestrial habitats (Williams and West 2000).

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Alligator weed is usually considered as one of the most significant threats to plant diversity that can disrupt the ecological balance in its invaded sites (Shen et al. 2005; Bassett et al. 2012). It is a highly competitive weed, displaces pasture as well as other plant species (Julien and Bourne 1998), and is considered as an invasive weed of cotton, maize, rice, soybean, and many vegetables (Lu et al. 2002; Ye et al. 2003). Alligator weed infestation has been reported to reduce 45, 19, and 20% yield in rice, maize, and vegetable crops, respectively (Yi 1992; Zhang et al. 2004; Andres et al. 2013). China spent US$72 million each year for the management of this problematic weed (Liu and Diamond 2005). In addition to competition with crops for moisture, nutrients, and space, alligator weed has a strong tendency to reduce crop yields through its allelopathic effects (Wu et al. 2007; Schooler et al. 2008; Xie et al. 2010). This weed is becoming a major threat to the native flora and fauna because of its interwoven stems in the form of dense mats, resulting in crop yield losses, navigation blocking and promoting floods (Holm et al. 1997).

Despite its importance as an invasive species, many areas across the globe have limited information about the invasiveness and expansion of alligator weed in both aquatic and terrestrial environments (Wang et al. 2008; Masoodi and Khan 2012). The aim of this paper is to synthesize the available literature on the ecology and management of alligator weed based on references available through international scientific literature databases (e.g. Agris –http://www.fao.org/agris; CAB International – http://www.cabi-publishing.org; and ISI Web of Science – http://www.isiknowledge.com). Rather than just re-reviewing the vast literature, our intention was to summarize and evaluate the published peer reviewed literature in order to highlight the research gaps in the ecology and management of alligator weed around the globe. The purpose of this review article is to create awareness about the extremely dangerous invasive alligator weed, its diverse ecological and economic threats, and management options along with future research priorities.

Ecology

Alligator weed has a high degree of genetic variability, leading to different ecotypes occupying different niches. It can grow in both aquatic and terrestrial systems of tropical, sub-tropical, and temperate regions (Julien and Stanley 1999; Masoodi et al. 2013). Although it is considered as a tropical plant, it can tolerate a wide variety of environmental conditions both in cool and warm regions. Alligator weed is more strongly invasive in temperate regions than in tropical or cold regions, having optimal temperatures for growth between 15 and 30 °C (Julien et al. 1995; Shen et al. 2005). Usually, it requires a warm growing season but has the potential to survive in extreme cold situations, including frosts (Coulson 1977; Ma and Wang 2004; Clements et al. 2011; Clements et al. 2014).

Seeds of alligator weed usually germinate or sprout in early summer in its native areas (Julien et al. 1995). Its aerial portion emerges more rapidly with the increase in temperature and starts flowering up to mid of summer. Alligator weed completes its flowering and set seeds till late summer. Increasing burial depths decrease its seedling emergence and vegetative growth (Shen et al. 2005). The response of alligator weed to light in the field conditions is conflicting. Longstreth et al. (1984) and Timmins and Mackenzie (1995) reported it as a shade-tolerant species while Davis et al. (1983) reported it as shade intolerant. Presence or absence of light has no significant effect on seedling emergence and vegetative growth of alligator weed.

Plants of alligator weed usually hibernate with the start of winter (Zuo et al. 2012; Niroula 2013). Julien et al. (1995) reported that alligator weed grows best and forms dense monospecific stands in the subtropical to cool, but not in cold and temperate climates. In cooler, high altitude regions, it has a shorter growing season and occurrence of frosts kills top growth and restricts biomass accumulation. Information on the ecology of its seedling emergence and vegetative biomass production is very useful for its proper management (Shen et al. 2005).

Although extensive research has been done on alligator weed, still many aspects regarding its ecology have not been addressed in past studies. Previous research on alligator weed ecology was mainly focused on vegetation ecology derived from laboratory and greenhouse studies (Shen et al. 2005). There is a lack of information on dormancy and how dormancy in alligator weed could be exploited for its management under field conditions. Although the genetic diversity of alligator weed has been studied in many countries, there is a lack of knowledge on the variation of alligator weed populations across different geographical locations and their adaptations to diverse climatic conditions. Despite the recognition of alligator weed as a problematic invasive plant, field-based studies to explore the mechanism of habitat adaptation of this species are relatively few. The response of alligator weed emergence from deeper soil layers in field conditions should also be tested for its effective management.

Biology

Botanical Description

Leaves and stems of alligator weed vary in size and shape. Fleshy and succulent stems usually grow horizontally or can float on the water surface by forming rafts or clumps that grow on the bank, reaches to the length of 100 cm. Leaves with distinctive midribs are arranged alternatively, and their size may range from 5 to 10 cm (Mandal and Mondal 2011; Flora of Panama 2016). Inflorescences are white, thin, and clover-shaped of 1.25–7.6 cm length and 1.3 cm in diameter, usually grow on stalks. To facilitate buoyancy, plants tend to have hollow stems which are larger than those growing on land (Julien et al. 1992). The stems are prostrate, decumbent, or ascending. These can be simple or branched, reaching >10 m long to form dense mats of interwoven hollow stems. At the stem nodes, fibrous roots may emerge which may float free in the water or may penetrate into the soil. The roots are thin and stringy, and trail in water from joints between plant segments or nodes (Julien et al. 1992).

Reproduction

Alligator weed is a perennial, low-growing, non-woody, an emergent semi-aquatic species that rarely sets seeds, and produced seeds are usually not viable (Julien 1995; Clements et al. 2014). In native areas, alligator weed produces viable seeds (Vogt 1973; Julien et al. 1992; Ensbey 2001); however, only vegetative reproduction has been reported in its introduced range (Julien 1995; Ensbey 2001). It reproduces vegetatively from the apical stem or axillary stem and root buds (Julien et al. 1995; Zhu et al. 2015). Alligator weed can grow in a variety of habitats, particularly in aquatic environments by penetrating its roots into the bank or substrate below the shallow water or by forming free-floating mats (Julien and Broadbent 1980; Julien et al. 1995; Clements et al. 2011). The weed expands its growth by forming large hollow stems, providing buoyancy in aquatic conditions to smaller solid to slightly hollow stems in terrestrial conditions (Julien et al. 1995). It creates new infestation through the efficient dispersion in the surrounding areas via stem fragmentation (Dugdale et al. 2010).

In aquatic situations, its roots develop in the soil at the water's edge/embedded in the bank or the substrate in shallow water bodies and float freely on the water surface. These buoyant stems stretch across the water surface, or along shorelines or under the soil, rooting at the materials. These weed mats are fragile (especially after being damaged by herbicides or biological control agents) and often break away as a result of water movement and stock or other physical interference (earth moving machinery), which can move the dislodged alligator weed propagules to long distances and can become the basis of new infestations (Julien et al. 1992; Buckingham 2002). It can double its growth horizontally in less than 2 months. It demonstrates very strong reproductive abilities that even small plant fragments are readily established and spread in novel environments (Martin 1972) due to its strong adaptability to varying climatic conditions (Julien et al. 1995; Buckingham 2002) and resistance to salinity, heavy metals, and herbicides (Balagtas-Burow et al. 1993; Naqvi et al. 1993; Eberbach and Bowmer 1995; Naqvi and Rizvi 2000 and Chuanbing 2007).

The rapid expansion of alligator weed around the globe is most likely the result of its massive vegetative propagation. The enormous ability of vegetative regeneration needs to be taken into account while designing sustainable management strategies against this species. Future research should focus on damaging aquatic populations of alligator weed to check its rapid introduction and expansion in new areas through water movements.

Invasiveness

Invasive plants hold definite characteristics to be more proficient in adapting and reproduce in newer habitats and therefore, information regarding the invasion of a species is crucial in term of its management (Mack et al. 2000). Alligator weed is known as an invasive species in many parts of the world, having a tremendous potential for vegetative reproduction (Julien et al. 1995; Sainty et al. 1998; Clements et al. 2011). From the invasive point of view, it has proved to be the second most important weed in the world after parthenium (Tanveer et al. 2015). Alligator weed's inherent potential of mitigating stresses through the regulation of defense mechanisms is responsible for its adaptation to various environmental conditions (Chatterjee and Dewanji 2012). The ability of alligator weed to persist in terrestrial, semi-aquatic, and aquatic environments, to rapidly spread roots along waterway banks, and to propagate via vegetative fragmentation and waterborne dispersal of vegetative propagules contributes towards its success as an invasive plant species (Mandal and Mondal 2011; Clements et al. 2014). Recently, You et al. (2016) concluded that increased propagule pressure could greatly facilitate the growth and potential invasion of alligator weed, especially when it grew in vegetative habitats. Chatterjee and Dewanji (2014) suggested that the invasion of alligator weed is associated with altered soil decomposition dynamics, the composition of soil micro-organisms and allelopathic inhibition of water blooms. Similarly, Schooler et al. (2007) found that the distribution and invasiveness of alligator weed depended on soil moisture and the latitude of the local habitat.

Currently, alligator weed is considered as one of the worst aquatic and terrestrial weeds, which has been invading various countries, including Australia, China, India, Indonesia, Myanmar, New Zealand, and the USA (Masoodi et al. 2013; Clements et al. 2014). It is also listed as a serious weed among most problematic weeds in 10 economically important crops of 30 different countries, as a principal weed in eight of these countries, and as a major weed in others (Coombs et al. 2004). Recently, it has been reported in France, Italy, Puerto Rico, Sri Lanka, Singapore Thailand, and Vietnam (Dugdale and Champion 2012). Alligator weed now occurs as an invasive exotic in subtropical to temperate regions of America, Asia, Australia, New Zealand, and a number of Pacific island nations. The weed became a serious aquatic invader after its introduction into Australia, Asia, and North America (Barreto et al. 2000; Burgin et al. 2010; Clements et al. 2011; Dugdale and Champion 2012). Additionally, it spreads into many parts of the world and is considered an invasive species in New Zealand, Australia, India, China, Indonesia, Burma, Thailand, Puerto Rico, and the United States (Julien et al. 1995; Stanley and Julien 1998; Geng et al. 2007; EPPO 2013).

Alligator weed has also been recognized as an invasive and troublesome weed of rice (*Oryza sativa* L.), maize (*Zea mays* L.), soybean (*Glycine max* L.), vegetables, and fruit trees in 23 different provinces of China (Lu et al. 2002; Ye et al. 2003; Andres et al. 2013). Presently, it occurs in most regions of Southern China, where it was initially introduced in the 1930s as a forage crop and now has become one of the worst weeds in those regions (Xu and Ye 2003; Ye et al. 2003; Wang et al. 2005). Because of its invasive nature, it has produced a threat to our biodiversity (Clements et al. 2011). In India, alligator weed has been reported in 17 states (Pramod et al. 2008; Masoodi and Khan 2012) and has assumed the alarming threat to the local biodiversity. According to Sekar (2012), *Alternanthera* is among the genera with the highest number of alien invasive species (five) in the Indian Himalayan Region. It was recorded only as an occasional invader of irrigated rice plantations in Brazil (Lorenzi 1991; Andres et al. 2013). In Australia, it is earning a place among the top 20 weeds of national significance nominated by the commonwealth government in 1999 (Thorpe 1999). Rapid growth rate, high photosynthetic ability, and high nitrogen use efficiency are some of the factors contributing to the invasiveness of alligator weed (Table 1). High genetic variability contributes to the success of this weed in South America (Jia et al. 2010) and there are varieties that could thrive under varying environmental conditions (Table 1). A previous study reported a high level of adaptability of alligator weed to climate change such as warmer and rainy environments where this weed proliferates rapidly (Chen et al. 2013). In Australia, clonal propagation is the only means of dispersal due to lack of viable seed set and this weed dominates aquatic environments than the terrestrial environment (Burgin and Norris 2008). On the contrary, in South America, this weed propagates through both seed and clonally and infests both the terrestrial and the aquatic environments (Pan et al. 2007; Jia et al. 2010). Alligator weed has tremendous potential to devastate agricultural and natural ecosystems (Burgin and Norris 2008) and recreational areas because it is not constrained by natural predators or other environmental constraints that exist within its native range (Bassett 2009). Efficient management of alligator weed requires information on its current and potential future distributions. Habitat suitability models in the coastal regions, climate-driven models at regional scales, and physiographic and anthropogenic models for local regions could be used for this purpose. These models and approaches could help early detection of alligator weed in new areas, helping its management more efficient.

Phenotypic Plasticity

Alligator weed exhibits a high level of phenotypic plasticity that enables it to survive extreme competitive environments (Tao et al. 2009). Alligator weed could modify anatomical structures to adapt to both wet and dry environments (Tao et al. 2009). Alligator weed can also adjust phloem fibre cell wall, collenchyma cell wall, and hair density to suit wet to dry environments (Tao et al. 2009). Most importantly, alligator weed can absorb oxygen from water, thereby can efficiently utilize diffused oxygen and can survive under water logged environments (Ayi et al. 2016). In addition, it cannot be controlled by enhancing interspecific competition for light as its biomass was found unaffected by shaded conditions (Bassett et al. 2011). A study indicated a higher tolerance level in alligator weed compared to the related species sessile joyweed (*A. sessilis*) (Chen et al. 2013). The results suggest that higher tolerance to waterlogging and higher photosynthetic capacity may partly explain the invasion success of alligator weed in wetlands (Chen et al. 2013). Under polluted environment with an enhanced level of nitrogen, the increased clonal spread was observed at high nitrogen concentrations, suggesting that alligator weed did not exhibit any toxicity symptoms but benefitted from excess nitrogen (Ding et al. 2014).

Impact on Agriculture and Biodiversity

Alligator weed can affect the agricultural community in a number of ways either by competing with crops, displacing native plants, disrupting natural water flow, preventing drainage, reducing oxygen levels beneath mats and by providing habitat for mosquito breeding (Julien et al. 1995; Buckingham 2002). As an aquatic plant, it produces large mats of stems and leaves, anchored by roots to the bank and extends across the water that disrupts the aquatic ecology by forming a dense blanket over the surface of the water. It also interferes with waterways, drainage, boat traffic, sport fishing activities, and restricts irrigation flow. Also, it reduces water quality by causing pollution from plant decomposition, and by preventing light penetration and oxygenation of the water, displaces native species and affects flow and sedimentation rates (Julien and Stanley 1999). Although livestock can feed on it, alligator weed is toxic and can cause blindness (photosensitization) and liver damage (Bourke and Rayward 2003). In many areas, alligator weed chokes waterways while in others; it invades pastoral and agricultural lands (Julien et

Table 1 Factors contributing to the invasion success of alligator weed in countries where this weed is a major problem

Country	Habitat	Year of introduction	Factor/s contributing to Invasion success	Reference
Australia	Aquatic /terrestrial	Introduced through shipment in 1944	Occasional flood events can disperse this weed. This weed was grown as a vegetable for some time.	Burgin and Norris (2008)
Argentina	Terrestrial / aquatic	Native	High genetic variability of *A. philoxeroides* in Argentina with different varieties adapted to different geographical conditions. For example, the growth rate of *A. philoxeroides* var. *obtusifolia* was lower than *A. philoxeroides* var. *acutifolia* that is adapted to low altitude.	Jia et al. (2010)
Brazil	Terrestrial/-aquatic	Native	High genetic variability. Propagation through seeds and clones.	Pan et al. (2007)
China	Terrestrial/-aquatic	1930s as animal feed	High growth rate, high photosynthetic rate and high nitrogen use efficiency,	Chen et al. (2015); Wang et al. (2016)
	Terrestrial/-aquatic		The bio control agent flea beetle (*Agasicles hygrophila*) was failed to thrive under cooler environment.	Lu et al. (2013)
	Crop fields		Climate change favours the spread. Increased annual precipitation and elevated temperature is favouring the growth rate and spread of this weed.	Chen et al. (2013)
India	Aquatic	1940s through packing material from cargo flight.	Rapid growth rate and spread	Masoodi et al. (2013)
New Zealand	Aquatic	Not documented	Negatively related to cover of native populations such as *Machaerina juncea*(R.Br.) T.Koyama, *Eleocharis acuta*R.Br., *Typha orientalis*C.Presl. and *Myriophyllum propinquum* L.	Bassett et al. (2012)
USA	Aquatic / terrestrial	1890s	High level of phenotypic plasticity	Geng et al. (2016)
			Rapid growth rate and limited control options under aquatic environment	Erwin et al. (2013)

al. 1995). Bassett et al. (2012) stated that invasion of alligator weed can decrease the plant diversity and may disrupt the ecological balance in invaded sites. Whereas in pasture ecosystems, it steadily increases biomass and displaces other species (Julien and Bourne 1998).

Allelopathic Potential

Allelopathic potential of alligator weed for the successful invasion of this alien species in new areas has been reported by Xie et al. (2010) and Wu et al. (2007). Paria and Mukherjee (1981) studied the allelopathic potential of alligator weed against mustard (*Brassica nigra, B. juneea, B. carinata*) and rice. They observed complete inhibition of mustard seed germination and seedling growth with 1:10 leaf extract, 1:5 leaf leachates, and 1:5 stem extract (Table 2). In rice bioassay, complete inhibition was noted only at 1:2.5 leaf extract, stem extract, and leaf leachate. According to Liuqing et al. (2007), under the treatment of 50 mg leaves of alligator weed, the root growth of the lettuce (*Lactuca sativa* L.) and barnyard grass [(*Echinochloa crus-galli* (L.) P. Beauv] was inhibited by 81 and 51%, respectively, and the shoot growth by 49 and 48%, respectively, which was significantly higher than the control treatment. An inhibition rate of barnyard grass root length was 54% under the treatment of the root extract of alligator weed, and the inhibition was much higher than that of stem and leaf extracts of alligator weed. Also, the inhibition rate of the root growth of lettuce enhanced significantly with the increase in dosage and the values were 54%, 61%, and 83% under the treatments of 10, 30, and 50 mg leaf of alligator weed, respectively. Root, stem and leaf water extracts of this weed also slightly stimulating to highly inhibiting the growth and enzyme activities of *Zoysia matrella* (Huang et al. 2017). Mandal and Mondal (2011) reported a maximum potentiality in the stem and root extracts than leaf extracts of alligator weed, causing a decrease in the spore germination percentage of edible pteridophytes *Ampelopteris prolifera* (Ketz.) Cop. The increase in filamentous growth and decrease in rhizoidal growth has been attributed to the presence of alkaloids and phenols in the extracts of alligator weed. It has been found that these toxic substances are synthesized in the leaf but gradually, they are translocated to various plant parts like stems and roots (Mandal and Mondal 2011).

Although several studies have been conducted on the allelopathy of alligator weed, information on the allelochemicals

Table 2 Allelopathic potential of alligator weed against different crops

Name of test species	Alligator weed extract	Effect on test species	Reference
Ampelopteris prolifera (Ketz.) cop.	Stem, root, leaf	Decrease in spore germination and rhizoidal growth	Mandal and Mondal (2011)
Brassica campestris			
B. nigra	Leaf extract 1:10	Complete seed germination and seedling growth inhibition	Paria and Mukherjee (1981)
B. juneea	Leaf leachate 1:5		
B. carinata	Stem extract 1:5		
Echinochloa crusgalli (L)			
P. Beauv. Var. Mitis (push). Peterm	Leaves (50 mg) incorporated in soil	Root (51%) and shoot (48%) growth inhibition	Liuqing et al. (2007)
Lactuca sativa L.	Leaves (50 mg) incorporated in soil	Root (81%) and shoot (49%) growth inhibition	Liuqing et al. (2007)
Lactuca sativa L.	Leave extract at highest concentrations	Reduction in the germination and radical growth	Kleinowski et al. (2016)
Oryza sativa L.	Leaf, stem extract, leaf leachate 1:2.5	Complete seed germination and seedling growth inhibition	Paria and Mukherjee (1981)
Lolium perenne L.	Water extracts	Reduced germination, inhibited the growth of the roots and stems, increased the relative conductivity and reduced the content of chlorophyll.	Zhen et al. (2009)
Zoysia matrella	Root, leaf and stem water extracts	Slightly stimulating to highly inhibiting the growth and enzyme activities	Huang et al. (2017)

produced and their functions are still limited. Moreover, the correlation between allelopathy and rapid expansion and invasion of alligator weed should also be considered for further research.

Management

Managing an invasive species, especially a weed, usually requires a combination of biosecurity approaches. Among them, one of the most common approaches for controlling weed is to eradicate a weed species from an area in which it has become naturalized. Alligator weed can usually be controlled by three principal means: chemical, mechanical, and biological. This weed is extremely difficult to control once established and its eradication is very costly, especially in developing countries (Sainty et al. 1998). Management can be very difficult in aquatic environments (Burgin and Norris 2008; Bassett et al. 2011; Erwin et al. 2013; Masoodi et al. 2013). Along with biological management options, awareness campaigns leading to the early detection and eradication would help to minimize the rapid spread of this weed. In Australia, the significant spread of this weed occurred as this weed was mistakenly grown as a backyard vegetable (Burgin and Norris 2008). For the management of this weed, attention should also be focussed on measures to prevent the separation of this weed including preventing new plant material entering, using weed hygiene protocols (such as washing contaminated equipment) and educating people to recognise it.

Physical Removal

Manual or mechanical approaches can be adapted for the management of alligator weed in small patches. These approaches prevent the regrowth of alligator weed by excavation of its mats and roots completely from the above and below-ground (Sainty et al. 1998). Implementation of physical approaches may vary, depending on the site characteristics, environmental sensitivity, and resources availability (Clements et al. 2014). In aquatic conditions, alligator weed forms less penetrating root systems than terrestrial lending itself for physical removal (Julien et al. 1992; Geng et al. 2007). It is recommended for an infestation of a small level, particularly in initial phases of invasion in a particular area (Van Oosterhout 2007). Physical approaches are more labor intensive at initial stages but may provide a substitute way to the multiple herbicidal applications over multiple years to eliminate regrowth of alligator weed in one instance. The recent development of organic farming and the increased demand for non-chemical control measures increased the importance of physical methods to manage this weed in aquatic and terrestrial ecosystems. More studies are thus required to weaken the regrowth capacity of alligator weed by removing or destroying its above- and below-ground biomass.

Chemical Control

Infestation over a large area is difficult to control through physical approaches because each node of alligator weed is capable of forming a new plant and fragments because mechanical damage encourages its spread (Johnson and Brooke 1989; Sainty et al. 1998). Therefore, multiple herbicide applications over multiple years are required for the complete destruction of emerging plants and underground root storages for complete exhaustion of plants eventually (Van Oosterhout 2007). Unfortunately, limited information is available for the long-term effectiveness of herbicides in controlling alligator weed at initial stages. Fewer herbicides, such as 2,4-D, glyphosate, fluridone, dicamba, dichlobenil, bentazone, propanil, pendimethalin, and dichloform are recommended to control this weed in Australia, New Zealand, Brazil, Indonesia, and the USA (Allen et al. 2007; Hofstra and Champion 2010; Clements et al. 2014). Different researchers obtained the best control of alligator weed by using different herbicides alone and as a tank mixture in drainage canal systems, terrestrial, rooted forms, aquatic, backyards, dry ditches, gardens, ornamentals, fruit trees, marshes, and in shallow water areas (Table 3).

Gunasekera and Bonilla (2001) tested dichlobenil, glyphosate, and metsulfuron-methyl and a mixture of glyphosate and metsulfuron-methyl against the terrestrial forms of alligator weed. They observed its regrowth, which was controlled by repeated treatments. According to Sushilkumar et al. (2008), metsulfuron-methyl was the most efficient herbicide to control the terrestrial form of alligator weed for at least 6 months. Repeated applications of glyphosate followed by metsulfuron-methyl at a six-month interval were required for long term control. Toscani et al. (1983) found complete control of alligator weed for 1 year with hexazinone and by the applications of glyphosate in dry ditches. Bowmer (1992) reported that alligator weed could be controlled by applications of dichlobenial followed by metsulfuron-methyl 9 months later or three sprays of metsulfuron-methyl over 18 months in terrestrial areas. Ensbey (2001) opined that many herbicides only kill the tops but do not affect older stems, rhizomes, or roots. The author recommended glyphosate for aquatic and dichlobenil for shallow water areas. Gunasekera and Bonilla (2001) tested glyphosate against the aquatic form of alligator weed at a two-month interval for three times. They observed regrowth, which was controlled by repeated treatments of glyphosate.

The most efficient long-term strategy for managing alligator weed is to use low concentrations of selective herbicides (metsulfuron and triclopyr) one to three times per year (Schooler et al. 2008). However, Ensbey (2005) stated that owing to weak translocation through roots and stems; glyphosate was not effective in terrestrial plants. Herbicides that mostly destroy leaves and shoots do not cause direct mortality to roots (Bowmer and Eberbach 1993; Tucker et al. 1994; Schooler et al. 2007) due to their inability to translocate to the roots. So, these herbicides are ineffective without continued inspections and repeated applications. Herbicide use around waterways is restricted, and plant material under the water surface is unaffected. In addition, alligator weed stores significant amounts of carbohydrates in below-ground material that are used to replace shoots and leaves after frequent disturbance (Wilson et al. 2007).

Chemical management of alligator weed is effective at a sustained reduction in biomass and can even exacerbate the problem. These herbicides, effective against alligator weed, have been known for some time. There is a need to make them more effective by understanding the factors affecting their efficacy. Herbicides that cause direct or indirect mortality to roots should be tested against this weed for its long-term effective management in aquatic and terrestrial ecosystems.

Herbicide Management

Although herbicide resistance is not reported in alligator weed, this weed evades herbicide application by detaching and fragmenting from the main plant which leads to further colonization of aquatic environments (Clements et al. 2012). Application of glyphosate or metsulfuron-methyl can result in viable propagules (Dugdale et al. 2010). Terrestrial forms of alligator weed exhibit some level of tolerance to glyphosate indicating the probability for this weed to be tolerant in many glyphosate-tolerant cropping systems (Tucker et al. 1994). An experiment reported that late post application of combined herbicides such as penoxsulam plus triclopyr controlled the germination and growth of this weed up to 87% as well as enhanced the rice grain yields up to 9320 kg ha^{-1} (Willingham et al. 2015). A study compared the absorption and translocation of two systemic herbicides; glyphosate and imazapyr and found reduced absorption and translocation of glyphosate compared to imazapyr (Tucker et al. 1994). Imazapyr and triclopyr amine could control alligator weed better in marshy areas (Allen et al. 2007).

Biological Control

Interest in managing introduced species is increasing with the growing awareness that biological invasions have large economic and environmental costs (Schooler et al. 2008). In Australia and the USA, a successful attempt was made through biological control of alligator weed with specific insects like a beetle (*Agasicles hygrophila*) and moth (*Arcola malloi*) (Johnson and Brooke 1989). Unfortunately, these insects are not considered suitable for controlling the alligator weed on large scale (Stewart et al. 1999; Hayes 2007; Winks 2007). Leaf beetle (*Agasicles hygrophila* Selman and Vogt) (Chrysomelidae), the moth (*Vogtia malloi pastrana*)

Table 3 Herbicides recommended for control of alligator weed

Type of habitat	Herbicide name	Dose	Reference
Aquatic	Glyphosate	3.24 kg ha^{-1}	Gunasekera and Bonilla (2001)
		1% *v*/v	Ensbey (2001), (2005)
Backyard situation	Metsulfuron-methyl	80 g ha^{-1}	Gunasekera and Adair (1999)
	Metsulfuron-methyl plus glyphosate mixture	80 g ha^{-1} + 1.7 kg ha^{-1}	Dugdale and Champion (2012)
	Metsulfuron-methyl plus glyphosate followed by dichlobenil	80 g ha^{-1} + 1.7 kg ha^{-1} 30 kg ha^{-1}	
	Metsulfuron-methyl followed by dichlobenil	80 g ha^{-1} + 30 kg ha^{-1}	
	Dichlobenil	60 kg ha^{-1}	
	Glyphosate	6.4 kg ha^{-1}	
	Glyphosate followed by dichlobenil	6.4 kg ha^{-1} 30 kg ha^{-1}	
Drainage canal system	Glyphosate plus fluridone mixture	0.18 + 0.12 kg 100 L^{-1} 0.36 + 0.24 kg 200 L^{-1}	Langeland (1986) Clements et al. (2014)
	Glyphosate plus dichlobenil	3.6 + 31 kg ha^{-1}	
Dry ditches,	Hexazinone	2.25 kg ha^{-1}	Toscani et al. (1983)
Garden, ornamentals and fruit trees	Dichlobenil	60 kg ha^{-1}	Gunasekera and Bonilla (2001)
Managed marshes	Triclopyr amine	4.8, 9.6, 14.4 L ha^{-1}	Allen et al. (2007)
	Imazapyr	1.2, 2.4, 3.6 L ha^{-1}	
Shallow water areas	Dichlobenil	60 kg ha^{-1}	Ensbey (2001)
Shallow drainage canals	Glyphosate	0.18–0.36 kg a.i. 100 L^{-1}	Langeland (1984)
	Fluridone	0.24 kg a.i.100 L^{-1}	
	Glyphosate plus Fluridone	0.18 + 0.12, 0.36 + 0.24 kg a.c. 100 L^{-1}	
	Glyphosate	0.24, 0.36, 0.48, 0.60, 0.96 kg a.e. 100 L^{-1}	
	Imazapyr	0.06, 0.12 kg a.e. 100 L^{-1}	
	Dimethylamine	0.32, 0.46 kg a.e. 100 L^{-1}	
	Diuron	3.84 kg a.i.100 L^{-1}	
	Fenatrol	3.90 kg a.i.100 L^{-1}	
	Amitrole	1.44 kg a.i.100 L^{-1}	
	Bromacil	0.96 kg a.i.100 L^{-1}	
	Hexazinone	0.96 kg a.i.100 L^{-1}	
	Triclopyr	0.36 kg a.i.100 L^{-1}	
Terrestrial form	Dichlobenil	67.5 kg ha^{-1}	Gunasekera and Bonilla (2001)
	Dichlobenil followed by metsulfuron-methyl	67.5 kg ha^{-1} 0.024 kg ha^{-1}	Bowmer (1992)
	Glyphosate	360 g L^{-1} 5 L ha^{-1} 100 ml 100 L^{-1}	Gunasekera and Bonilla (2001) Schooler et al. (2008) Chandrasena et al. (2011)
	Glyphosate followed by metsulfuron-methyl	360 g L^{-1} + 63 g ha^{-1} 3.5 kg ha^{-1} + 0.024 kg ha^{-1}	Gunasekera and Bonilla (2001) Sushilkumar and Vishwakarma (2008)
	Imazapyr	2.5 L ha^{-1}	Langeland (1986); Tucker et al. (1994)
	Metsulfuron-methyl	24, 40, 63, 80 g ha^{-1} 4.52 g, 10 g 100 L^{-1}	Langeland (1986); Bowmer (1992); Milvain et al. (1995); Ensbey (2001); Gunasekera and Bonilla (2001); Sushilkumar et al.

Table 3 (continued)

Type of habitat	Herbicide name	Dose	Reference
			(2008); Schooler et al. (2008); Chandrasena et al. (2011)
	Triclopyr	0.36 kg 100 L^{-1} 3 L ha^{-1}	Langeland (1986) Schooler et al. (2008)
Terrestrial shallow water	Dichlobenil	60 kg ha^{-1}	Milvain et al. (1995)

(phycitidae), and the thrips (*Amynothrips andersoni* O'Neill) (Thripidae) are especially promising plant feeding insects on alligator weed (Vogt 1973; Spencer and Coulson 1976; Coulson 1977; Buckingham 1996). Leaf beetle strips the leaves from the stems and *V. malloi pastrana* bores inside the stems. Heavy damage by either species kills the stems thereby, causing alligator weed mat to breakup, clearing the waterway. The thrips *A. andersoni* feeds on the young apical leaves. Heavily damaged plants are often stunted.

Tan et al. (2002) found *Fusarium* as an alternate of glyphosate for the control of alligator weed without affecting the germination and growth of numerous crops including rice, wheat, maize, oilseed rape, and broad bean. They observed that *Fusarium* at the rate of 1×10^5 spores ml^{-1} provided good weed infections and resulted in the complete wilting of the plant in 8–9 days after the inoculation. Pomella et al. (2007) discovered a fungus *Nimbya* (Alternaria) *alternantherae* (Holcomb and Antonopoulus) Simmons and Alcorn, in Brazil in 1997, which was found to damage alligator weed. Fungus conidia were more effective than mycelia suspension and inoculum concentrations of 1×10^5 and 1×10^6 conidia per ml provided significant levels of control in greenhouse and field experiments, respectively. It shows that *N. alternantherae* has the potential to be an effective mycoherbicide for alligator weed. Stewart et al. (2000) recorded a decline in dry weight of alligator weed as a result of feeding by increasing the population of *A. hygrophila* in New Zealand.

Nowadays, utilization of natural products obtained from plants is being made as a potential weed control tool. Extracts, residues, and allelochemicals from different plants and fungi significantly inhibited shoot growth of alligator weed. There is a need to identify the active ingredients in the plants and fungal metabolites so that these chemical constituents may lead towards the synthesis of natural plant products to manage this weed.

Cultural Control

Extensive research has been done on the chemical (Bowmer and Eberbach 1993; Tucker et al. 1994; Ensbey 2005; Schooler et al. 2007, 2008) and biological ways (Vogt 1973; Spencer and Coulson 1976; Coulson 1977; Buckingham 1996; Stewart et al. 2000; Tan et al. 2002; Pomella et al. 2007) to manage alligator weed, but limited information is present on the cultural management of this weed. In different agroecosystems, the cultural control includes manipulating farming practices to suppress weed growth and production, while promoting the development of crops (Barberi 2002). Future research should focus on the selection of competitive crop cultivars against alligator weed. The areas where heavy infestations of alligator weed are reported increased seeding rates and narrow row spacing of crops could be a viable option to have a competitive advantage against this weed (Ali et al. 2017). Moreover, reduction of alligator weed emergence and improvement of crop competitive ability could also be achieved by intercropping of crops and employing proper fertilizer management techniques.

Conclusions

Manual control can be an effective management strategy to eradicate the weed from lakes, but it is costly. Mechanical removal of alligator weed mats is expensive and often results in the dispersal of a large number of vegetative fragments that can exacerbate the infestation. Biological control offers the only long-term sustainable control method. No doubt, the alligator weed flea beetle has managed to control the aquatic form of alligator weed in the warmer climates of Australia. However, the beetle has been unsuccessful in controlling the terrestrial form and does not control the weed in cooler temperate climates. There is a need to examine methods to integrate herbicides with biological, cultural, and mechanical control strategies and studying their effects on biomass of alligator weed population in varying climatic conditions.

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