DOI: 10.17138/TGFT(7)280-289

*ILC2018 Keynote Paper**

Weed leucaena and its significance, implications and control

Leucaena como maleza: Importancia, implicaciones y control

SHANE CAMPBELL[1], WAYNE VOGLER[2], DANNIELLE BRAZIER[2], JOSEPH VITELLI[3] AND SIMON BROOKS[2]

[1]*School of Agriculture and Food Sciences, The University of Queensland, Gatton, QLD, Australia.* agriculture.uq.edu.au
[2]*Invasive Plant and Animal Science Unit, Biosecurity Sciences, Department of Agriculture and Fisheries, Tropical Weeds Research Centre, Charters Towers, QLD, Australia.* daf.qld.gov.au
[3]*Invasive Plant and Animal Science Unit, Biosecurity Sciences, Department of Agriculture and Fisheries, Eco-Sciences Precinct, Brisbane, QLD, Australia.* daf.qld.gov.au

Abstract

Leucaena (*Leucaena leucocephala*) is widely recognized in many countries as a commercially valuable plant, particularly when used as a nutritious fodder in subtropical and tropical regions. However, it is also considered an environmental weed in some countries due to its ability to form dense infestations in disturbed areas, where it is not proactively managed or grazed. These different perspectives have made leucaena a contentious species. Ideally, landholders and relevant jurisdictions in charge of invasive species need to work together to minimize its spread as a weed and manage existing infestations. To date, the response has been varied, ranging from no action through to some jurisdictions formally recognizing leucaena as an environmental weed within relevant legislation and applying requirements to minimize its impact. Between these extremes, there are initiatives such as an industry Code of Practice (i.e. The Leucaena Network in Australia), recommending that those growing leucaena adhere to certain principles and practices to minimize the risk of spread from their operations. The biology of weed leucaena (e.g. large seed production, relatively long-lived seed banks) and the situations in which it spreads (e.g. roadsides and riparian systems) pose management challenges to landholders and relevant jurisdictions. Adaptive management and experimental research are necessary to identify effective control strategies for a range of situations.

Keywords: Conflict, contentious, ecology, herbicide, management, tree legumes.

Resumen

Leucaena (*Leucaena leucocephala*) es ampliamente reconocida en muchos países como una planta económicamente valiosa, particularmente cuando se usa como forraje de alto valor nutritivo en regiones subtropicales y tropicales. Sin embargo, en algunos países también es considerada una maleza ambiental debido a su capacidad para formar infestaciones densas en áreas perturbadas donde las poblaciones no son pastoreadas ni manejadas en forma proactiva. Estas diferentes perspectivas han hecho de la leucaena una especie contenciosa. Idealmente, los usuarios de las tierras y las autoridades a cargo del control de especies invasoras deberían trabajar juntos para minimizar la diseminación de la especie como maleza y manejar adecuadamente las infestaciones existentes. Hasta la fecha, las reacciones han sido variadas, desde la no acción por parte de algunas autoridades hasta el reconocimiento formal de la leucaena como una maleza ambiental dentro de la legislación existente y la aplicación de normas para minimizar su impacto. Entre estos extremos existen iniciativas tales como el Código de Prácticas desarrollado por la Red de Leucaena en Australia, que recomienda que los que cultivan leucaena se adhieran a ciertos principios y prácticas para minimizar el riesgo de su diseminación. La biología de la leucaena como maleza (p.ej., alta producción de semillas, relativamente larga viabilidad de la semilla en el suelo) y las situaciones en las que se disemina (p. ej., bordes de carretera y sistemas ribereños) plantean

Correspondence: S. Campbell, School of Agriculture and Food Sciences, The University of Queensland, Gatton Campus, Gatton, QLD 4343, Australia. Email: shane.campbell@uq.edu.au

*Keynote paper presented at the International Leucaena Conference, 1–3 November 2018, Brisbane, Queensland, Australia.

desafíos de manejo para los productores y las autoridades. Formas de manejo adaptativo e investigación experimental son necesarios para identificar estrategias de control efectivas que deben considerar una variedad de situaciones.

Palabras clave: Conflicto, controversia, ecología, herbicida, leguminosas arbóreas, manejo.

Introduction

Leucaena (*Leucaena leucocephala*) is increasingly recognized around the world for its beneficial properties, particularly as a source of nutritional fodder, timber, fuelwood and shade (Walton 2003a, 2003b; Shelton and Dalzell 2007; Olckers 2011). It has also been used in restoration programs to restore degraded lands, improve soils, reduce erosion and stabilize sand (e.g. Shelton and Dalzell 2007; Normaniza et al. 2008; Roose et al. 2011; Wolfe and Bloem 2012; CABI 2018). Its ability to invade areas where it is not wanted, i.e. may become a weed, is also becoming increasingly recognized (Walton 2003a, 2003b; Shelton and Dalzell 2007; Olckers 2011).

Leucaena production in most countries occupies only a small percentage of the potential area where it could be grown. The risk of it becoming an even more problematic species could therefore increase greatly if steps are not put in place to minimize the risk of it escaping from existing naturalized infestations and cultivated plantations.

In this paper, we discuss the significance of leucaena as a global weed and consider actions and activities that are being or could be implemented to minimize its impacts. Key aspects of the biology/ecology of leucaena and available control options are also discussed in the context of developing management strategies to prevent its spread and/or control infestations having negative environmental impacts.

The significance of leucaena as a weed

While the native distribution of leucaena (i.e. Mexico and Central America) is relatively restricted on a global scale, a combination of deliberate and non-deliberate dispersal has led to it becoming one of the more widely naturalized species around the world (Figure 1). In a comprehensive review of the pest status of leucaena, Walton (2003a) suggested that it could be naturalized in more than 105 countries throughout the world's subtropics and tropics. This number appears to have increased since then to more than 125 countries according to some global invasive species databases (GISD 2015; CABI 2018).

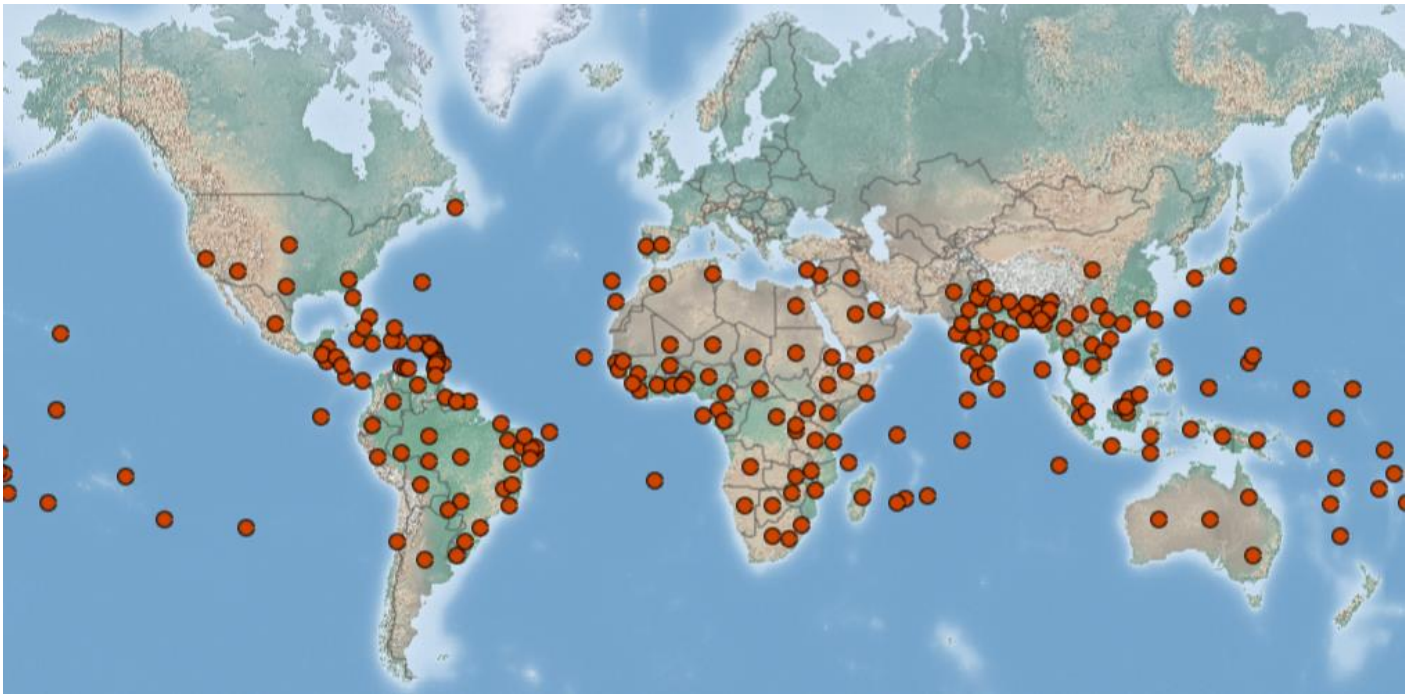

Figure 1. Global distribution of *Leucaena leucocephala*; sourced from the Invasive Species Compendium (CABI 2018). Individual points are representative of either a region, jurisdiction, country or continent. For example, this map shows that in Australia, leucaena is present in Queensland, New South Wales, The Northern Territory and Western Australia, but does not give specific locations of all known infestations.

In terms of world regions, the largest numbers of countries with naturalized populations of leucaena are located in the Pacific Ocean region, Africa, Asia and South America, followed by the Caribbean, Central America, the Indian Ocean region, Australasia, North America and to a lesser extent Europe and the Middle East (Walton 2003a; CABI 2018). Walton (2003a) suggested that leucaena was considered a weed in more than 25 of these countries, while the more recent Invasive Species Compendium database (CABI 2018) lists more than 50 countries where leucaena has been reported to be invasive. Based on a recent review of the potential distribution of 10 invasive alien trees, it appears that leucaena is globally distributed across a large portion of its potential range (Wan et al. 2018). Further expansion of its current range is most likely to occur predominantly through continued spread within already invaded countries.

Not all countries recognize leucaena solely as a weed, with some categorizing it as being a 'contentious' or 'conflict' species (FAO 2009; Clarkson et al. 2010; Olckers 2011). Plants given these classifications are recognized as having some attributes that make them useful or desirable and other attributes that make them problematic (Clarkson et al. 2010; Olckers 2011). Of the 3 subspecies of *L. leucocephala*, subspecies *leucocephala* is generally considered to have the greatest weed potential and is the most widely naturalized. The more recently cultivated *L. leucocephala* ssp. *glabrata* is considered to have fewer weedy attributes but is still recognized as having the potential to become a weed if not adequately managed (Shelton et al. 2003; Walton 2003a; Olckers 2011). Infestations of *L. leucocephala* ssp. *glabrata* have been reported at several locations in Australia (Shelton et al. 2003; Walton 2003a, 2003b).

Leucaena is predominantly recognized as being a weed of roadsides (Figure 2), forest margins, riparian habitats, ruderal areas in peri-urban environments and other disturbed areas (Shelton et al. 2003; Walton 2003a, 2003b; Olckers 2011; CABI 2018). Despite its widespread distribution, its impact is not well documented in the scientific literature. It is generally reported as having an ability to form dense monospecific thickets that could render extensive areas of disturbed ground essentially unusable and inaccessible, reduce biodiversity and potentially threaten endemic species of conservation value (Walton 2003b; Yoshida and Oka 2004; Costa et al. 2015; GISD 2015).

Figure 2. Roadside infestation of leucaena near Brisbane (Australia).

Biology and ecology of leucaena from a weed perspective

Many tetraploid leucaena species such as *Leucaena leucocephala* have biological and ecological attributes that facilitate their ability to become invasive weeds in areas where they are not proactively managed. Plants can live for a relatively long time (>30 years) under favorable conditions, even if regularly grazed (Jones and Bunch 1995; 2000). Once mature, they frequently produce large quantities of seed (Raghu et al. 2005; Marques et al. 2014). Tetraploid plants such as leucaena are self-fertile, with only a small percentage of out-crossing, so even an isolated plant can produce pods with viable seeds and be the source of a new infestation (Walton 2003b; Olckers 2011). While it appears that most seed falls and stays within close proximity to the parent plants, several dispersal mechanisms can facilitate the movement of seeds into new areas, including human activity, animals and water dispersal (Shelton et al. 2003; Walton 2003a, 2003b).The longevity of an established seed bank in the absence of further replenishment becomes important for those tasked with managing infestations. It helps determine the potential duration of control activities, particularly if eradication of the infestation is the end goal (Campbell and Grice 2000; Panetta 2004; Panetta et al. 2011). Having a hard seed coat, leucaena seeds are long-lived with several sources in the literature suggesting periods of 10–20 years and some even potentially longer (Walton 2003a, 2003b; Olckers 2011). In contrast, a study undertaken by Marques et al. (2014) in a Brazilian forest found that leucaena formed a persistent short-lived seed bank (viability 1–5 years). They suggested that under typically hot and humid conditions, such as those experienced at the field site in Brazil, seeds of tropical legumes may break dormancy faster, leading to more rapid depletion of soil seed banks (McDonald 2000).

A study of the potential longevity of seed banks of more than 10 weeds, including leucaena, was initiated in 2009 in the dry tropics of north Queensland. Seeds placed in mesh packets were buried under a range of conditions including different soil types, burial depths and levels of pasture cover [see Bebawi et al. (2015) for details on the methodology]. At 96 months a small percentage (<4%) of viable leucaena seed remained in some treatments if seeds were buried below ground (between 2.5 and 20 cm), but no surface-located seeds remained viable (Figure 3) (F. Bebawi et al. unpublished data). A seedling-emergence trial has also been running conjointly since May 2016. Preliminary results indicate that there have been approximately 9 discrete rainfall periods over the first 2 years that have been favorable for germination and seedling establishment; yet only around 20% of the initial seed has germinated and emerged. The ability of leucaena to germinate multiple times throughout a year while maintaining a persistent seed bank enhances the likelihood of establishment and recruitment occurring over a prolonged period, making it more challenging to control (Campbell and Grice 2000).

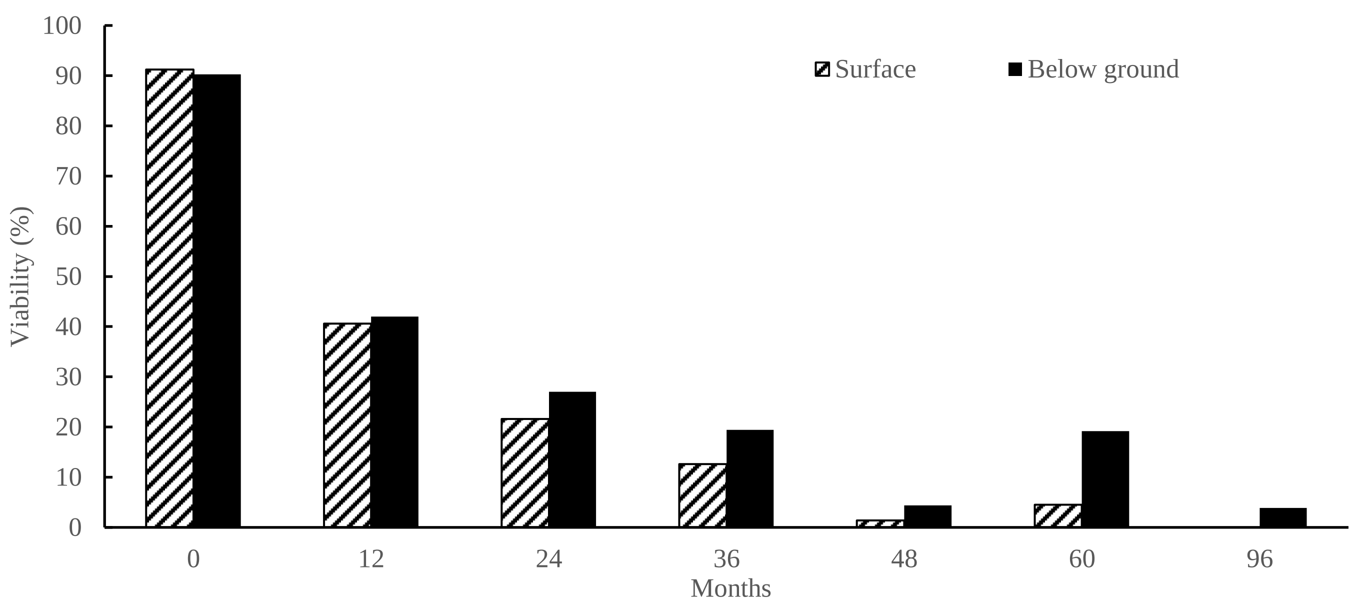

Figure 3. Changes in the viability of *Leucaena leucocephala* seeds over time following placement on the soil surface or burial below ground (2.5–20 cm).

Knowing the time for leucaena seedlings to reach reproductive maturity will aid effective management. Weeds with short timelines to maturity pose greater difficulty, with more frequent control activities required to prevent new plants from reaching reproductive maturity and replenishing soil seed reserves (Campbell and Grice 2000). Leucaena appears to be capable of reaching reproductive maturity within 12 months in many situations, but potentially as quickly as 4 months under ideal conditions (Walton 2003a, 2003b; Olckers 2011).

Control options for leucaena

Up until the present time there has been limited investment into research on control of weedy leucaena with research organizations tending to focus on higher priority species such as those declared under legislation. The main research has been to identify effective herbicides that could be applied to individual plants and scattered infestations (Walton 2003a). Some preliminary investigations into biological control options have been explored in South Africa (Olckers 2011). Some adaptive research has also been undertaken by landholders and natural resource management and community-based organizations trying to deal with specific situations where leucaena has become a problem within their jurisdictions (e.g. Folkers 2010).

Despite limited information on specific control options for weedy leucaena, several of the mechanical and chemical techniques developed for other woody weeds (Vitelli and Pitt 2006) may be relevant. If available, mechanical control would be an appropriate option for treating dense infestations of leucaena using equipment such as bulldozers (with blade, stick-rake or blade-plough attachments) or tractors and excavator-style machinery fitted with mulching devices or other destructive equipment. Any equipment that severs the root system below ground should cause high mortality but, if the plant is cut off at ground level such as during mulching, there is a higher likelihood of significant re-shooting occurring. In a series of control trials undertaken in the Mackay region of Queensland, the use of a cutter bar operating 30 cm below ground resulted in 100% mortality (Folkers 2010). This is likely to be followed by extensive seedling emergence.

Control of re-shooting plants and seedling regrowth can be undertaken with herbicides applied using a few different techniques. However, leucaena is a fairly difficult plant to control with herbicides compared with some other woody weeds, with highest mortality usually achieved by controlling younger plants, particularly if foliar spraying is the preferred method.

The basal bark technique, which involves spraying the stem of plants up to a height of around 30–40 cm from ground-level with herbicides mixed with diesel or oil-based products is consistently one of the most effective treatments on larger plants. Cutting plants off close to ground level and spraying the cut stem immediately afterwards is another effective option (Figure 4) but it is expensive and impractical for large areas unless machinery is used such as a mulcher with the herbicide applied immediately after treatment. In Australia, a triclopyr/picloram- (Access™) based product mixed with diesel is registered for both basal bark and cut stump applications on leucaena (Queensland Government 2016). In Hawaii triclopyr is recommended for basal bark and cut stump applications (Leary et al. 2012).

Figure 4. A roadside infestation of leucaena near Townsville (Australia) treated using the cut stump method.

In Australia, early screening work and more recent adaptive-style trials have shown that foliar applications of glyphosate, clopyralid and triclopyr/picloram-based products can kill leucaena. However, results were often variable, and mortality tended to decrease with increasing plant size (Pest Management Research 2002; Walton 2003a; Folkers 2010). There are no current label registrations for any herbicides to be applied using foliar applications in Australia but permits have been approved previously by the Australian Pesticides and Veterinary Medicines Authority (APVMA) for certain situations. For example, minor use permit PER9395 was issued by APVMA in 2007 for the control of leucaena seedlings on mine rehabilitation sites using a foliar application of triclopyr/picloram (150/50 g a.i./100 L water) (APVMA 2018). In Hawaii triclopyr is recommended for foliar application on leucaena plants that are less than 6 feet tall (Leary et al. 2012).

To increase the range of herbicide options to control leucaena in Australia, a collaborative exercise between industry, producers, government and Dow AgroSciences (now Corteva Agriscience™) resulted in 3 trials being implemented during December 2015 and January 2016 with final assessments undertaken 12 months later. A total of 18 herbicide treatments (including an untreated control) were applied using either basal bark, cut stump, gas gun (low-volume, high-concentration), stem blaze or frill, or the ground application of residual herbicides. The results showed that the registered basal bark techniques (both the traditional and newer thin-line method which involves spraying a more concentrated mix to the bottom 5 cm of stem) using triclopyr/picloram (Access™) consistently gave the best results but some other options also showed promise. In particular, cut stump applications of aminopyralid/metsulfuron-methyl (Stinger™) mixed with water and an aminopyralid/picloram gel (Vigilant™ II) provided greater than 80 and 60% efficacy, respectively. Ground applications of picloram granules (Tordon™ Granules) also showed promise, with limited impact on surrounding grasses and legumes. Ineffective treatments included cut stump applications using glyphosate (Glyphosate 360®) and metsulfuron-methyl (Brush-Off®), gas gun applications using metsulfuron-methyl (Brush-Off®) and aminopyralid/metsulfuron-methyl (Stinger™) and ground applications of tebuthiuron (Graslan®) and hexazinone (Velpar® L). Based on these results, the gas gun application method (low-volume, high-concentration) does not appear to be an effective option for leucaena control, possibly due to the small bi-pinnate leaf and insufficient herbicide translocating into the large biomass of mature plants (M. Vitelli pers. comm.).

A relatively new and novel stem injection technique that uses a specialized applicator and encapsulated dry herbicides is currently showing promise for a range of woody plants, including leucaena. It could have application for treating unwanted plants, particularly in sensitive areas such as waterways and national parks and in areas that are inaccessible to other equipment, such as hillslopes (Goulter et al. 2018). In Hawaii, stem injection applications using aminopyralid are an available option for leucaena control (Leary et al. 2012).

The use of fire as a control option for leucaena has not been formally tested, but warrants investigation. Anecdotal reports are variable, ranging from nil effects (Figure 5) to reasonable mortality, but this could be reflective of variability in the fires implemented. It appears that, if relatively high-intensity fires are imposed, plant mortality is possible, particularly for smaller plants (Wolfe and van Bloem 2012). Nevertheless large-scale seedling regrowth should be expected with seed scarification potentially occurring as a result of exposure to high temperatures for a short period (Walton 2003a). While this has the potential to exacerbate the problem, it can be advantageous as part of an integrated management strategy by increasing the rate of depletion of soil seed reserves, when combined with follow-up control (Campbell and Grice 2000).

Figure 5. Leucaena re-shooting after a fire in Central Queensland (Australia).

Given the benefits of leucaena, biological control has not been a high research priority. A biological control program in South Africa in 1999 resulted in the release of a seed beetle *Acanthoscelides macrophthalmus* Schaeffer, with the aim of trying to prevent establishment/replenishment of persistent soil seed banks (Olckers 2011). The beetle has now established in another 13 countries (Australia, Benin, Ethiopia, India, Japan, China, Cyprus, Senegal, Taiwan, Thailand, Togo, Vanuatu and Vietnam) as a result of seed contamination or accidental introductions (Raghu et al. 2005; Wu et al. 2013; iBiocontrol 2018). The beetle reduces the viability of seeds, but its effectiveness is variable depending on a range of factors (Olckers 2011; Egli and Olckers 2012; Sharratt and Olckers 2012; Ramanand and Olckers 2013; English and Olckers 2014). In many instances, soil seed banks are still sufficient for seedling recruitment to occur. A sap-sucking psyllid, *Heteropsylla cubana* Crawford, has also been accidentally introduced into many countries, where it is having negative impacts on the productivity of leucaena for commercial purposes, but has not reduced the weediness of leucaena, as infestations are still expanding where the psyllid is present (Olckers 2011).

A range of land management practices can also play an important role in the management of leucaena. It is not an overly competitive species (particularly in the seedling and juvenile stages), so maintaining a healthy pasture within leucaena paddocks and in surrounding areas will greatly reduce seedling recruitment and spread into new areas. Furthermore, if commercial plantings and/or infestations of leucaena are grazed in a manner that defoliates the plants and prevents/minimizes the production of pods, this will greatly reduce the amount of seed that can be dispersed into other areas (Walton 2003a; 2003b). Periodic cutting back of leucaena in paddocks may be required if an increasing proportion of plants grow beyond the reach of livestock and start producing large quantities of seed. Incorporation of grazing as part of management strategies for weed infestations of leucaena is an option that could be explored, either initially to reduce its abundance or as a follow-up technique to utilize the regrowth. The use of goats to control leucaena also warrants further investigation as anecdotal evidence suggests that they will consume not only available foliage but also bark and will keep ring-barking plants, resulting in many eventually dying (M. Shelton pers. comm.). In the absence of grazing, utilization of infestations such as through harvesting for fuelwood and fodder has proven highly effective in minimizing the impacts and spread of leucaena in some countries (e.g. Thailand and parts of Indonesia) (M. Shelton pers. comm.). Nevertheless, given the ecology of leucaena, land managers planning on tackling large established infestations need to be prepared to make a long-term commitment, irrespective of the techniques to be used. Many weed management programs fail because a large area is treated initially. This is often the easiest part, with follow-up treatment being much more difficult, particularly if environmental conditions favor large-scale germination and seedling growth. Control of isolated or small patches before they get the opportunity to spread and establish large and persistent seed banks is the best preventative strategy.

Mitigation strategies

Leucaena has been included in formal weed prioritization and/or risk assessment processes (e.g. Pheloung et al. 1999; Walton 2003a; Nel et al. 2004; Gordon et al. 2011; Reddy 2014) within several countries to determine appropriate strategies to minimize its potential or current impacts at various jurisdictional levels (e.g. local, regional, provincial or national). Depending on its classification or the level of risk, the response has been varied, ranging from no action through to some jurisdictions formally recognizing leucaena as an environmental weed within relevant legislation.

Given the beneficial attributes of leucaena, few countries have used legislative powers as a strategy to prevent, minimize or manage its impacts within their jurisdictions. An exception is South Africa where it is listed as a Category 2 weed under the National Environmental Management: Biodiversity Act 2004 (Act No. 10 of 2004). Category 2 weeds include species that have economic benefits (e.g. agroforestry and fodder species) and are not otherwise prohibited. According to the Act, such species may be imported, harbored, propagated and traded only if a permit is obtained. This classification allows leucaena to be planted and commercially grown in demarcated areas provided steps are taken to control spread (Nel et al. 2004). Outside of demarcated areas, leucaena is considered the equivalent of a Category 1b invasive species, which means that it must be controlled or eradicated where possible (L. Henderson pers. comm.).

While not declared at a national or even a state/territory level in Australia, leucaena has been declared by several local government authorities in Queensland (Walton 2003a; 2003b), which is the equivalent of the third tier of government in a national context. At the higher levels of government, relevant states and territories provide information (e.g. fact sheets) on the potential weed impacts of leucaena as well as options to control infestations. In Queensland, the Biosecurity Act 2014 also legislates that everyone has a general biosecurity obligation (GBO) to take reasonable and practical steps to minimize the risks associated with invasive plants and animals under their control, including leucaena (Queensland Government 2016). In Western Australia, *L. leucocephala* is a permitted species, but it has been classified as a very high environmental weed risk in the Pilbara and Kimberley regions (Revell et al. 2019). Consequently, in these regions leucaena is not approved for use on the extensive areas of pastoral lease (government-owned crown land) but can be grown on freehold land (though this represents less than 2% of the area).

For contentious plants such as leucaena, Clarkson et al. (2010) suggested that a range of non-legislative options could be considered, including the use of codes of practice, subsidies, compensation, bonds, levies or insurance schemes. A voluntary Code of Practice was developed in 2000 by The Leucaena Network, a group of graziers, scientists and extension officers dedicated to advocating the responsible use of leucaena in northern Australia (Shelton and Dalzell 2007; Christensen 2019). It has the key principle that leucaena should be planted only if it is to be proactively managed and if responsibility is accepted to control plants that establish outside planted areas. Eleven recommended practices are identified with a focus on avoiding planting leucaena near potential weed-risk zones, minimizing seed set in grazed stands, diminishing the risk of live-seed dispersal and control of escaped plants from grazed stands. Although voluntary, the implementation of a self-auditing process or some sort of certification measures would be beneficial for the leucaena industry to demonstrate a level of compliance with the Code of Practice.

The recent investment in Australia by industry and government into research aimed at developing sterile leucaena varieties (McMillan et al. 2019; Real et al. 2019) is a positive and proactive initiative. If the environmental risks associated with sterile leucaena can be demonstrated to be minimal, jurisdictions that currently ban or discourage the growing of leucaena, may consider allowing the introduction of sterile varieties in certain situations. This would lead to an expansion of the leucaena industry not only in Australia but also potentially in other countries where weed concerns are preventing it from being grown or promoted for commercial purposes.

Conclusion

Leucaena is a very good example of a contentious plant given its many beneficial attributes, while also having the potential to become a major environmental weed. It has biological and ecological attributes that allow it to disperse from its source and to establish in new areas, particularly disturbed environments. Once it becomes entrenched in an area, the relatively long-lived nature of plants and soil seed banks, combined with an ability for new plants to reach reproductive maturity within a short timeframe, makes successful control a difficult, prolonged and expensive proposition. Legislation at an appropriate jurisdictional level has been used sparingly and often aimed at minimizing the environmental impacts of leucaena, while still allowing its commercial use, albeit with certain restrictions/requirements. For leucaena growers, proactive management of leucaena to minimize spread from their land will greatly reduce the likelihood of new infestations establishing from commercial operations. Practices identified in the Code of Practice, developed by The Leucaena Network in Australia, are a good starting point and could be modified to suit specific situations within different countries. For successful management of weed infestations of leucaena, an integrated approach will be required in most instances to deal not only with the original infestation but also the regrowth/recruitment that will occur so long as there is a viable soil seed bank. Options that could be incorporated, depending on available resources, include utilization (e.g. cutting for firewood, fodder), land-management practices (e.g. competitive pastures and strategic grazing), biological, chemical and mechanical control and perhaps the use of fire in some situations. However, ongoing research to improve control options for a range of situations and to develop sterile leucaena varieties is necessary if future expansion of leucaena is to be allowed in areas where jurisdictions currently restrict/prevent its use due to weed concerns. An on-going dialogue between all organizations with a vested interest in leucaena from both positive and negative perspectives is also critical if industry expansion of leucaena is to occur in a manner that minimizes environmental impacts.

Acknowledgments

We gratefully acknowledge the contributions of those who have directly and indirectly contributed to this paper. In particular, Michael Burgis, Marie Vitelli and Chris Love were responsible for undertaking the more recent herbicide research that is summarized in the control section. We are grateful to Dr Faiz Bebawi who initiated a long-term weed seed burial trial that included leucaena, with some preliminary results presented in this paper. Dr Terence Olckers and Lesley Henderson kindly gave their input on the legislative status of leucaena in South Africa. Similarly, Drs Clinton Revell and Daniel Real provided advice on restrictions associated with growing leucaena in Western Australia. Associate Professor Max Shelton provided information which enhanced the manuscript. We are also appreciative of input from Drs Hayley McMillan and Joe Scanlan who gave valuable feedback on earlier drafts of the paper.

References

(Note of the editors: All hyperlinks were verified 4 August 2019.)

APVMA (Australian Pesticides and Veterinary Medicines Authority). 2018. PER9395, Access & Grazon DS/Mine rehabilitation/*Leucaena leucocephala*. Australian Pesticides and Veterinary Medicines Authority Permits Search. Australian Government, Canberra, ACT, Australia. portal.apvma.gov.au/permits

Bebawi FF; Campbell SD; Mayer RJ. 2015. Seed bank longevity and age to reproductive maturity of *Calotropis procera* (Aiton) W.T. Aiton in the dry tropics of northern Queensland. The Rangeland Journal 37:239–247. doi: 10.1071/RJ14130

CABI (Centre for Agriculture and Bioscience International). 2018. Invasive Species Compendium: *Leucaena leucocephala* (leucaena). CABI, Wallingford, UK. cabi.org/isc/datasheet/31634

Campbell SD; Grice AC. 2000. Weed biology: A foundation for weed management. Tropical Grasslands 34:271–279. bit.ly/2yCBFbl

Christensen B. 2019. The Leucaena Network and the Leucaena Code of Practice. Tropical Grasslands-Forrajes Tropicales 7:331–332. doi: 10.17138/TGFT(7)331-332

Clarkson JR; Grice AC; Friedel MH; Setterfield SA; Ferdinands K. 2010. The role of legislation and policy in dealing with contentious plants. Proceedings of the 17th Australasian Weeds Conference, Christchurch, New Zealand, 26−30 September 2010. p. 474−477. bit.ly/2GL0O8m

Costa JT; Fonseca ICB; Bianchini E. 2015. Population structure of the invasive species *Leucaena leucocephala* (Fabaceae) in a seasonal semi-deciduous forest, southern Brazil. Australian Journal of Botany 63:590−596. doi: 10.1071/BT14308

Egli D; Olckers T. 2012. Oviposition patterns and egg mortality in *Acanthoscelides macrophthalmus* (Chrysomelidae: Bruchinae), a biological control agent of *Leucaena leucocephala* (Fabaceae) in South Africa. African Entomology 20:111−118. doi: 10.4001/003.020.0114

English KF; Olckers T. 2014. Does the size of the seeds and seed pods of the invasive tree *Leucaena leucocephala* (Fabaceae) affect their utilization by the biological control agent *Acanthoscelides macrophthalmus* (Chrysomelidae: Bruchinae)? African Entomology 22:872−879. doi: 10.4001/003.022.0412

FAO (Food and Agriculture Organization of the United Nations). 2009. Conflict species. FAO, Rome, Italy. bit.ly/2KepeZH

Folkers A. 2010. Management of weedy leucaena in the Mackay Whitsunday region. Final Report, Blueprint for The Bush Project. Mackay Regional Pest Management Group, Mackay, QLD, Australia.

GISD (Global Invasive Species Database). 2015. Species profile: *Leucaena leucocephala*. bit.ly/2KsZUy4

Gordon DR; Tancig KJ; Onderdonk DA; Gantz CA. 2011. Assessing the invasive potential of biofuel species proposed for Florida and the United States using the Australian weed risk assessment. Biomass and Bioenergy 35:74−79. doi: 10.1016/j.biombioe.2010.08.029

Goulter KC; Galea VJ; Riikonen P. 2018. Encapsulated dry herbicides: A novel approach for control of trees. Proceedings of the 21st Australasian Weeds Conference, Sydney, Australia, 9−12 September 2018. p. 247−250. bit.ly/2T53CSk

iBiocontrol. 2018. Biological control of weeds: A world catalogue of agents and their target weeds. ibiocontrol.org

Jones RJ; Bunch GA. 1995. Long-term records of legume persistence and animal production from pastures based on Safari Kenya clover and leucaena in subtropical coastal Queensland. Tropical Grasslands 29:74−80. bit.ly/2yBU3RB

Jones RJ; Bunch GA. 2000. A further note on the survival of plants of *Leucaena leucocephala* in grazed stands. Tropical Agriculture (Trinidad and Tobago) 77:109−110. bit.ly/2M0DEyX

Leary J; Beachy J; Hardman A. 2012. Practitioner's guide for effective non-restricted herbicide techniques to control and suppress invasive woody species in Hawaii. Weed Control 10. University of Hawaii, Honolulu, HI, USA. hdl.handle.net/10125/33257

Marques AR; Costa CF; Atman APF; Garcia QS. 2014. Germination characteristics and seedbank of the alien species *Leucaena leucocephala* (Fabaceae) in Brazilian forest: Ecological implications. Weed Research 54:576–583. doi: 10.1111/wre.12107

McDonald CK. 2000. Variation in the rate of hard seed breakdown of twelve tropical legumes in response to two temperature regimes in the laboratory. Australian Journal of Experimental Agriculture 42:387–396. doi: 10.1071/EA99099

McMillan HE; Liu G; Shelton HM; Dalzell SA; Godwin ID; Gamage H; Sharman C; Lambrides CJ. 2019. Sterile leucaena becomes a reality? Tropical Grasslands-Forrajes Tropicales 7:74–79. doi: 10.17138/TGFT(7)74-79

Nel JL; Richardson DM; Rouget M; Mgidi TN; Mdzeke N; Le Maitre DC; Van Wilgen BW; Schonegevel L; Henderson L; Neser S. 2004. Proposed classification of invasive alien plant species in South Africa: Towards prioritizing species and areas for management action. South African Journal of Science 100:53–64. hdl.handle.net/10204/2083

Normaniza O; Faisal HA; Barakbah SS. 2008. Engineering properties of *Leucaena leucocephala* for prevention of slope failure. Ecological Engineering 32:215–221. doi: 10.1016/j.ecoleng.2007.11.004

Olckers T. 2011. Biological control of *Leucaena leucocephala* (Lam.) de Wit (Fabaceae) in South Africa: A tale of opportunism, seed feeders and unanswered questions. African Entomology 19:356–365. doi: 10.4001/003.019.0219

Panetta FD. 2004. Seed banks: The bane of the weed eradicator. Proceedings of the 14th Australian Weeds Conference, Wagga Wagga, NSW, Australia, 6–9 September 2004. p. 523–526. bit.ly/33diRgY

Panetta FD; Cacho O; Hester S; Sims-Chilton N; Brooks S. 2011. Estimating and influencing the duration of weed eradication programmes. Journal of Applied Ecology 48:980–988. doi: 10.1111/j.1365-2664.2011.02000.x

Pest Management Research. 2002. 2001–2002 Technical highlights annual report on weed and pest animal research. Department of Natural Resources and Mines, Brisbane, QLD, Australia.

Pheloung PC; Williams PA; Halloy SRA. 1999. A weed risk assessment model for use as a biosecurity tool evaluating plant introductions. Journal of Environmental Management 57:239–251. doi: 10.1006/jema.1999.0297

Raghu S; Wiltshire C; Dhileepan K. 2005. Intensity of pre-dispersal seed predation in the invasive legume *Leucaena leucocephala* is limited by the duration of pod retention. Austral Ecology 30:310–318. 10.1111/j.1442-9993.2005.01475.x

Ramanand H; Olckers T. 2013. Does height of exposure in the canopy influence egg mortality in *Acanthoscelides macrophthalmus* (Coleoptera: Chrysomelidae), a biological control agent of *Leucaena leucocephala* in South Africa? Biocontrol Science and Technology 23:545–554. doi: 10.1080/09583157.2013.790344

Real D; Han Y; Bailey CD; Vasan S; Li C; Castello M; Broughton S; Abair A; Crouch S; Revell C. 2019. Strategies to breed

sterile leucaena for Western Australia. Tropical Grasslands-Forrajes Tropicales 7:80–86. doi: 10.17138/TGFT(7)80-86
Reddy GVP. 2014. Risk assessments and management practices for the major invasive plants recorded in the horticultural ecosystem of the Western Pacific. In: Nandwini D, ed. 2014. Sustainable horticultural systems: Sustainable Development and Biodiversity, Vol 2. Springer, Cham, Switzerland. p. 315–327. doi: 10.1007/978-3-319-06904-3_14
Revell CK; Moore GA; Real D; Crouch S. 2019. Environmental adaptation of leucaena in Western Australia – challenges and opportunities. Tropical Grasslands-Forrajes Tropicales 7:112–119. doi: 10.17138/TGFT(7)112-119
Roose E; Bellefontaine R; Visser M. 2011. Six rules for the rapid restoration of degraded lands: Synthesis of 17 case studies in tropical and Mediterranean climates. Sécheresse 22:86–96. doi: 10.1684/sec.2011.0300
Sharrat MEJ; Olckers T. 2012. The biological control agent *Acanthoscelides macrophthalmus* (Chrysomelidae: Bruchinae) inflicts moderate levels of seed damage on its target, the invasive tree *Leucaena leucocephala* (Fabaceae) in the KwaZulu-Natal coastal region of South Africa. African Entomology 20:44–51. doi: 10.4001/003.020.0106
Shelton HM; Dalzell SA; McNeill FL. 2003. A survey of the weed status and management of *Leucaena leucocephala* (Lam.) de Wit in Queensland. Plant Protection Quarterly 18:42–47. bit.ly/2V4xlym
Shelton M; Dalzell S. 2007. Production, economic and environmental benefits of leucaena pastures. Tropical Grasslands 41:174–190. bit.ly/2yC0FiT
Queensland Government. 2016. Factsheet: Leucaena (*Leucaena leucocephala*). The State of Queensland, Department of Agriculture and Fisheries, Brisbane, QLD, Australia. bit.ly/2T2FQqm
Vitelli JS; Pitt JL. 2006. Assessment of current control methods relevant to the management of the biodiversity of Australian rangelands. The Rangeland Journal 28:37–46. doi: 10.1071/RJ06016
Walton C. 2003a. Leucaena (*Leucaena leucocephala*) in Queensland. Department of Natural Resources and Mines, Brisbane, QLD, Australia. bit.ly/2IBCUOj
Walton C. 2003b. The biology of Australian weeds. 42. *Leucaena leuocephala* (Lamark) de Wit. Plant Protection Quarterly 18:90−98. bit.ly/2vKAcOH
Wan JZ; Zhang ZX; Wang CJ. 2018. Identifying potential distributions of 10 invasive alien trees: Implications for conservation management of protected areas. Environmental Monitoring and Assessment 190:739. doi: 10.1007/s10661-018-7104-6
Wolfe BT; van Bloem SJ. 2012. Subtropical dry forest regeneration in grass-invaded areas of Puerto Rico: Understanding why *Leucaena leucocephala* dominates and native species fail. Forest Ecology and Management 267:253–261. doi: 10.1016/j.foreco.2011.12.015
Wu LH; Wang CP; Wu WJ. 2013. Effects of temperature and adult nutrition on the development of *Acanthoscelides macrophthalmus*, a natural enemy of an invasive tree, *Leucaena leucocephala*. Biological Control 65:322–329. doi: 10.1016/j.biocontrol.2013.03.015
Yoshida K; Oka S. 2004. Invasion of *Leucaena leucocephala* and its effects on the native plant community in the Ogasawara (Bonin) Islands. Weed Technology 18:1371–1375. doi: 10.1614/0890-037X(2004)018[1371:IOLLAI]2.0.CO;2

(Accepted 6 February 2019 by the ILC2018 Editorial Panel and the Journal editors; published 3 September 2019)