SUSTAINABLE CONTROL OF INVASIVE JAPANESE KNOTWEED

Dr Daniel Jones[1,2] and Professor Daniel Eastwood[1], [1]Department of Biosciences, Swansea University, Singleton Park, Swansea, SA2 8PP, UK; [2]Advanced Invasives Ltd, Institute of Life Science, Swansea University, Singleton Park, SA2 8PP, UK. E-mail: daniel.ll.jones@gmail.com. ORCID ID: 0000-0002-3192-6450, Department of Biosciences, Swansea University, Singleton Park, Swansea, SA2 8PP, UK. E-mail: d.c.eastwood@swansea.ac.uk. ORCID ID: 0000-0002-7015-0739. Corresponding author: Daniel Jones. E-mail: daniel.ll.jones@gmail.com Telephone: +44 7967 408844. Invasive alien weeds cause significant damage in their 'new' ecosystems.
The authors consider approaches to the control of Japanese knotweed in the UK.

Keywords: Integrated pest management (IPM); integrated weed management (IWM); sustainability; Japanese knotweed; *Fallopia japonica* var. *japonica*; invasive alien plants (IAPs); invasive non-native species (INNS); glyphosate; herbicide

Dr Daniel Jones

Professor Daniel Eastwood

Summary

Control and management of invasive plants frequently differs from agricultural weed control as plant establishment and development progresses in less intensively managed systems. This is particularly the case for rhizome-forming invasive plants, such as Japanese knotweed (*Fallopia japonica* var. *japonica*) as minimum disturbance regimes permit the accumulation of significant below ground reserves that allow recovery from many physical, biological, chemical and integrated control methods. Here, we review the ongoing work of Jones *et al*. (2018), who established the world's largest and longest running invasive knotweed field trial. Using an integrated weed management (IWM) approach to testing, this research evaluated 19 different control treatments over three years to minimise pesticide use and increase the sustainability of controlling this ecologically and economically damaging species. Through consideration of plant biology, it was found that glyphosate-based herbicide treatments that exploited phenological changes in rhizome source-sink were significantly more effective than all other treatments. These results provide a roadmap to the more effective and efficient control of rhizome-forming invasive plants and emphasise the importance of scale appropriate empirical evidence to inform regulators when considering non-agricultural weed control.

Introduction

Weed management context

Within intensively managed arable agricultural systems, weed control is directed toward immature annual and perennial plants, during a 'critical period' extending for a relatively short time after crop emergence. This is because at this time, resource depletion by weed species may exert a major negative effect upon crop yield (Swanton *et al*. 2008). Agronomic weed management may be achieved using a range of weed control methods, including: cultural/preventative (e.g. soil cultivation, disrupting weed establishment), physical (mechanical methods or hand weeding), biological (biocontrol or bioherbicides), chemical (plant protection products; PPPs) and integrated weed management (IWM). True IWM systems combine cultural, physical, biological and/or chemical methods; integrated herbicide management systems use a range of PPPs to mitigate selection of resistant weed populations (Van der Weide *et al*. 2008, Harker & O'Donovan 2013, Cordeau *et al*. 2016).

In contrast, control of invasive weed species, or invasive alien plants (IAPs; see Table 1 for definitions) is commonly undertaken in less intensively managed systems, or unmanaged areas such as abandoned agricultural land, riparian areas and brownfield sites. Here, IAPs tend to be large and

Figure 1. Japanese knotweed (*Fallopia japonica* var. *japonica*) growing vigorously along the banks of the River Taff in Cardiff (UK).

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Table 1. Alien plant key terms (derived from Richardson & Pyšek 2006). Conceptually, the invasion process is best understood as a series of biogeographical, environmental and reproductive barriers that an introduced species must overcome to become alien (casual alien), naturalised and invasive alien plants (IAPs), respectively. IAPs are characterised by the 'escape' pathway of introduction, as feral crops (e.g. oilseed rape, *Brassica napus* subsp. *napus*) and ornamental plant species (e.g. *F. japonica*) (Hulme et al. 2008).

Key term	Definition
Alien plants	Plants present in an area due to human-mediated transport
Casual alien plants	Plants that occasionally reproduce outside cultivation, but fail to establish permanently outside of cultivation, as they do not form self-replacing populations
Naturalised plants	Alien plants that form self-replacing populations for ≥10 years without (or despite) direct human intervention, by recruitment from propagules capable of independent growth
Invasive Alien Plants (IAPs)	Naturalised plant subset that produces reproductive offspring, often in large numbers, at considerable distances from parent plants, displaying potential to spread over a large area

well-established so that plant persistence and development processes are often unhindered by weed control methods typically applied in agriculture. This is particularly true of rhizome-forming invasive species, such as Japanese knotweed (*Fallopia japonica* var. *japonica*) where minimal disturbance regimes permit the long-term development of significant carbohydrate reserves within perennating rhizome organs below the soil surface (>50 cm). Storage reserves permit recovery from repeated intentional disturbance and biological control; while physical size, depth, resilience and strong seasonal changes in source-sink strength of such organs preclude effective chemical control using many herbicides, as insufficient herbicide active ingredient is accumulated within storage tissues (Jones 2015).

Debate around invasive plant management

Most alien plants introduced by humans do not become invasive and some are important food or fibre crops. Those that do become naturalised and classified as IAPs require suitable environmental conditions and physical characteristics which allow them to colonise and outcompete native flora, i.e. invasibility of a habitat and invasiveness of the incoming species.

IAPs create a range of negative ecological and socioeconomic impacts within their recipient ecosystem(s) (Vilà *et al*. 2011), though the evidence base underpinning such assertions and the economic and environmental cost of management are subject to ongoing contentious debate (Richardson & Ricciardi 2013, Thompson 2014). IAP control and management interventions may be undermined when the evidence-

Table 2. Invasive Alien Plant (IAP) control programme objectives key terms and definitions.

Key term	Definition
Eradication	'the elimination of every single individual of a species from an area to which recolonization is unlikely to occur' (Myers *et al.* 1998)
Maintenance management	involves 'controlling an invasive weed to the extent that further spread and dispersal is limited and the damage that the species causes is tolerable' (Panetta 2015)

base supporting intervention is not empirical and/or where it is not of suitable spatial scale and temporal duration. Consequently, control method selection is frequently based on personal, contractor or herbicide manufacturer preference and expedience (Kettenring & Adams 2011). Accordingly, IAP control methods may have low economic and environmental sustainability, characterised by low efficacy, excessive labour and herbicide inputs and high CO_2 outputs (Kabat *et al*. 2006, Tyler *et al*. 2006).

The terms used to define control, management and eradication are used interchangeably with respect to invasive plant management; however, they mean very different things (Table 2). Confirming eradication can be difficult for invasive plants, where a resting stage (e.g. seed and/or bud bank) is often resistant to treatments and may not be detected for long periods. The viable persistence of such diaspores generally determines the minimum duration of an eradication programme (Klimešová & Klimeš 2007, Panetta 2015). Notably, the effort required to achieve eradication is far greater than that of maintenance control, even though the methods used may be the same. This often results in a mismatch between the objectives of a management programme and the funding available to undertake control methods, leading to insufficient resourcing to achieve the actions required. Reasonable total cost estimates to inform decision-making investment in eradication and/or management efforts are paramount and anecdotal reports or commercial tenders require scrutiny if expected outcomes are to be achieved (Panetta 2015).

Japanese knotweed: a particular case in point

In the UK, there are four invasive knotweed species, collectively referred to as Japanese knotweed *sensu lato* (*s.l.*; in the broader sense). Japanese knotweed (*Fallopia japonica* var. *japonica*) is the most common of these species and it is widely distributed throughout the UK, despite being restricted to asexual (clonal) dispersal principally via rhizome fragments and direct rhizome extension (Bailey *et al*. 2009). Negative impacts of Japanese knotweed on native ecology and the built environment are directly related to the rhizomatous perennial growth of this species.

Knotweed rhizomatous storage reserves affect management strategy by enabling the plant to recover from physical and biological control methods, even when applied over long time periods (>3 years). While complete physical excavation

Figure 2. Panorama of Jones *et al.* (2018) primary Japanese knotweed field trial site in Taffs Well (near Cardiff, UK), highlighting the vigour of the knotweed monoculture pretreatment (2012) and control and management progress during ongoing testing (2018).

of all below ground biomass is possible in short timescales, it has not been evaluated empirically. It is also an order of magnitude more costly and carbon intensive than chemical control methods and cannot be applied at the landscape scale. Such physical techniques are challenging to achieve as reliable regeneration has been reported from rhizome fragments weighing ~0.06 g (though as little as 0.01 g has been successfully propagated) and human error is frequently reported (Macfarlane 2011).

Furthermore, the physical size of mature knotweed plants (above and below ground biomass may exceed 2 and 3 kg per m^2, respectively), depth of belowground growth (Jones 2015 reported rhizome extending more than 2.5 m below the soil surface), resilience and seasonal changes in source-sink strength of the rhizome network must be accounted for within effective chemical control programmes: it is challenging to poison large volumes of the resilient above and belowground biomass and achieve effective translocation of glyphosate-based herbicide to knotweed rhizome, much of which is distant from the point of herbicide application (Jones *et al*. 2018).

Sustainably meeting the challenge

The UK provides an interesting case study for the management of widespread weed species that cause both environmental and socioeconomic impact. Government legislation aims to minimise further Japanese knotweed dispersal in the UK, while existing knotweed stands are targeted for managed control. The costs associated with knotweed remediation in the UK was estimated at £165.6 million per annum (Williams *et al*. 2010) and national 'best practice' guidance for managing knotweed was introduced by the UK Government Environment Agency in 2006 (Managing Knotweed on Development Sites: The Knotweed Code of Practice). However, in 2016 this guidance was withdrawn with no replacement and similarly to the European Union (EU) and North America, there is no longer a reliable source of evidence-based 'best practice' to guide costly management decision-making.

To provide robust evidence to inform best practice, Jones *et al*. (2018) created a novel four-stage mechanistic model that targeted the control strategy to resource allocation and rhizome source-sink strength during Japanese knotweed growth (Figure 3). The control methods aimed to effect rhizome depletion, minimise within season resource acquisition and/or herbicide uptake, movement and metabolism. The key objective of the project was to minimise PPP use by following an IWM approach. In order to achieve this aim, the world's largest and longest running Japanese knotweed field trial was established across three comparable sites in South Wales, UK. Sufficient temporal and spatial scale were requisite, as knotweed is a long-lived perennial species frequently exhibiting significant lateral rhizome extension. Each control treatment was tested in triplicate 225 m^2 treatment plots (with the exception of covering), with one control plot at each field-trial site.

Nineteen physical (e.g. covering), chemical (e.g. herbicide applications) and integrated (e.g. cutting before herbicide application) control methods were tested over three years (Table 3). Complete physical excavation was not included due to prohibitive cost and imazapyr could not be tested as it is not authorised for use in the EU. It is noteworthy that most field-based invasive plant control trials (worldwide) test fewer than 5 control methods simultaneously (Kettenring & Adams 2011).

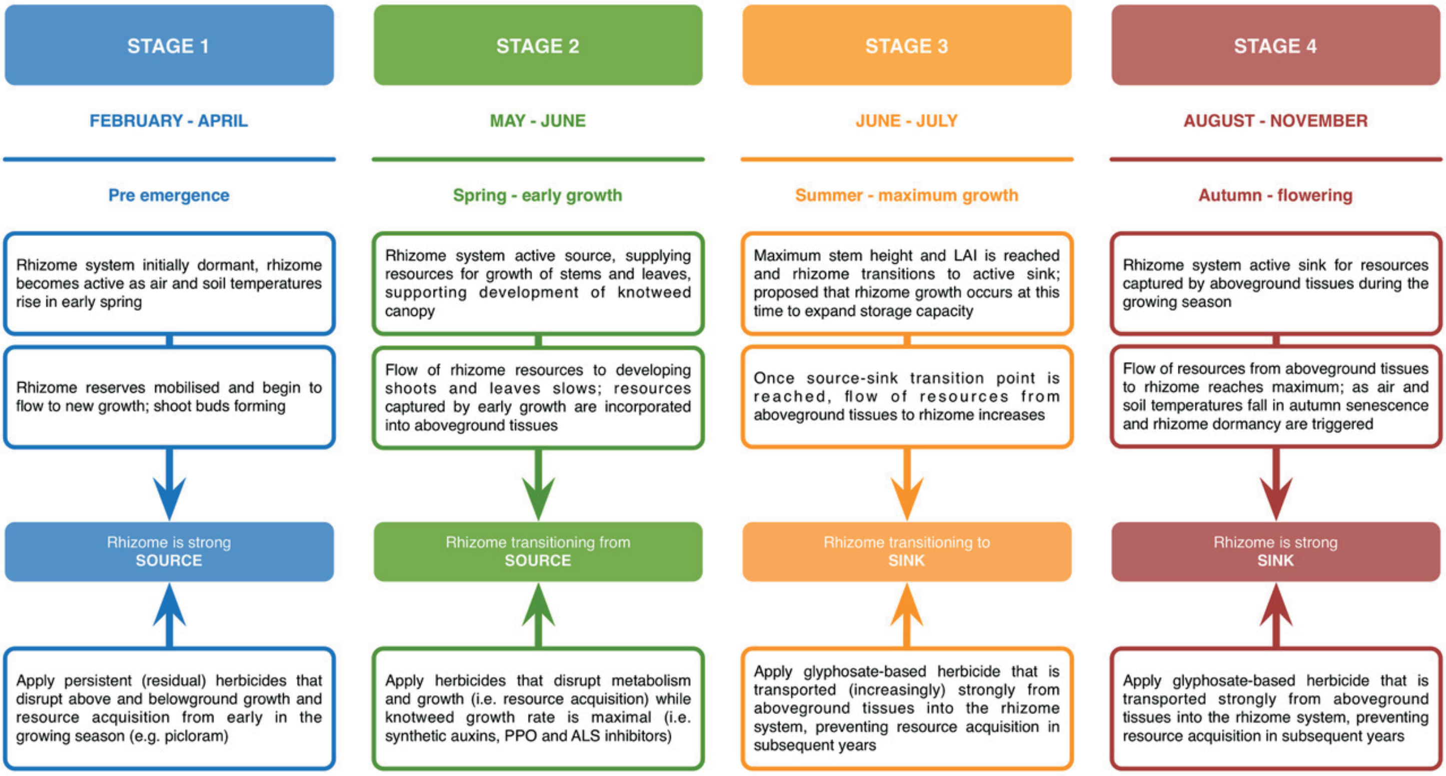

Figure 3. Four stage mechanistic model of phenological changes in *F. japonica* growth, resource allocation and rhizome source-sink strength during the growing season. LAI = leaf area index. Note linkage of above and belowground growth processes with changes in source-sink strength and that rhizome tissue sink strength increases through the growing season from June, reaching a peak in August–November during flowering and senescence. Control treatment application should account for seasonal changes in rhizome source-sink strength. The precise timing of stages 1 to 4 are dependent upon local conditions. Reproduced from Jones *et al.* (2018) with permission.

Key findings

Of the 19 Japanese knotweed control methods tested, long term covering of knotweed with a robust geomembrane (TG d4) was the least effective treatment, as defined by the response variables basal cover and stem density reduction over time (i.e. did not differ significantly from the untreated control). This finding is crucial, as covering was the only physical control method that was feasible for the sustained depletion of rhizome energetic reserves. Others, such as hand-pulling of shoots, hand-digging and mowing, strimming, and cutting, are likely to increase rhizome dispersal, aside from being impractical and expensive for established knotweed stands. Further, the ineffectiveness of covering demonstrates that it is unlikely to be possible to deplete the energy reserves of established knotweed stands within decadal timescales.

Application of glyphosate, an aromatic amino acid (AAA) biosynthesis inhibitor, provided the greatest basal cover and stem reduction whether as a summer and autumn spray application (a3), single autumn spray (a1) or autumn stem injection (c1). However, repeated annual application was needed to provide long-term control. Other integrated physical and chemical control methods, e.g. summer cutting and autumn glyphosate application (TG d1) and integrated chemical control methods (a4 to a13) did not improve Japanese knotweed control compared to glyphosate alone. Therefore, the time and cost of additional treatments without improved control is unnecessary. Additionally, unlike glyphosate, synthetic auxins, acetolactate synthase (ALS) and protoporphyrinogen oxidase (PPO) inhibitors cannot be used near water in the UK where knotweed commonly grows and picloram is now withdrawn from use in the EU.

Moreover, treatments integrating physical (e.g. cutting) and earlier herbicide application methods reduce later season glyphosate-based treatment efficacy. This is presumably because the translocation of glyphosate to the rhizome is reduced by damage to plant vascular tissues and a weakened aboveground biomass source. Therefore, management strategies targeting within-season rhizome depletion or minimising resource acquisition are not advised for Japanese knotweed control. Such approaches will reduce economic sustainability by increasing operational costs and reduce environmental sustainability by increasing herbicide use and the risk of further dispersal.

Glyphosate specifically targets the rhizome source-sink transition point and mass flow of photosynthates through the phloem to the rhizome in summer onwards (Figure 3 Stage 3). While autumn glyphosate FR foliar spray (a1) showed a slower decrease in control response variables over time than summer and autumn glyphosate HR foliar spray (a3) and autumn glyphosate stem injection (c1), it remains an effective and practical treatment for knotweed control. Importantly, in the first year of treatment, autumn glyphosate stem injection required fifteen times more glyphosate per unit area than summer and autumn glyphosate HR foliar spray and it is more labour intensive to apply. The key is adequate herbicide coverage of each knotweed stem allowing subsequent translocation of glyphosate to active meristem tissue or growing point, as translocation of glyphosate in rhizomes to proximate

Table 3. Physical, chemical and integrated *F. japonica* control treatments, showing treatment group, herbicide active ingredient (a.i.), application rate, application method and timing. Underlined herbicide a.is. indicate product mix; italicised processes represent physical components of integrated control treatments; Roman numerals represent multi-seasonal application of control treatments. Treatment group codes are assigned: a = soil and foliar spray herbicide application methods; b = cut and fill herbicide application method; c = stem injection herbicide application method; d = physical and integrated physical and chemical control treatments. Specific timing of seasonal application was: early spring (stage 1) = March; late spring (stage 2) = May; summer (stage 3) = June; autumn (stage 4) = September. Reproduced from Jones et al. (2018) with permission.

Treatment group	Active ingredient (ai; g L^{-1})	Application rate (kg AE ha^{-1})	Application method	Application timing
a1	Glyphosate (360)	3.60	Foliar spray	Autumn
a2	Glyphosate (360)	2.16	Foliar spray	Autumn
a3	Glyphosate (360)	2.16	Foliar spray	i) Summer ii) Autumn
a4	2,4-D amine (500) Glyphosate (360)	4.50 3.60	Foliar spray	i) Late spring ii) Autumn
a5	Glyphosate (360) Glyphosate (360) + 2,4-D amine (500)	2.16 2.16 + 4.50	Foliar spray Foliar spray	i) Summer ii) Autumn
a6	2,4-D amine (500) Glyphosate (360) + 2,4-D amine (500)	2.80 3.60 + 2.80	Foliar spray Foliar spray	i) Late spring ii) Autumn
a7	Glyphosate (360) + 2,4-D amine (500) Glyphosate (360) + 2,4-D amine (500)	2.16 + 2.80 2.16 + 2.80	Foliar spray Foliar spray	i) Late spring ii) Autumn
a8	Picloram (240) Glyphosate (360)	2.69 3.60	Soil and foliar spray Foliar spray	i) Early spring ii) Autumn
a9	Glyphosate (360) + Aminopyralid (30) & Fluroxypyr (100) Glyphosate (360)	2.16 + 0.06 & 0.20 2.16	Foliar spray Foliar spray	i) Late spring ii) Autumn
a10	Aminopyralid (30) & Fluroxypyr (100) Glyphosate (360)	0.06 & 0.20 3.60	Foliar spray Foliar spray	i) Late spring ii) Autumn
a11	Glyphosate (360) + Flazasulfuron 25 % w/w Glyphosate (360)	2.16 + 0.15 2.16	Foliar spray Foliar spray	i) Late spring ii) Autumn
a12	Flazasulfuron 25 % w/w Glyphosate (360)	0.15 3.60	Soil and foliar spray Foliar spray	i) Early spring ii) Autumn
a13	Glyphosate (360) + Flumioaxazin (300) Glyphosate (360)	2.16 + 0.03 2.16	Foliar spray Foliar spray	i) Late spring ii) Autumn
b1	Glyphosate (360)	87.12	Cut and fill	Autumn
c1	Glyphosate (360)	65.00	Stem injection	Autumn
d1	*Cutting* Glyphosate (360)	N/A 3.60	Clearing saw Foliar spray	i) Summer ii) Autumn
d2	*Excavation* Glyphosate (360)	N/A 3.60	Excavator Foliar spray	i) Early spring ii) Autumn
d3	*Excavation* Picloram (240) Glyphosate (360)	N/A 2.69 3.60	Excavator Soil and foliar spray Foliar spray	i) Early spring ii) Early spring iii) Autumn
d4	*Covering*	N/A	Geomembrane	Early spring

active and dormant meristems is limited (i.e. all stems must receive treatment). Our findings show that timing and coverage, rather than absolute dose of herbicide, are critical to achieve effective control.

Conclusions

There are strong environmental, ecological and economic cases for the management of IAPs to minimise their negative impacts. However, invasive plant management is hindered by the absence of scale appropriate empirical evidence to support control method selection and plant traits which are effective against control, e.g. rhizome bud bank. Consequently, control programmes may have less than optimal results in terms of economic and environmental sustainability. Terminology is critically important when defining clear programme objectives (i.e. control, management, eradication) and long-term assessment of IAP control and post-treatment habitat recovery is needed to establish best practice.

In the case of Japanese knotweed, an approach that works with the seasonal resource translocation between above- and below-ground biomass and adequate herbicide coverage is the key to success. Physical disruption of the plant or increasing use of herbicide application will not give better control and may be less effective and costly. There is increasing public concern (real and perceived) about the widespread use of herbicides, and glyphosate in particular, resulting in increased PPP deregulation and reduced concentration and application rates (Hillocks 2013, Myers *et al.* 2016). Experimental data that define best practice are essential to inform regulators when considering non-agricultural weed control. While the use of PPPs to control perennial IAPs is relatively small, the detrimental environmental, economic and amenity impacts are significant, such that the loss of effective PPPs should be of concern. In the absence of glyphosate, the only effective alternative for Japanese knotweed control would be complete physical excavation and disposal which would be significantly more expensive and arguably more environmentally harmful due to increased associated CO_2 emissions and the risk of further spread.

References

Bailey JP, Bímová K, Mandak B. (2009). Asexual spread versus sexual reproduction and evolution in Japanese Knotweed *s.l.* sets the stage for the ''Battle of the Clones". *Biological Invasions*; **11**: 1189–1203.

Cordeau S, Triolet M, Wayman S, *et al.* (2016). Bioherbicides: Dead in the water? A review of the existing products for integrated weed management. *Crop Protection*; **87**: 44–49.

Harker KN, O'Donovan JT (2013). Recent Weed Control, Weed Management, and Integrated Weed Management. *Weed Technology*; **27(1)**; 1–11.

Hillocks RJ (2013) Impact of EU pesticide reduction strategy and implications for crop protection in the UK and the rest of Europe. *Outlooks on Pest Management*; **24(5):** 1–4.

Hulme P, Bacher S, Kenis M, *et al.* (2008). Grasping at the routes of biological invasions: a framework for integrating pathways into policy. *Journal of Applied Ecology*; **45**: 403–414.

Jones D, Bruce G, Fowler MS, *et al.* (2018). Optimising physiochemical control of invasive Japanese knotweed. *Biological Invasions*; **20(8)**: 2091–2105.

Jones D (2015). Japanese Knotweed *s.l.* Taxa and Introduced *Petasites* Species: Biosystematics, Ecology and Control. PhD Thesis, Swansea University, Swansea, UK.

Kabat TJ, Stewart GB, Pullin AS (2006). Are Japanese knotweed (*Fallopia japonica*) control and eradication interventions effective? Centre for Evidence-Based Conservation (CEBC) Systematic Review No. 21.

Kettenring KM, Adams CR (2011). Lessons learned from invasive plant control experiments: a systematic review and meta-analysis. *Journal of Applied Ecology*; **48**: 970–979.

Klimešová J, Klimeš L (2007). Bud banks and their role in vegetative regeneration – A literature review and proposal for simple classification and assessment. *Perspectives in Plant Ecology, Evolution and Systematics*; **8**: 115–129.

Macfarlane J (2011). Development of strategies for the control and eradication of Japanese knotweed. PhD Thesis, University of Exeter, Exeter, UK.

Myers JP, Antoniou MN, Blumberg B *et al.* (2016). Concerns over use of glyphosate-based herbicides and risks associated with exposures: a consensus statement. *Environmental Health*; **15(19)**: 1–13.

Myers JH, Savoie A, Van Randen E (1998). Eradication and Pest Management. Annual Review of Entomology **43:** 471–91.

Panetta (2015). Weed eradication feasibility: lessons of the 21st Century. *Weed Research*; **55**: 226–238.

Richardson DM, Ricciardi A (2013). Misleading criticisms of invasion science: a field guide. *Diversity and Distributions*; **19**: 1461–1467.

Richardson DM, Pyšek P (2006). Plant invasions: merging the concepts of species invasiveness and community invasibility. *Progress in Physical Geography*; **30**: 409–431.

Swanton CJ, Mahoney KJ, Chandler K *et al.* (2008). Integrated Weed Management: Knowledge-Based Weed Management Systems. *Weed Science*; **56**:168–172.

Thompson K (2000). Where Do Camels Belong? The story and science of invasive species. Profile Books Ltd, London, UK.

Tyler C, Pullin AS, Stewart GB (2006). Effectiveness of Management Interventions to Control Invasion by Rhododendron ponticum. *Environmental Management*; **37(4)**: 513–522.

Van der Weide RY, Bleeker PO, Achten VTJM, *et al.* (2008). Innovation in mechanical weed control in crop rows. *Weed Research*; **48**: 215–224.

Williams F, Eschen R, Harris A, *et al.* (2010). The Economic Cost of Invasive Non-Native Species on Great Britain. CABI, Wallingford, UK.

Dr Dan Jones is an Honorary Researcher at Swansea University's Department of Biosciences and Managing Director of Advanced Invasives, a consultancy founded to bring evidence-led thinking to the commercial management of invasive plant species. Dan specialises in the detection, mapping and sustainable control of invasive alien plant species and current work addresses habitat restoration, invasive plant ecology and ecophysiology.

Professor Dan Eastwood is Head of Swansea University's Department of Biosciences. Dan is interested in the biology of fungi and has published over 30 journal papers exploring fungal development, growth and ecology. Dan supervises postgraduate research students investigating a diverse range of ecological topics including ecological restoration and rare dune plants. He also provides steering expertise on invasive plant research at Advanced Invasives.