**Himalayan balsam, *Impatiens glandulifera*: Its ecology, invasion and management**

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*Impatiens glandulifera* Royle (Balsaminaceae) is recognised as one of the most widespread invasive non-native plants in Europe. Once popular for its tall stature and pink flowers adorning riverbanks in the UK and elsewhere, this invasive species has received increased attention over the last 20 years. However, recently, this attention has moved from its floristic attractiveness and has focused on the negative impacts the species has on native species and habitats. This has promoted research studying the potential impacts of the species, both above and belowground.

Native to the western Himalayas, *I. glandulifera* was originally introduced outside of its native range for the first time to Great Britain in 1839. Following this, the species was introduced into mainland Europe and vigorous growth rates and prolific seed production have aided its rapid range expansion, with its distribution only limited by available high moisture habitats (Beerling & Perrins, 1993; Pyšek & Prach, 1995). *I. glandulifera* is now widespread throughout Europe and is also invasive in parts of Canada, the USA and New Zealand, with limited occurrence in Japan (Cockel & Tanner, 2012).

Within its introduced range, *I. glandulifera* invades a variety of different habitat types. It occurs throughout the UK along riverbanks and in damp woodlands (Pattison *et al*., 2018; Seeney *et al*., 2019) and can also invade ruderal habitats and transportation networks in Europe (Follak et al., 2018). It is increasingly seen to invade managed woodlands (Krtivojević et al., 2012) and mountain regions in Europe, where negative impacts have been recorded on the native plant community (Kieltyk and Delimat, 2019).

Within these habitats, *I. glandulifera* has the tendency to form dense monospecific stands that can compete with native plant species for space, light and nutrients. The species has been shown to have negative impacts on native plant species diversity (Kieltyk & Delimat, 2019) and invertebrate populations (Tanner *et al*., 2013). Furthermore, it can degrade ecosystem services such as erosion control, pollination and decomposition (Helsen *et al*., 2018, Martinez-Cillero *et al*., 2019). In addition, large stands near water bodies can restrict access to the area for recreation activities impacting on cultural ecosystem services (Martinez-Cillero *et al*., 2019).

*Impatiens glandulifera* is included on the list of invasive alien species of Union concern (Regulation (EU) 1143/2014). This listing means EU Member Countries will need to implement measures against *I. glandulifera*, and the other 36 plant species listed, where the following measures will need to be taken: (1) prevention, (2) early detection and rapid eradication of new invasions and (3) management of populations that are already widely spread. The species is also listed on the European and Mediterranean Plant Protection Organisation (EPPO) List of Invasive Alien Plants, where EPPO strongly recommend countries which are endangered by listed species take measures to prevent their introduction and spread, or manage unwanted populations.

Raising public awareness on the problems associated with invasive alien plant species is essential to increase support for management actions against a species with known negative impacts (Lindemann-Matthies, 2016; Novoa *et al*., 2017). For *I. glandulifera* there is now a wealth of scientific research on the negative impacts of the species on ecosystems and ways of controlling its populations. However, for control measures to be really successful, public involvement is essential, and if harnessed in an appropriate manner, can be highly effective (Pages *et al*., 2019). Engagement with stakeholders is a critical aspect of invasive plant management, both in terms of manual and biological control (Shackleton *et al*., 2019).

*Impatiens glandulifera* has been the subject of an intensive biological control research programme in the UK and a rust fungus, *Puccinia komarovii* var. *glanduliferae* was first released into UK populations of the weed in 2014 (Varia *et al*., 2016). Comprehensive analyses exist of the success rates of biological control agents (Schwarzländer *et al*. 2018), but far less is known about the consequences of such introductions for the structure of natural communities and the prospects for their restoration, if the agent establishes successfully (van Wilgen *et al*., 2013). In order to address this problem, a joint research programme, led by Royal Holloway University of London, with partners at CABI and the University of Reading, and entitled *Community consequence of introducing a biological control agent* was initiated in 2015. As part of the wider realisation of impact from this research, a stakeholder workshop was held at Royal Holloway in January 2019. The audience consisted of researchers and a wide variety of public and private stakeholders, all of whom had an interest in the management of *I. glandulifera* populations. A series of presentations covering all aspects of the ecology, invasiveness and control were presented and the original research presented is collected together in this special issue of the journal.

*Impatiens glandulifera* is usually considered an invader of riparian habitats, but Cuda *et al*. (2020) present a review of its ability to invade woodland ecosystems. While effects on the native woodland flora as less pronounced than those on herbaceous vegetation in wetland areas, the plant appears to exert a considerable detrimental effect on the soil microbial population, particularly mycorrhizal fungi. One might expect that the relatively shady environment of woodland would have a restrictive effect on the growth of the plant, compared to exposed riverine systems, however this does not appear to be the case.

The theme of shade tolerance and plasticity in response of the plant to light is continued by Gruntman *et al*. (2020). In a common garden experiment, the authors subjected plants from native and introduced populations to high and low light conditions. They then examined the plasticity in morphological and physiological traits that provide shade tolerance or avoidance. Plants from introduced populations showed much greater plasticity, particularly in physiological traits associated with photosynthesis. It is likely that this facilitates the spread of the plant into areas which might at first be considered unsuitable for invasion, such as woodland.

The majority of ecosystem-level effects of *I. glandulifera* in invaded areas tend to focus on biotic parameters, such as plant and invertebrate diversity or soil microbiology. Effects on the physical environment are far less considered, but Greenwood *et al*. (2020) show that these must not be ignored either. Using the statistical technique of the analysis of inequality, they show that sediment flux is considerably more variable on river banks invaded by the weed, compared with uninvaded areas. Soil colonised by *I glandulifera* is inherently less stable, contributing to a greater risk of erosion. These findings highlight the potential pitfalls of a successful control programme. If the weed is greatly reduced in abundance, either by manual or biological means, then consideration also needs to be given to stabilisation of the soil, to prevent further loss of sediment.

Ellison *et al*. (2020) present the first field results from the rust release programme in the UK. These clearly show the potential for successful biological control of this weed, but also highlight some of the major barriers to success. While environmental conditions play a role in determining rust establishment, the primary factor appears to be the genetic constitution of the weed. Some weed populations appear to have high levels of resistance to a rust strain originating from India. However, some of these populations appear to be susceptible to a second strain of the fungus, originating from Pakistan, while other populations appear to be resistant to both fungal strains. Clearly, other strains of the fungal pathogen need to be found, or other factors manipulated to make biological control of the weed more predictable.

One hitherto unconsidered factor in the establishment of a fungal biological control agent is the indigenous fungal community within the plant, collectively termed the microbiome. Currie *et al*. (2020) present results showing that the presence of endophyte fungi within the foliar tissues of the weed can have considerable detrimental effects on the establishment of the rust fungus and may represent a phenotypic barrier to its success. The mechanisms are currently unknown, but most probably though the activation of plant defence pathways. Intriguingly, the endophyte community within *I. glandulifera* is far simpler than in many native plants, offering hope that it could be manipulated, thereby enabling this phenotypic layer of resistance to the pathogen to be removed.

Elsewhere, Wood *et al*. (2020) present the first results from a controlled experiment, designed to examine how quickly native communities of plants and invertebrates may recover following manual or biological control of the weed. While several groups of soil dwelling invertebrates appeared to recover quickly following manual control, effects in biological control treatments, where the rust fungus was applied, were also seen. In particular, Collembola responded positively to the application of the pathogen, offering hope that natural communities may be resilient enough to re-establish rapidly, if biological control is successful.

It is clear that *I. glandulifera* represents a significant threat to native ecosystems in many temperate areas of the world. However, there is much hope for the future, in terms of its control. The variety of papers presented within this issue serve to highlight many of the reasons for its invasion success in different areas. By unravelling these relations, and combining our knowledge with previous research, we should be in a position to realise ecologically and economically efficient control methods in the near future.

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