Appendix S1

Supplement to:

Regional adaptation of integrated pest management to control invasive forest insects

M Stastny *et al*.

Published in *Frontiers in Ecology and the Environment*

M Stastny *et al*. – Supporting Information

Panel S1. Online survey methodology, long-form questionnaire, and species list of insect pests

To help us explore the control outcomes of integrated pest management (IPM) programs developed to manage a forest insect pest in one region and adopted by another, we wished to incorporate diverse perspectives and research insights of forest-health and IPM specialists from around the world. We therefore developed an online survey to identify specific examples (case studies) of pest control programs and collect qualitative information on the underlying factors contributing to their relative success and challenges. We delivered the survey via a secure online tool (Lime Survey) developed and hosted by the University of New Brunswick (UNB), Canada; the project was reviewed by the UNB Research Ethics Board and is on file as REB 2021-100. The survey was sent to over 60 IPM practitioners and researchers, who were also invited to share the survey with colleagues. The recipients were selected haphazardly on the basis of subject-matter expertise and to provide research representation from academia, government, and industry, spanning as broad a geographic distribution as possible.

The survey consisted of a series of multiple-choice questions (see the full survey below), most accompanied by space for comments to explain or elaborate on answers. While we focused on invasive (non-native) forest insect pests, we also encouraged the respondents to consider examples of native pests whose ranges or outbreaks patterns have seen notable shifts such that they now pose new, invasive-like challenges to forest management—these instances were a small minority of the responses. For each entry (case study), the survey presented a series of questions to document the pest species targeted for management, the target region of the program, and whether the program had been based on previous experience with this pest in another region. Multiple entries were allowed per participant if they wished to provide information on more than one pest species; however, most participants submitted single entries.

Participants were asked to provide a qualitative assessment of the level of control the program was providing in the target region, and whether any research had identified potential differences between the two or more regions invaded by this pest that could inform and influence program outcome either prior to its implementation or post hoc. If research had been conducted, they were asked if the findings of this research led to adaptation of the program for the context of the new target region. Finally, respondents were asked to rank the following categories of factors in terms of their relative importance as challenges to this IPM program: Biological Variation, Abiotic Environment, Scale and Capacity, Regulatory Context, and Cultural Context. We encouraged participants to share their knowledge irrespective of whether it has been published in peer-review journals or not, in order to collect “on-the-ground” assessments that included gray literature, expert opinions, etc.

We received a total of 37 survey responses (entries) that were completed partially (ie without the optional comments) or fully. All responses were anonymous and participant identities were not disclosed to any of the authors of this paper, although it would not be strictly unidentifiable as only a limited number of experts work on a given pest species in a specific region. To focus on insect pests (see species list below), five entries on tree pathogens (fungi, nematodes) were excluded. We compiled the survey results to obtain a qualitative assessment of the relative importance of the factors discussed in this paper, and to check for any strong trends in the responses, using all entries as independent case studies for our purposes. More generally, we examined all responses to better inform the issues and questions discussed in our paper, and to broaden its perspectives.

An open data file with anonymized, short-form results of the survey (responses to multiple-choice questions), excluding all long-form answers with information that could identify the participants, is available on Zenodo: https://doi.org/10.5281/zenodo.13749152.

Online Survey Questionnaire (long-form)

1. Please specify one (1) non-native forest pest you have worked on in the context of Integrated Pest Management (IPM).
(If you are willing to provide information on additional species, please complete this survey first, then click on the survey link again and repeat the survey to generate a new submission for each species.)

2. During your involvement in the IPM of this species, which geographic region(s) did this specific programme target? (select all that apply)

- ☐ Western Europe
- ☐ Eastern Europe
- ☐ Mediterranean Basin
- ☐ Middle East
- ☐ Western / Central Asia
- ☐ South Asia
- ☐ East Asia
- ☐ Africa
- ☐ North America
- ☐ Mexico / Central America
- ☐ South America
- ☐ Australia / New Zealand
- ☐ Pacific Islands

Other region, or refine your answer:

3. What level of pest control has this specific programme achieved in the target region?

- ◉ No control

- [ ] Very limited control
- [ ] Partial or inconsistent control
- [ ] Satisfactory control
- [ ] Complete control
- [ ] Unsure

4. Are you aware of any assessments of this programme's outcomes that have been published? Could you provide a reference or a link to any such publications?

5. Was the design/implementation of the programme based on previous experience with the control of this specific pest in other regions (geographic areas, countries, jurisdictions, etc.)? If you answered yes, could you specify?

- [ ] Yes
- [ ] No
- [ ] Unsure

Please specify:

6. Are you aware of any research that had identified or investigated potential differences (e.g. environmental, biological/ecological, regulatory, economic, cultural, etc.) between the two or more regions invaded by this pest that could inform and influence the programme's outcome?

- [ ] Yes – this research was conducted prior to the programme's implementation
- [ ] Yes – this research was conducted in response to the programme's initial outcomes
- [ ] Yes – both of the above
- [ ] Not aware of any
- [ ] Unsure

7. Based on the findings of this research, has the design/implementation of this programme been adjusted/modified (i.e., adapted) for the context of the new target region? In your opinion, how important was this adaptation for improving the programme's outcome?

- ☐ Yes – and this adaptation was critical
- ☐ Yes – and this adaptation had a significant impact
- ☐ Yes – but this adaptation had only a minor impact
- ☐ Yes – but this adaptation was not important
- ☐ No adaptation has been attempted
- ☐ Unsure

8. In your opinion, which of the following categories of factors has presented the greatest challenges in the adoption/implementation of this programme given the specific situation in your region?

- ☐ A) Biology/ecology of the pest and host system
- ☐ B) Environmental conditions
- ☐ C) Economic considerations (capacity, scale, etc.)
- ☐ D) Regulatory context
- ☐ E) Societal/cultural context

Please elaborate, or provide another factor if not included above.

9. Are you aware of any other examples (not discussed in your answers above) where IPM tactics or programmes developed elsewhere were implemented in another area without modifications, and this lack of regional adaptation resulted in limited efficacy? Conversely, are you aware of any examples whose success may be attributed to specific adjustments (adaptation) to the design/implementation by taking into account regional circumstances? Please specify the example and elaborate if possible:

List of species represented by the case studies in the responses to the online survey:

Anoplophora glabripennis

Adelges tsugae

Cameraria ohridella

Dendroctonus valens

Dryocosmus kuriphilus

Glycaspis brimblecombei

Gonipterus platensis

Gonipterus sp. 2

Ips grandicolis

Ips typographus

Leptocybe invasa

Leptoglossus occidentalis

Matsucoccus josephi

Pineus boerneri

Pityophthorus juglandis

Profenusa thomsoni

Rhynchophorus ferrugineus

Sirex noctilio

Lymantria dispar dispar

Tetropium fuscum

Thaumastocoris peregrinus

Xylosandrus crassiusculus

M Stastny *et al*. – Supporting Information

Panel S2. Control outcomes for *Sirex noctilio* in different invaded regions—supplement to Figure 1

The woodwasp *Sirex noctilio* (Hymenoptera: Siricidae) is a textbook example of a global invasive forest pest (Slippers *et al*. 2012, 2015). This hymenopteran insect attacks several species of pines and is native to Europe, western Asia, and northern Africa. It has also invaded South Africa, Australasia, China, and South and North America in the last century. In the Southern Hemisphere, where North American and European pines are planted for commercial purposes, severely damaging outbreaks have been recorded (Krivak-Tetley *et al*. 2021). In Australia, one of the first regions invaded by *S noctilio*, a unique management program was developed that focused largely on classical biological control (Carnegie and Bashford 2012). Several specialist natural enemies from the native range of the pest, including parasitoids and a nematode (*Deladenus siricidicola*) that sterilizes female wasps, were released in Australia. The mass rearing and release of this nematode (and of its different strains) among affected pine stands were reported as integral to successful management, although other interventions were deployed simultaneously, including silvicultural measures, or the release of insect parasitoids (Corley *et al*. 2019). Based on the reported success in Australia, nematode strains as well as the rearing and release protocols were exported to other countries in the invaded range (eg Brazil, Argentina, Chile, and South Africa). Nematode-centered management programs were implemented throughout, with variable success. Issues related to compatibility between nematode strain, fungus and the target pest, and associated variation in strain virulence may have affected the efficacy of this biological control (Kroll *et al*. 2013; Mlonyeni *et al*. 2018; Morris *et al*. 2020). Release protocols and implementation as well as local climatic factors were suggested as additional causal factors contributing to the limited success of these secondary programs (Lantschner *et al*. 2019). For instance, incomplete control provided by the nematode-based management plans in South Africa were related to the development of techniques for a region with winter rainfall that subsequently required adaptation to a region with summer rainfall (Hurley *et al*. 2012). In addition to these biological and environmental factors, differences among regions in the scale and capacity to implement IPM programs and the regulatory and cultural context can impact the success of secondary programs. For example, in Argentina, commercial pine plantations occur in the northeast and the southwest of the country. In both regions, management interventions were based on inadequate monitoring and suffered from low quantity and quality of biocontrol agents. While nematode releases nationwide have been similar, the impact of *S noctilio* remains particularly noticeable in the southwest where pines are planted on cattle and sheep farms, mostly under government subsidies (Corley *et al*. 2019). In these stands, recommended forest management practices are often not followed, leading to overcrowding and tree stress that in turn promote pest populations and exacerbate their impacts (Lantschner and Corley 2015; Krivak-Tetley *et al*. 2021). Different management considerations exist in the US, where native species of wood wasps preclude the release of *D siricidicola* as biocontrol agents. Regulations to mitigate risks of non-target effects have limited the use of nematodes and influenced the management approach, potentially increasing spread and economic impacts (Evans-Golner 2008; Hajek *et al*. 2021).

References

Carnegie AJ and Bashford R. 2012. *Sirex* woodwasp in Australia: current management strategies, research and emerging issues. In: Slippers B, de Groot P, and Wingfield MJ (Eds). The *Sirex* woodwasp and its fungal symbiont: research and management of a worldwide invasive pest. Dordrecht, the Netherlands: Springer.

Corley JC, Lantschner MV, Martínez AS, *et al*. 2019. Management of *Sirex noctilio* populations in exotic pine plantations: critical issues explaining invasion success and damage levels in South America. *J Pest Sci* **92**: 131–42.

Evans-Goldner L and Bunce LK. 2009. United States *Sirex* woodwasp program update. In: McManus KA and Gottschalk KW (Eds). Proceedings of the 19th US Department of Agriculture Interagency Research Forum on Invasive Species 2008. Newtown Square, PA: US Department of Agriculture Forest Service.

Hajek AE, Gardescu S, and Delalibera Jr I. 2021. Summary of classical biological control introductions of entomopathogens and nematodes for insect control. *BioControl* **66**: 167–80.

Hurley BP, Croft P, Verleur M, *et al*. 2012. The control of the *Sirex* woodwasp in diverse environments: the South African experience. In: Slippers B, de Groot P, and Wingfield MJ (Eds). 2012. The *Sirex* woodwasp and its fungal symbiont: research and management of a worldwide invasive pest. Dordrecht, the Netherlands: Springer.

Krivak-Tetley FE, Lantschner MV, Lombardero MJ, *et al*. 2021. Aggressive tree killer or natural thinning agent? Assessing the impacts of a globally important forest insect. *Forest Ecol Manag* **483**: 118728.

Kroll SA, Morris EE, Long SJ, and Hajek AE. 2013. Parasitism of *Sirex noctilio* by non-sterilizing *Deladenus siricidicola* in northeastern North America. *Biol Control* **67**: 203–11.

Lantschner MV and Corley JC. 2015. Spatial pattern of attacks of the invasive woodwasp *Sirex noctilio*, at landscape and stand scales. *PLoS ONE* **10**: 0127099.

Lantschner MV, Aukema BH, and Corley JC. 2019. Droughts drive outbreak dynamics of an invasive forest insect on an exotic host. *Forest Ecol Manag* **433**: 762–70.

Mlonyeni OX, Wingfield BD, Greeff JM, *et al*. 2018. Population variation in traits of *Deladenus siricidicola* that could influence the biocontrol of *Sirex noctilio* in South Africa. *Int J Pest Manage* **64**: 324–32.

Morris EE, O'Grady P, Csóka G, and Hajek AE. 2020. Genetic variability among native and introduced strains of the parasitic nematode *Deladenus siricidicola*. *J Invertebr Pathol* **173**: 107385.

Slippers B, de Groot P, and Wingfield MJ (Eds). 2012. The *Sirex* woodwasp and its fungal symbiont: research and management of a worldwide invasive pest. Dordrecht, the Netherlands: Springer.

Slippers B, Hurley BP, and Wingfield MJ. 2015. *Sirex* woodwasp: a model for evolving management paradigms of invasive forest pests. *Annu Rev Entomol* **60**: 601–19.