The science of the emerald ash borer (Coleoptera: Buprestidae): where are we after 10 years of research?

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In early 2002, a metallic green buprestid beetle (Coleoptera: Buprestidae) was determined to be associated with extensive decline and mortality of ash trees in Detroit, Michigan, United States of America and Windsor, Ontario, Canada. The beetle was not previously known in North America and so was thought to be an introduced species. This hypothesis was confirmed when the beetle was identified as *Agrilus planipennis* Fairmaire, a species native to eastern Asia. Later in 2002, Haack *et al.* (2002) published the first report of emerald ash borer (EAB) in North America. Since that time, EAB has become the most significant forest health issue in eastern North America, killing tens of millions of trees and causing serious ecological and economic impacts.

At the time when EAB was first detected in North America, there was little or no information available on the species. The species had been documented in the 1960s, 1980s, and again the late 1990s to be attacking North American ash trees (*Fraxinus americana* Linnaeus and *Fraxinus velutina* Torrey (Oleaceae)) that had been planted in China, but the accounts were not widely available outside of China (Wei *et al.* 2004). However, in the period since the discovery of the insect in North America, there have been over 360 peer-reviewed papers published. This is a massive body of work to produce in such a short period of time.

In the fall of 2013 we organised a symposium at the Entomological Society of Canada annual meeting to review the research conducted on this devastating insect pest. The objective of the symposium was to take a look back at what we had learned about this species in the 10 years since its discovery, and take stock of what information was still urgently required. The symposium consisted of a series of review presentations on the current state of knowledge on various topics regarding EAB given by experts from both Canada and the United States of America. This special issue of *The Canadian Entomologist* presents a series of review papers and new research based on these presentations.

The first three papers in this issue review the life history and ecology of EAB. Poland *et al.* (2015) provides fundamental information on the life cycle of this invasive insect, including detailing previously unknown mating behaviours and how mating is facilitated by a variety of tactile and olfactory cues. They also present valuable new information on host plant selection, including visual and chemical orientation, which increases our understanding of EAB. Their review also details information on host plant resistance in EABs native range in Asia, as well as potential factors influences differences in susceptibility among North American ash species. Lyons (2014) details the various predators, parasitoids, and pathogens, native to North America, that have begun to cause substantial mortality to EAB in its introduced range. Silk and Ryall (2014) review the pheromone ecology of EAB, highlighting

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important findings about the role of host volatiles attractive to EAB, as well as the first-ever discovery of a female-produced pheromone in any species within the Buprestidae. They argue that further research on factors influencing male responses to the female-produced pheromone is still required.

The next two papers review how detection and control methods of EAB have evolved. Ryall (2015) reviews the impressive variety of sampling tools and techniques that have been developed since 2002, including developments in trapping, branch sampling, and remote sensing. Here, the critical gaps in knowledge are the lack of a cost-benefit analysis of the various options and a determination of how to further maximise probability of detection in early low-density infestations. Bauer *et al.* (2015) details the effort at classical biological control in the United States of America to explore for natural enemies in its native range in China, and rear and release selected parasitoids into the United States of America. Ongoing research is investigating establishment and impact of these parasitoids across the infested area in the United States of America. Chemical controls of EAB have also been an area of intense research, with recent reviews published elsewhere (Herms and McCullough 2014).

Some aspects of the ecological and economic impacts of EAB are discussed in new studies by Campbell *et al.* (2015) and Smith *et al.* (2015). Previous studies (Gandhi and Herms 2009a, 2009b) have shown the ecological impacts of tree mortality caused by EAB. In their contribution Smith *et al.* (2015) present new work that builds on these earlier studies to show that high levels of ash mortality are caused by EAB, regardless of forest community composition and structure. Longer-term studies showing the impacts of loss of ash on forested areas have not yet been finalised, however their data suggests that changes in the vegetation will significantly alter the composition and function of forests. Campbell *et al.* (2015) review the economics of EAB management and present a new analysis of the value of different detection methods when determining a detection strategy. They show that some methods may have high value but also very high costs. Ideally, sampling programmes use a variety of methods, with maximum value for minimum cost.

To close this review two papers examine how EAB has dispersed and been managed in North America. Siegert *et al.* (2015) examine the history of how EAB has spread in North America and the difficulties in preventing movement of populations. They argue that more research is required to understand both local and long distance dispersal of EAB, especially in response to different management tactics. Finally, McCullough *et al.* (2015) describe results of simulation modelling and pilot studies directed towards developing tactics to slow ash mortality caused by EAB. Their results indicate that protecting a small fraction of ash trees with an injectable insecticide, in combination with girdling and removal of trap trees, was able to reduce the rate of EAB population growth. This provides valuable information to stakeholders attempting to manage this devastating insect.

It is our sincere hope that this compendium of research on the EAB will be a useful contribution to the community of researchers and managers of this important insect. We also hope that these reviews can serve an entry point for new students of EAB before they dive into the extensive and ever-expanding body of knowledge. Our impression is that over the past 12 years a great deal has been learned about EAB, but there is still much territory to explore. To aid in that endeavour the authors of many of the reviews have attempted to identify paths for future research. We think many of these paths will lead to new ways to manage EAB and reduce the risk to the rest of North America. We now know that EAB has been in North America longer than we ever thought (Siegert *et al.* 2014) so it is possible that the next devastating pest is already with us. Thus we also hope that what has been learned about EAB, and the mistakes that have been made, will help guide future responses to new invasive species.

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