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# Flight activity of wood- and bark-boring insects at New Zealand ports

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## Abstract

**Background:** Bark- and wood-boring forest insects spread via international trade. Surveys frequently target new arrivals to mitigate establishment. Alternatively, monitoring pest activity in exporting countries can inform arrival and establishment risk.

**Methods:** We report >3 years data from daily sampling of bark- and wood-boring insects that are associated with recently felled *Pinus radiata* D. Don at five New Zealand ports.

**Results:** Average catch differed between ports and months with *Arhopalus fesus* (Mulsant), *Hylurgus ligniperda* F., and *Hylastes ater* (Paykull) comprising 99.6% of the total catch. *Arhopalus fesus* was absent during winter with *Hylastes ater* and *Hylurgus ligniperda* activity between June and August representing 3.5 and 3.7% of total catch, respectively. Maximum temperature and wind speed influenced flight activity of all three species but not universally across all ports. Flight activity transitioned to a nonlinear pattern above 20°C. *Arhopalus fesus* has a unimodal flight risk period between late-September and late-April. *Hylastes ater* was also unimodal except in Dunedin where it was bimodal like *Hylurgus ligniperda* was in all regions with spring and mid- to late-summer activity periods. Although *Hylastes ater* was observed during winter, the probability of a flight event during winter was between 0 and 0.02 per week. *Hylurgus ligniperda* flight probability was zero in Dunedin and low at all other ports from May to August.

**Conclusions:** Modelling seasonal changes in flight probability can inform risk-based phytosanitary measures. We demonstrate the utility of maximum temperature and seasonality as a predictor of wood commodity infestation risk. Such predictors allow National Plant Protection Organisations to develop standards that protect the post-treatment phytosanitary security of individual consignments.

**Keywords:** Biosecurity, ecological risks, export logs, forest entomology, phytosanitary, quarantine, regulated pests, trade

## Introduction

Bark- and wood-boring insects have spread widely as a result of international trade (Brockhoff et al. 2006; Haack 2006). Protected within solid wood products, or within live plants (Liebhold et al. 2012), they move with commodities and are likely to continue to colonise new areas as trade volumes increase (Liebhold et al. 2017). These risks have been reduced via the successful implementation of ISPM 15 that has resulted in a reduction in the movement of wood boring insects in

wood packaging material (Haack et al. 2014). The cryptic nature of bark- and wood-boring pests make them difficult to detect cost-effectively at the border. Surveillance for the purposes of detecting recent incursions in the importing country can reduce the number of successful establishments because it can facilitate eradication, i.e., early detection increases the probability of a successful eradication programme (Tobin et al. 2014). There are a number of tools and strategies used in surveillance programmes; however, trapping programmes that use

a synthetic chemical lure (or combination of lures) are commonly used to survey for bark- and wood-borer activity at ports and their immediate surrounds due to their high efficacy and relatively low cost (Allison et al. 2018; Chase et al. 2018; Flaherty et al. 2018; Rassati et al. 2014). Such surveys characterise the phenology of the native fauna and existing exotic species (Brockerhoff et al. 2006; Wylie et al. 2008) and has reported range expansion of species both within and outside their native biogeographic range (Rassati et al. 2018). Such surveys have also documented new establishments of exotic species (Rassati, Faccoli, Petrucco Toffolo et al. 2015). Import trade volumes were positively correlated with the number of alien wood-boring beetle species detected during a surveillance survey at Italian ports (Rassati, Faccoli, Petrucco Toffolo et al. 2015), and the volume (or value) of imported goods was determined to be a strong predictor of bark- and wood-boring beetle interceptions (Haack 2001; Huang et al. 2012). These findings suggest that import data can be used to direct limited surveillance resources to commodities and sites that represent the greatest likelihood of interceptions and, hence, the greatest risk of a new alien species incursion.

Wood commodity trade pathways, e.g. logs, are complex systems that can be widely variable over time (Piel et al. 2008). Although logs are known to present specific phytosanitary risks (USDA 1992), little is known regarding changes in the phytosanitary risk of consignments from different regions and at different times of the year. Similarly, factors within the exporting country that can influence the phytosanitary risk profile of individual consignments can be temporally and spatially variable and are poorly understood. Surveillance for new exotic organisms that arrive at ports (or transitional facilities) around the world is undertaken in some countries to inform management actions that are intended to prevent the establishment of new species. However, surveillance to monitor populations of resident pest species of wood commodities during the period between harvest and export is less common; however, postharvest phytosanitary risks are a significant component of any pest risk assessment conducted by countries importing wood commodities. By comparison, there is extensive monitoring of pest populations of horticultural crops in areas of production that is a critical component of risk profiling to inform the implementation of risk-based, or systems, approaches to pest management and phytosanitary measures (Moore et al. 2016; Walker et al. 2017). In a forestry context, pre-export surveys have the potential to identify geographic and temporal differences in the potential phytosanitary risk profile of specific export wood consignments. Pre-export surveys are particularly important when considering systems-based approaches to the management of phytosanitary risk.

Systems approaches use multiple measures applied at different points (and times) within the supply chain that in combination may reduce or eliminate the need for single end-point phytosanitary treatments, such as fumigation, when the phytosanitary risk is shown to be negligible (Allen et al. 2017). A systems approach may incorporate risk-based approaches to phytosanitary

measures, e.g., a Pest Free Place of Production ((PFPP), IPPC 1999) or an Area of Low Pest Prevalence ((ALPP), IPPC 2005), that may apply to one or more particular geographic regions or at certain times of the year, such as winter. However, phytosanitary measures, including systems approaches, must have appropriate procedures to maintain the phytosanitary security of a consignment and, hence, the validity of the phytosanitary certification issued by the National Plant Protection Organisation (IPPC 2016).

Supporting evidence to underpin the implementation of an ALPP as part of a systems approach to phytosanitary measures requires an understanding of the changing infestation risk profile that may occur along the supply chain for individual wood consignments. This is important because different mitigation measures are required at different points along the supply chain. For instance, measures that minimise the infestation of freshly felled trees in a plantation (debarking, rapid extraction, etc.) are very different to those employed on a port (application of a phytosanitary treatment, appropriate storage, etc.). Understanding the population dynamics of forest insects at major wood exporting ports provides information to support alternative risk-based phytosanitary treatments as it is one place where individual export consignments can have long residence times as they await shipment.

In 2017, New Zealand exported 19.2 million m<sup>3</sup> of roundwood logs, primarily *Pinus radiata* D. Don, from plantation forests (MPI 2019), which is equivalent to 14.4% of the 2016 world trade in industrial roundwood (FAO 2016). Two thirds of New Zealand's log exports passed through the five ports we surveyed: Whangarei, Tauranga, Napier, Nelson and Dunedin, of which Tauranga and Whangarei are the two largest log-exporting ports (MPI & Statistics NZ, Unpublished data).

We report here the results from three years of continuous trapping to assess the flight activity of seven bark- or wood-boring species (*Arhopalus fesus* (Mulsant), *Hylastes ater* (Paykull), *Hylurgus ligniperda* F., *Mitrastethus baridioides* Redtenbacher, *Pachycotes peregrinus* (Chapuis), *Prionoplus reticularis* White, and *Sirex noctilio* (F.)) at the five major log- and timber-exporting ports in New Zealand. These species are the most common bark- and wood-boring species that are associated with recently felled *Pinus radiata* in New Zealand. Actual abundance in managed plantation forest stands ranges from very abundant (*Hylurgus ligniperda*), to comparatively rare (*S. noctilio*) (Pawson, Unpublished Data). These data can be used to identify potential areas and/or temporal periods when the activity of these key pest species is low or non-existent (i.e. no phytosanitary risk) within the port environment.

## Methods

Three flight intercept traps were deployed at each of five ports in New Zealand (Additional File: Fig. A1). Ports were sampled at the following cities, from North to South: Whangarei, Tauranga, Napier, Nelson, and Dunedin. Traps were placed in operational log storage yards and separated by at least 50 m. Because of safety

requirements, trap placement was dictated by the availability of zones within the log yards that were not subject to traffic and log yard operations (Additional File: Fig. A2). Traps at each port were established at different times ranging from 25 July to the 21 November 2013 and the traps were removed from all sites on 28 September 2016. Although 13 of the 15 traps were operated continuously at the same location for the duration of the study, two of the traps at Port Nelson had to be moved in January and May 2016, respectively, because the log yard operations were expanded (Additional File: Table A1).

Insects were sampled using black cross-vane flight intercept traps (Kerr et al. 2017). Traps were made from 600 × 210 mm Mulflute™ polypropylene sheets (Mulford International, Christchurch, New Zealand), topped with a Mulflute™ (210 × 210 mm) rain cover, and a black funnel (216 mm diameter) that directed catch into our collection system (Figure 1). Traps were baited with separate 150 ml dispensers (450 × 50 mm, 150 µm polyethylene tubing (Accord Plastics, Masterton, NZ) with felt strips) of ethanol (Nuplex Specialties NZ, Mt. Wellington, New Zealand) and PINECHEM 500 (Lawter (NZ), Mt. Maunganui, New Zealand. (Note: This is a discontinued product that can be made on special request to the manufacturer)) a mixture of alpha- and beta-pinene that was shown by our mass spectrometry analysis to consist of an average concentration of 71% alpha-pinene and 18% beta-pinene and other minor monoterpenes. The release rates of ethanol were ~0.02 g/day and PINECHEM 500 ~0.76 g/day, respectively. Release rates were calculated on the basis of ambient temperature conditions with 36 daily measurements between January and February 2013. These semio-chemicals were known to be the best available attractants at the time of the trapping programme for the species of forest insect targeted by our trapping programme (Kerr et al. 2017). Flight intercept traps were connected to a cylindrical aluminium housing with an internal motor that rotated a circular carousel of plastic containers that would contain the insects caught by the trap (6286PTCL - SQ PET JAR 58MM 233ML, Stowers, New Zealand). The motor automatically activated at 24-h intervals and moved the carousel to the next (unused) plastic container thereby separating the trap catches every 24 hours (Figure 1). Cross-vane traps were hung from a metal Y-post at a top height of ~1.5 m with a piece of 50-mm-diameter PVC pipe that connected the trap funnel to the body of the cylindrical aluminium housing. The flight intercept trap and plastic containers were coated with alpha-cypermethrin (RipCord Plus, BASF New Zealand Limited, Auckland, New Zealand) every 4 weeks to kill insects and minimise the potential for insects to move between plastic containers within the carousel. Traps were visited for maintenance and to collect samples at fortnightly intervals between 1 April to 30 September and monthly from 1 October to 31 March. Trap contents were removed, and the numbers of: *A. ferus*; *Hylurgus ligniperda*; *Hylastes ater*; *Prionopus reticularis*; *S. noctilio*; *Pachycotes peregrinus*; and *M. baridioides* were recorded, if present. In cases where traps malfunctioned between maintenance periods, the

total trap catch within the carousel was pooled to note the total number of insects collected rather than daily catches. In total this affected 1,925 catch days of a total sampling period of 16,974 days.

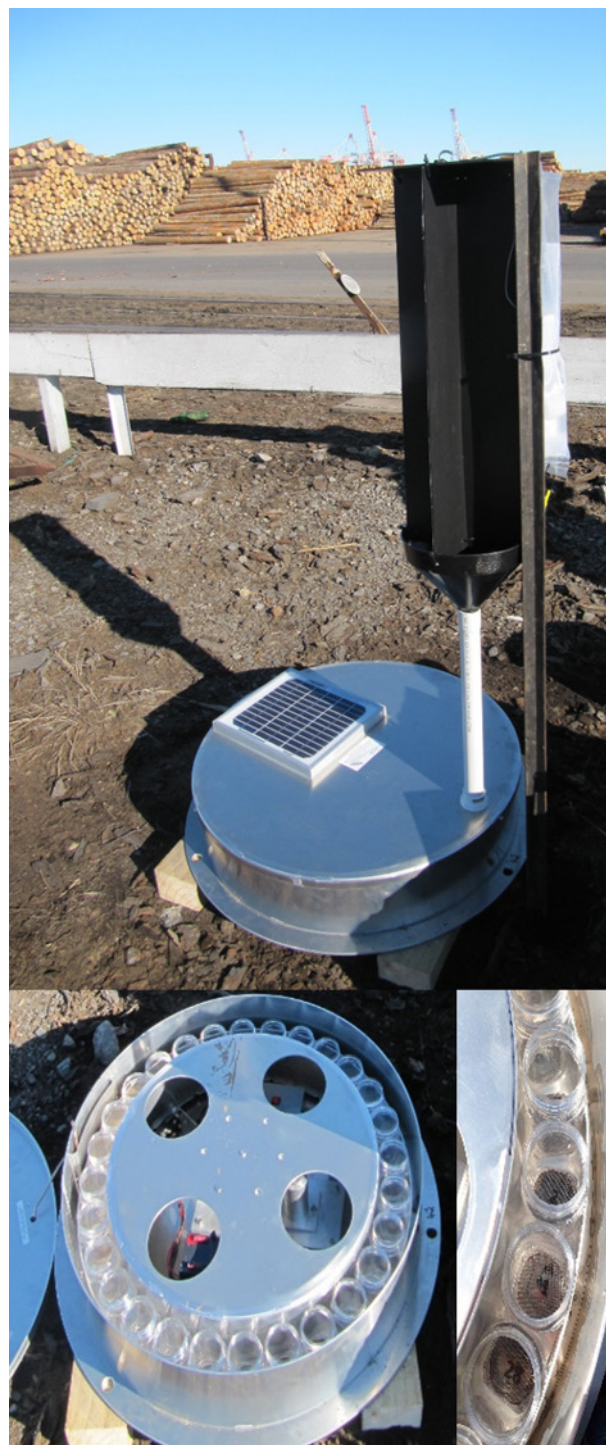


FIGURE 1: Flight intercept trap attached to a bespoke separator system for monitoring daily insect activity (top image). Internal carousel (bottom left image) and sample containers (bottom right image).

Raw meteorological data (temperature, relative humidity, wind speed) were used to analyse the effect of local weather on insect flight activity. Meteorological stations were present on four of the five ports with data for Dunedin (Port Otago) sourced from Musselburgh (-45.90129, 170.5147), the closest meteorological station situated 12 km from the port. The raw meteorological data were summarised with the extensible time series package (R-xts) (Ryan & Ulrich 2018) using R version 3.4.1 (R Development Core Team 2017) to provide daily (12:00 am to 23:59 pm) and evening (20:00 pm to 23:59 pm) summaries for each variable.

Monthly export log volumes were recorded for the individual ports. The monthly export log volumes were provided by the New Zealand Ministry for Primary Industries (Ministry for Primary Industries and Statistics New Zealand, Unpublished data). The relationship between monthly log volume and trap catch was assessed as the quantity of logs stored is expected to influence the strength of the semio-chemical odour (pinenes and ethanol) plume emanating from the port. Hence, it may influence the relative attraction of the site to dispersing beetles.

Landscape composition, particularly the forest cover surrounding a port, has been shown to influence the abundance of bark- and wood-boring beetles in traps at ports (Rassati et al. 2018). To assess this we calculated the percent cover of "Exotic Forest" and "Forest - Harvested" classes of the New Zealand Landcover Database Version 4 that documents landcover in 2012 (Landcare Research 2015). Cover was calculated in a 5 km radius of each trap and averaged for each of the three traps at a given port. No trend was observed in a graphical analysis of flight activity (trap catch) as a function of landscape forest context surround the ports (Additional File: Fig. B12) hence forest cover was not included in further analyses.

### Analysis/modelling details

The phenological data we collected were analysed with respect to climatic variables (temperature, wind speed, and humidity) and export log volumes to determine key drivers that promote or suppress flight activity. We used these data to make predictions of the probability of flight activity for each species at each port.

### Effect of seasonality, meteorology, and export volume on flight activity

The effects of seasonality and meteorology on species-specific flight activity (i.e. trap count) were analysed using generalized additive models (GAMs). Total trap catch varied between species (Table 1) and flight activity models were only generated for the three most abundant species, *A. ferus*, *Hylastes ater*, and *Hylurgus ligniperda*. The total trap catch data required to model the flight activity of all other species was insufficient because of the low numbers trapped of the duration of the study. Daily trap catch was transformed into catch per 100 trap day and summed across each port at weekly intervals between 10 July 2013 and 28 September 2016. Transformation of daily catch data into units of catch per 100 trap days permits communication of low catch rates that would otherwise be expressed as small fractions of an individual during the sampling period. As an example of this transformation, if 100 traps were established and then these traps were checked on a daily basis, then the total observed catch on any given day amongst those traps would reflect the catch per 100 trap days.

To analyse species-specific seasonal changes in flight activity, GAMs included a *port effect* and a *season* (weeks of the year; *Week effect*). The port effect allows for variation in flight activity between ports, whereas weeks of the year represents the seasonal trend. An interaction term for 'Port' and 'Week' was used to account for differences in the way that trap counts varied over time at different ports. Because export volumes were collinear with other variables, they were eliminated from the model. See Additional File for specific details of seasonal GAM models and Figs. B1-B3 showing a scatter plot of daily catch versus monthly export volume.

To analyse the effect of meteorology on flight activity, individual GAM models were constructed separately for each species by meteorological variable. The meteorological variables were averaged within the weekly trapping period as follows: average daily maximum temperature (°C); average evening maximum temperature (°C); average daily instantaneous wind speed ( $m^{-1}s^{-1}$ ); average evening instantaneous wind speed ( $m^{-1}s^{-1}$ ); average daily humidity (%) and average evening humidity (%). Daily averages were used to model

TABLE 1: Trap catch of forest insects captured at five ports in the North and South Islands of New Zealand between the 10 July 2013 and 28 September 2016.

Port	Species							Total catch	Total trap days
	<i>Arhopalus ferus</i>	<i>Hylastes ater</i>	<i>Hylurgus ligniperda</i>	<i>Mitrastethus baridioides</i>	<i>Pachycotes peregrinus</i>	<i>Prionoplus reticularis</i>	<i>Sirex noctilio</i>		
Whangarei	111	20	632	0	0	1	2	766	2,806
Tauranga	166	33	721	0	0	0	0	920	3,258
Napier	758	118	1,104	1	0	0	2	1,983	2,833
Nelson	628	50	657	0	0	0	3	1,338	3,160
Dunedin	111	429	50	0	0	14	0	604	2,991
<b>Total catch</b>	1,774	650	3,164	1	0	15	7	5,611	15,048

flight activity of *Hylastes ater* and *Hylurgus ligniperda* because both species are predominantly diurnal with evening averages used to model the nocturnal *A. ferus* (Pawson et al. 2017). See Additional File for specific details of individual meteorological GAM models.

#### Daily probability of flight at ports

The probability of flight as a function of season was analysed separately for *A. ferus*, *Hylastes ater* and *Hylurgus ligniperda* at each port. We first transformed the daily capture data into binary presence/absence data by re-coding all trap catches greater than zero, then aggregated this daily binary data on a weekly temporal resolution to increase the number of trap-days on which the probability of flight was estimated. This was performed by summing the daily indicators of beetles in each trap (i.e. either 0 or 1) across weekly (7-day) intervals, and across all traps at each port (i.e. 3 traps), providing a daily probability of flight for each week expressed as a binomial proportion (out of a maximum of 21 trap-days). The minimum possible value of 0 is indicative of no single capture during that week at that port, while the maximum possible value of 21 is indicative of positive trap capture in every trap on every day of that week at a port. Across all ports the average week comprised 19.4 trap-days due to the malfunctioning of some traps. Our approach reduces environmental stochasticity (e.g. rainy days) or biased data (e.g. carousel malfunctions) compared with the alternative of modelling a maximum of 3 trap-days on a daily resolution.

GAMs with a binomial error and logit link including a first-autoregressive covariance structure were used to analyse the impact of season on the probability of flight of *A. ferus*, *Hylastes ater*, and *Hylurgus ligniperda*. Species-specific models included *Port* and *Week* (weeks of the year), and their interaction. The model parameters were estimated using penalised quasi-likelihood. Since the response variable was the presence of beetles in traps out of a maximum of 21 trap-days, a GAM with a binomial distribution was used to analyse these data. In a binomial GAM with  $n_i > 1$ , over-dispersion can occur. In the analysis of the binomial GAMs of daily probability of flight, a binomial response showed evidence of over-dispersion. The penalised quasi-likelihood was therefore applied, as per recommendations by Wood (2006). In all cases, cyclic cubic regression splines were used. Penalties were based on the second-order derivatives and the automatic smoothing parameter selection was obtained through minimisation of a generalised cross validation (GCV) and the unbiased risk estimator (UBRE) (Wood 2006). Graphical tools such as Pearson residual plots were used to test for model validation. Auto-correlation plots were used to assess temporal autocorrelation. For *Hylurgus ligniperda*, over-dispersion was detected, and the standard errors were corrected using a quasi-binomial model.

## Results

Over the three years of trapping on five ports around New Zealand, 5,611 individuals of the seven target

forest insects were captured (Table 1). Over half of these (56.4%) were *Hylurgus ligniperda*, while another 31.6% were *A. ferus* and 11.6% were *Hylastes ater*. Very few *Sirex*, *Prionoplus* and *Mitrastethus*, and no *Pachycotes* were collected. As a result, species-level analyses were restricted to the three most abundant species, *A. ferus*, *Hylastes ater*, and *Hylurgus ligniperda* that differed in average catch both between ports and months (Additional File: Fig. A3). *Arhopalus ferus* was captured in higher numbers in Napier and Nelson, while *Hylastes ater* was most abundant in Dunedin. *Hylurgus ligniperda* showed the opposite pattern to *Hylastes ater* and was the most commonly caught species at every port except Dunedin, where only 50 individuals were collected over three years of trapping.

#### Impact of season on flight activity

The flight activity of all three focal species (*A. ferus*, *Hylastes ater*, and *Hylurgus ligniperda*) varied significantly with season across all of the ports sampled ( $P < 0.001$ ; Additional File: Table B1). The monthly export volume was strongly collinear with the 'port' variable and was removed from the model (Additional File). The estimated flight activity of *A. ferus* was highest in February across all ports, but very low from early April until early November (Figure 2; Additional File: Fig. B1). No *A. ferus* were observed in traps between 26 April and 8 October and only 30 (1.7% of total catch) were caught between 1 April and 1 November across all years. The two bark beetle species had low estimated activity during the Southern Hemisphere winter period (1 June to 30 August). *Hylastes ater* exhibited two significant peaks in estimated flight activity in Dunedin where it was most abundant; the first in April and the second in October (Figure 2; Additional File: Fig. B2). *Hylastes ater* had a single spring peak in Napier but activity was generally low at other ports with minor autumn activity (Figure 2). Total actual trap count of *Hylastes ater* across all ports between June and August was only 23 (3.5% of total catch) across all years. *Hylurgus ligniperda* also displayed a bimodal pattern in estimated activity, with the first peak in late summer (February-March) and another in late spring (October-November) across most ports, although this second peak was most pronounced in Napier (Figure 2; Additional File: Fig. B3). The flight activity of *Hylurgus ligniperda* in Dunedin was low throughout the year. The total actual trap count for *Hylurgus ligniperda* across all ports between June and August was only 118 (3.7% of total catch) across all years.

#### Impact of weather on flight activity

Maximum temperature affected the flight activity of *A. ferus*, *Hylastes ater* and *Hylurgus ligniperda* over the entire trapping period at most ports (Additional File: Table B2). Only *A. ferus* at Tauranga and *Hylastes ater* at Whangarei and Napier showed no effect of maximum temperature on flight activity (Additional File: Table B2). The flight activity of all three species showed similar trends across all of the ports, with activity increasing in a nonlinear pattern once maximum temperatures reached about 20 °C (Fig. 3, Additional File: Figs. B4-B6). However, instances where maximum temperature was not a significant factor, or where the relationship was

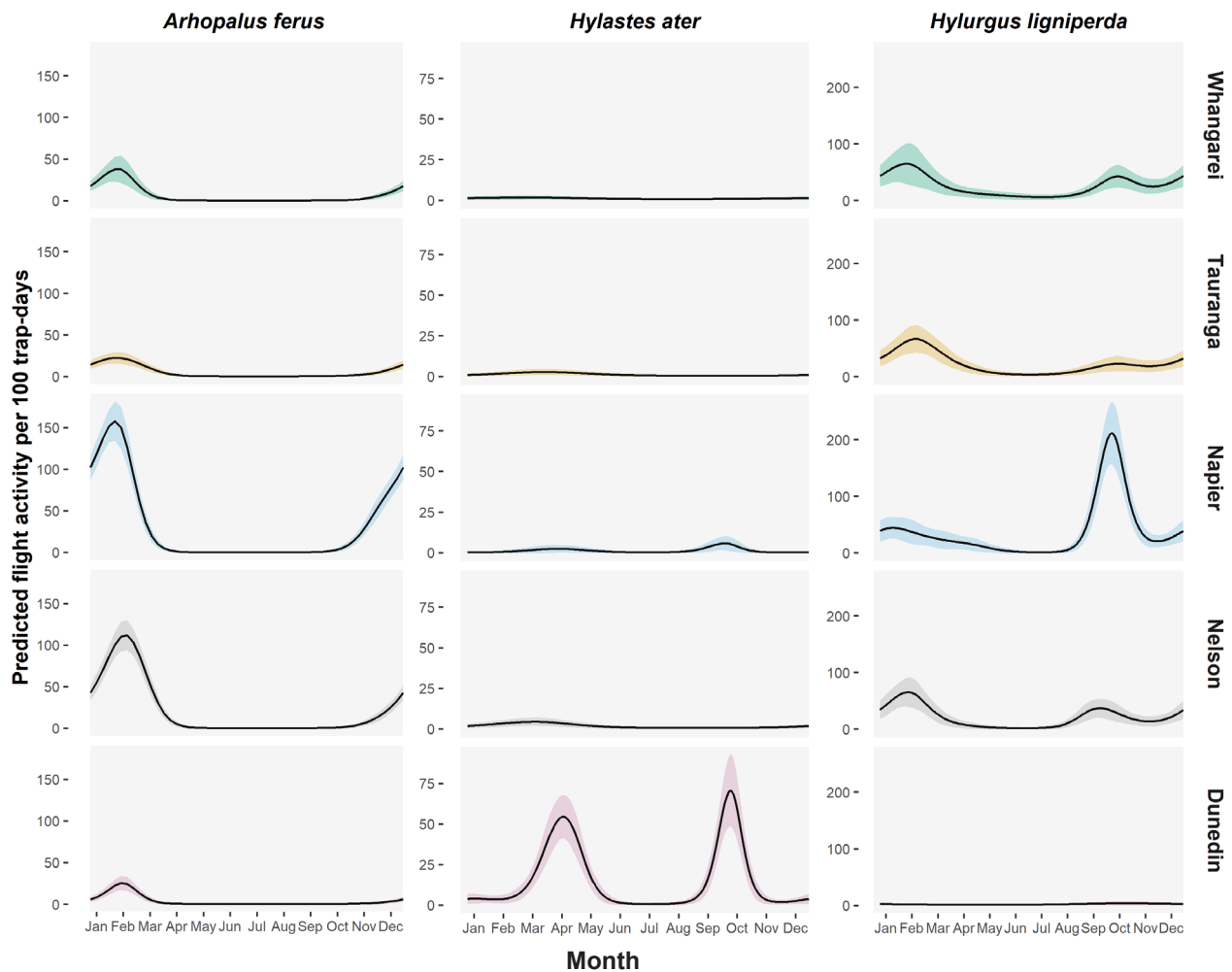


FIGURE 2: Estimated flight activity per 100 trap days with 95% confidence intervals of *Arhopalus ferus*, *Hylastes ater* and *Hylurgus ligniperda* by port throughout the year using the quasi-Poisson GAM approach.

linear, occurred when a particular species was captured in relatively low numbers at a particular port.

Average wind speed affected the activity of *A. ferus* ( $F=32.09$ ,  $P<0.001$ ) and *Hylastes ater* ( $F=23.72$ ,  $P<0.001$ ) (Additional File: Table B3), but did not affect the activity of *Hylurgus ligniperda* over the entire trapping period ( $F=0.56$ ,  $P>0.05$ ; Additional File: Table B3). There was no interaction between the effect of average wind speed and port. The fitted function indicated that the flight activity of *A. ferus* and *Hylastes ater* peaks during calm conditions ( $0 \text{ m}^{-1}\text{s}^{-1}$ ) and declines rapidly with increasing wind speed (Additional File: Fig. B7). For *A. ferus*, this decline continues to the highest recorded wind speeds, but the activity of *Hylastes ater* begins to increase again above a wind speed of approximately  $7 \text{ m}^{-1}\text{s}^{-1}$  (Additional File: Fig. B7). Humidity did not have an effect on the seasonal flight activity of any of our focal forest insect species (all  $P>0.05$ , Additional File: Table B4).

#### Probability of flight

A GAM with a binomial distribution best described the relationship between the probability of flight and weeks of the year for *A. ferus* and *Hylastes ater*, whereas the quasi-binomial GAM best fitted the probability of

*Hylurgus ligniperda* flight. For *A. ferus* and *Hylurgus ligniperda*, weeks of the year affected the probability of flight over the entire trapping period for all ports ( $P<0.05$ , Additional File: B, Table B5). For *Hylastes ater*, weeks of the year affected the probability of flight over the entire trapping period for all ports, except in Whangarei ( $P < 0.001$ ; Additional File: Table B5).

The probability trends for *A. ferus* at each port were very similar in shape, but flight activity in Napier and Nelson was almost twice that of Whangarei at the same time of year (Figure 4). The plot shows that the probability of flight for the five ports increased steeply from late September (excluding Dunedin, which increased gradually from early November) and reached a maximum level in early February before decreasing sharply. On the basis of three years sampling, very little or no *A. ferus* flight activity is predicted from late-April until early-October (Additional File: Table B6). The probability model showed that *Hylastes ater* displays a bimodal seasonality pattern. The probability of flight in Dunedin, where abundances were highest, peaked in mid-April and late October (Figure 4). The probability of flight for *Hylastes ater* was low in the summer months (December and January), and close to zero through

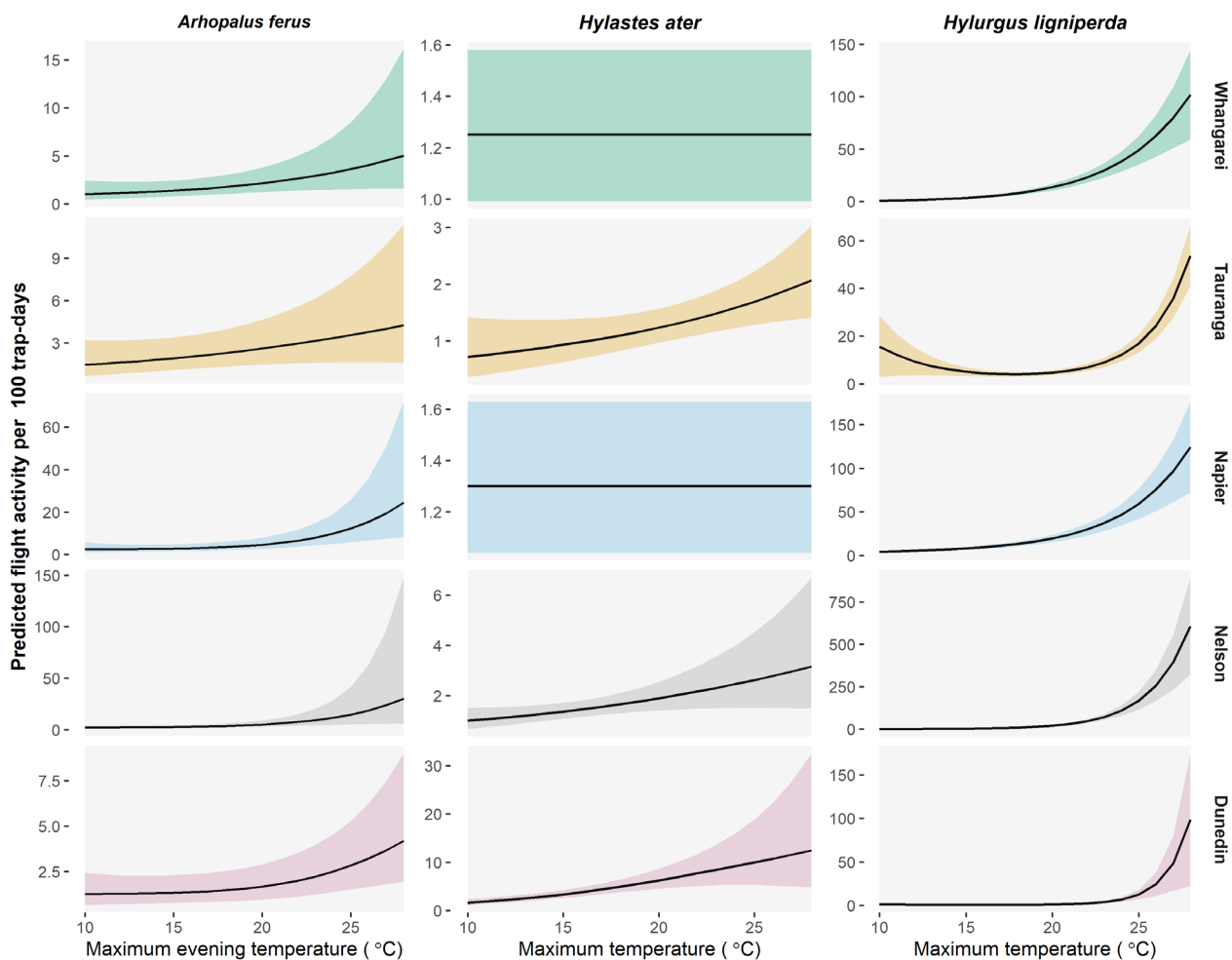


FIGURE 3: Estimated flight activity at ports per 100 trap days with 95% confidence intervals by maximum evening temperature for *Arhopalus ferus* and maximum daily temperature for *Hylastes ater* and *Hylurgus ligniperda* using additive modelling.

the winter (June to August) (Additional File: Table B6). *Hylurgus ligniperda* displayed a similar bimodal seasonal pattern in the probability of activity, with peaks in early February and late September (Figure 4). The probability of flight was low from May to August at all ports for *Hylurgus ligniperda*, but only reached zero in Dunedin (Additional File: Table B6). Although low, *Hylurgus ligniperda* was the most likely species to be present during the winter period.

## Discussion

Major sea ports and airports are a focal point of trade between countries. Consequently, these facilities are also the main entry and exit points for insects associated with trade. Although most port surveillance programmes that target forest insects are designed to detect and report new organisms as they enter a country (Brockerhoff et al. 2006; Rassati, Faccoli, Marini et al. 2015; Rassati, Faccoli, Petrucco Toffolo et al. 2015), detection is unlikely to be perfect (Skarpaas & Økland 2009). Knowledge of which pest species are present on a port, and when they are active, can also be used to identify when and where export phytosanitary risks are greatest. This permits

the application of appropriate treatments that are commensurate to the identified phytosanitary risk and ensures appropriate precautions can be made to prevent re-infestation after treatment. Conversely, phenological data of forest pests at ports could be used to define periods when export phytosanitary risk is minimal. If the phytosanitary risks can be proven that they do not exceed the maximum pest limit of the importing country then phytosanitary treatments may potentially be avoided.

The flight activity of New Zealand's most significant forest insect pests of bulk wood exports varied substantially between species and ports. Maximum temperature was a significant predictor of flight activity, with little activity occurring when temperatures were below 15°C. Consequently, little or no flight activity occurred during the colder winter months (June to August), particularly at the more southerly ports and for *A. ferus* and *Hylastes ater*, which displayed short, predictable peaks in activity at certain times of the year. Our collection data and predictive models show that *A. ferus* is not active at any of the five ports we sampled from May to September, while *Hylastes ater* is mostly inactive across the country from June to August. The

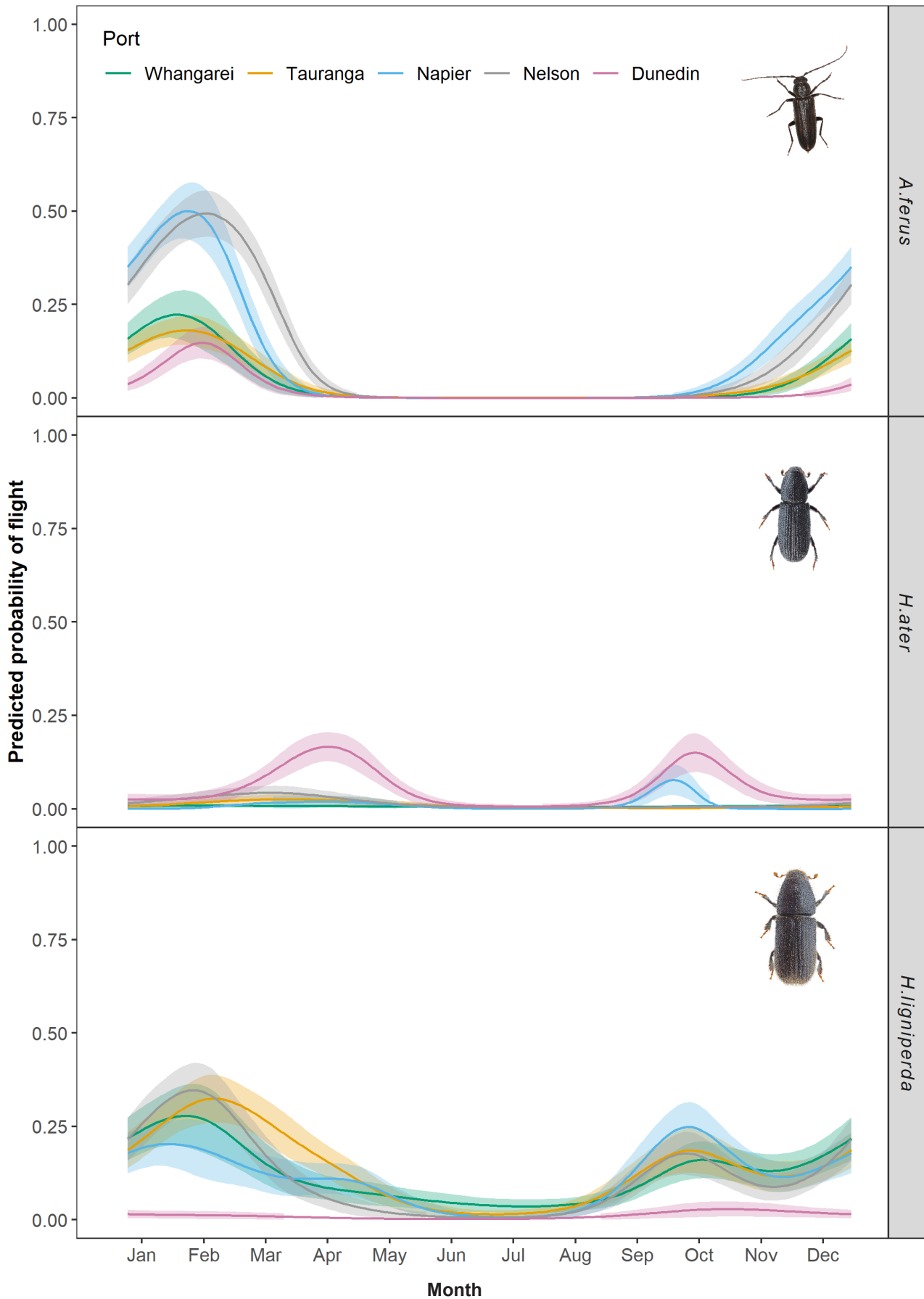


FIGURE 4: Predicted probability of flight and 95% confidence intervals of *Arhopalus ferus*, *Hylastes ater* and *Hylurgus ligniperda* by port throughout the year using a GAM approach.



seasonality of *Hylurgus ligniperda* varied slightly with latitude. Individuals were collected during every month of the year at the two most northerly ports (Whangarei and Tauranga), but were inactive from May to August at the most southerly port of Dunedin. These results suggest that the seasonality of *Hylurgus ligniperda* is affected in part by temperature, with some adult beetles emerging whenever the climate is suitable for flight activity. *Arhopalus fesus* and *Hylastes ater* by contrast, displayed the same strict seasonality patterns across the country, suggesting that warmer temperatures during winter are not sufficient to trigger emergence or induce flight activity of adult individuals.

Using our detailed phenological data on the most significant forest insect pests of concern in *P. radiata* forests in New Zealand, we are able to identify both ports and times of the year when the probability of infestation of logs in a port environment is low. This could allow for the potential implementation of an ALPP. We found that the probability of flight activity was close to zero during June and July for all of our target species at Dunedin, Nelson, and Napier, and also at the northernmost ports for *A. fesus* and *Hylastes ater*. The probability of flight activity for *Hylurgus ligniperda* at Whangarei and Tauranga was also low, but above zero. These data indicate an ALPP exists at export ports for the lower two-thirds of New Zealand during at least the middle of winter (June, July). However, the implementation of an ALPP is reliant on the delivery of logs from the forest to the port that have an infestation level below that of a maximum pest limit that is required by trading partners. This may be achievable during winter if 'just in time' practices ensure that logs are harvested and removed from the forest when meteorological conditions determine that flight activity, and hence post-harvest infestation, is unlikely (Meurisse et al. unpublished data).

Haack (2001), Huang et al. (2012), and; Rassati et al. (2015b) showed that there was a relationship between the volume (and value) of imported goods and the number of bark- and wood-boring beetle interceptions. From an export perspective, however, we found no relationship between the volume of wood exported from a port (on a monthly basis) and the numbers of forest insects we caught in our traps (Additional File: Fig. B11). We had expected to see an increase in trap catch when log volumes increased because greater volumes of stored wood will produce a larger odour plume that should be more attractive to dispersing insects. There are alternative explanations that we have not tested, including site-specific effects, type of trap (see below) and competition between odour plumes (i.e., logs piles versus traps) that could explain this result.

A potential concern for trading partners may be that we utilised only one type of trap because taxonomic bias between different trap designs is a known confounding factor when monitoring flying insects (Hanula et al. 2011; Kerr et al. 2017). However, we are confident that our trap type, its colour and the lures that we used were the best available to capture our target pest species (Brockerhoff et al. 2006; Kerr et al. 2017). The semiochemicals we used are proven to be highly attractive to these wood-boring

species (Brockerhoff et al. 2006) because they mimic the volatiles emitted by dead and dying trees that these insects (all deadwood feeders) use to locate new hosts. However, the relative attraction of different species to these lures has yet to be formally quantified. The Flight Intercept Trap (FIT) design is also particularly good at capturing beetles because the target pest species in our study react to barriers by dropping to the ground (or in the case of a FIT, into a collection container). Abiotic factors, e.g. aspect, slope, proximity to deadwood sources, and or physical structures are also known to influence trap catch (Brockerhoff et al. 2006, 2017). However, an intensive study that defines factors that would maximise the capture rates of forest insects within ports has not been done. Our traps were positioned where they would not interfere with normal port operations, but these trap placements may not have been optimal for the detection of insects. Alternative trapping locations, such as adjacent land, among nearby trees and in wood waste sites may yield slightly different results (Rassati, Faccoli, Marini et al. 2015; Rassati, Faccoli, Petrucco Toffolo et al. 2015). Such trapping could potentially assist in defining phytosanitary risk at a port by estimating risks posed by source populations within the broader landscape that are within the dispersal capabilities of target species (Meurisse & Pawson 2017).

### Additional File

Appendix A: Site information and collection of meteorological variables.

Appendix B: Generalized additive models (GAMs) of the effects of season, weather, and volume on flight activity of forest insects.

### Competing interests

The authors declare that they have no competing interests.

### Authors' contributions

SP conceived the study and prepared the manuscript with CW. Trap network was managed by JK. CS completed the analysis. All authors contributed to, reviewed, and approved final manuscript.

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## References

- Allen, E., Noseworthy, M., & Ormsby, M. (2017). Phytosanitary measures to reduce the movement of forest pests with the international trade of wood products. *Biological Invasions*, 19(11), 3365-3376. <https://doi.org/10.1007/s10530-017-1515-0>
- Allison, J., Strom, B., Sweeney, J., & Mayo, P. (2018). Trap deployment along linear transects perpendicular to forest edges: impact on capture of longhorned beetles (Coleoptera: Cerambycidae). *Journal of Pest Science*, 92, 299-308. <https://doi.org/10.1007/s10340-018-1008-7>
- Brockerhoff, E.G., Bain, J., Kimberley, M., & Knížek, M. (2006). Interception frequency of exotic bark and ambrosia beetles (Coleoptera: Scolytinae) and relationship with establishment in New Zealand and worldwide. *Canadian Journal of Forest Research*, 36(2), 289-298. <https://doi.org/10.1139/x05-250>
- Brockerhoff, E.G., Chinellato, F., Faccoli, M., Kimberley, M., & Pawson, S.M. (2017). Effects of elevation and aspect on the flight activity of two alien pine bark beetles (Coleoptera: Curculionidae, Scolytinae) in recently-harvested pine forests. *Forest Ecology and Management*, 384, 132-136. <https://doi.org/10.1016/j.foreco.2016.10.046>
- Brockerhoff, E.G., Jones, D., Kimberley, M.O., Suckling, D., M., & Donaldson, T. (2006). Nation-wide survey for invasive wood-boring and bark beetles (Coleoptera) using traps baited with pheromones and kairomones. *Forest Ecology and Management*, 228, 234-240. <https://doi.org/10.1016/j.foreco.2006.02.046>
- Chase, K.D., Stringer, L.D., Butler, R.C., Liebhold, A.M., Miller, D.R., Shearer, P.W., & Brockerhoff, E.G. (2018). Multiple-lure surveillance trapping for Ips bark beetles, Monochamus longhorn beetles, and *Halyomorpha halys* (Hemiptera: Pentatomidae). *Journal of Economic Entomology*, 111(5), 2255-2263. <https://doi.org/10.1093/jee/toy190>
- FAO. (2016). *Global Forest Products Facts and Figures* (2016) (pp. 1-16). Rome: Food and Agricultural Organisation.
- Flaherty, L., Gutowski, J.M.G., Hughes, C., Mayo, P., Mokrzycki, T., Pohl, G., Silk, P., Van Rooyen, K., & Sweeney, J. (2018). Pheromone-enhanced lure blends and multiple trap heights improve detection of bark and wood-boring beetles potentially moved in solid wood packaging. *Journal of Pest Science*, 92, 309-325. <https://doi.org/10.1007/s10340-018-1019-4>
- Haack, R.A. (2001). Intercepted Scolytidae (Coleoptera) at U.S. ports of entry: 1985-2000. *Integrated Pest Management Reviews*, 6(3-4), 253-282. <https://doi.org/10.1023/A:1025715200538>
- Haack, R.A. (2006). Exotic bark- and wood-boring Coleoptera in the United States: recent establishments and interceptions. *Canadian Journal of Forest Research*, 36(2), 269-288. <https://doi.org/10.1139/x05-249>
- Haack, R.A., Britton, K.O., Brockerhoff, E.G., Cavey, J.F., Garrett, L.J., Kimberley, M., Lowenstein, F., Nuding, A., Olson, L.J., Turner, J., & Vasilaky, K.N. (2014). Effectiveness of the international phytosanitary standard ISPM No. 15 on reducing wood borer infestation rates in wood packaging material entering the United States. *PLoS ONE*, 9(5), e96611. <https://doi.org/10.1371/journal.pone.0096611>
- Hanula, J.L., Ulyshen, M.D., & Horn, S. (2011). Effect of trap type, trap position, time of year, and beetle density on captures of the redbay ambrosia beetle (Coleoptera: Curculionidae: Scolytinae). *Journal of Economic Entomology*, 104(2), 501-508. <https://doi.org/10.1603/EC10263>
- Huang, D., Zhang, R., Kim, K.C., & Suarez, A.V. (2012). Spatial pattern and determinants of the first detection locations of invasive alien species in mainland China. *PLoS ONE*, 7(2), e31734. <https://doi.org/10.1371/journal.pone.0031734>
- IPPC. (1999). *ISPM10: Requirements for the establishment of pest free places of production and pest free production sites. CPM-2 adopted, revised 2015*. Rome, IPPC, FAO.
- IPPC. (2005). *ISPM22: Requirements for the establishment of areas of low pest prevalence. CPM-7 adopted, revised 2015*. Rome: IPPC, FAO.
- IPPC. (2016). *ISPM 7: Phytosanitary certification system. 2011-04 CPM-6 adopted revised 2016*. Rome, IPPC, FAO.
- Kerr, J.L., Kelly, D., Bader, M.K.F., & Brockerhoff, E.G. (2017). Olfactory cues, visual cues, and semiochemical diversity interact during host location by invasive forest beetles. *Journal of Chemical Ecology*, 43(1), 17-25. <https://doi.org/10.1007/s10886-016-0792-x>
- Landcare Research (2015). LCDB v4.1 - Land cover database version 4.1, Mainland New Zealand. Retrieved from <https://lris.scinfo.org.nz/layer/48423-lcdb-v41-land-cover-database-version-41-mainland-new-zealand/>
- Liebhold, A.M., Brockerhoff, E.G., Garrett, L.J., Parke, J.L., & Britton, K.O. (2012). Live plant imports: the major pathway for forest insect and pathogen invasions of the US. *Frontiers in Ecology and the Environment*, 10(3), 135-143. <https://doi.org/10.1890/110198>
- Liebhold, A.M., Brockerhoff, E.G., & Kimberley, M. (2017). Depletion of heterogeneous source species pools predicts future invasion rates. *Journal of Applied Ecology*, 54(6), 1968-1977. <https://doi.org/10.1111/1365-2664.12895>
- Meurisse, N., & Pawson, S. (2017). Quantifying dispersal of a non-aggressive saprophytic bark beetle. *PLoS*

- ONE*, 12(4), e0174111. <https://doi.org/10.1371/journal.pone.0174111>
- Moore, S.D., Kirkman, W., & Hattingh, V. (2016). Verification of inspection standards and efficacy of a systems approach for *Thaumatotibia leucotreta* (Lepidoptera: Tortricidae) for export citrus from South Africa. *Journal of Economic Entomology*, 109(4), 1564-1570. <https://doi.org/10.1093/jee/tow139>
- Ministry for Primary Industries (2019). *Exports by forestry product - years ended 31 December 1980 to 2017*. Ministry for Primary Industries, Wellington. Retrieved 16 October 2019 from <https://www.teururakau.govt.nz/news-and-resources/open-data-and-forecasting/forestry/wood-product-markets/>
- Pawson, S.M., Marcot, B.G., & Woodberry, O.G. (2017). Predicting forest insect flight activity: A Bayesian network approach. *PLoS ONE*, 12(9), e0183464. <https://doi.org/10.1371/journal.pone.0183464>
- Piel, F., Gilbert, M., De Cannière, C., & Grégoire, J.C. (2008). Coniferous round wood imports from Russia and Baltic countries to Belgium. A pathway analysis for assessing risks of exotic pest insect introductions. *Diversity and Distributions*, 14(2), 318-328. <https://doi.org/10.1111/j.1472-4642.2007.00390.x>
- R Development Core Team. (2017). *R: A language and environment for statistical computing*. Version 3.4.1. R Foundation for Statistical Computing, Vienna, Austria: <http://www.R-project.org/>
- Rassati, D., Faccoli, M., Marini, L., Haack, R.A., Battisti, A., & Petrucco Toffolo, W. (2015). Exploring the role of wood waste landfills in early detection of non-native wood-boring beetles. *Journal of Pest Science*, 88(3), 563-572. <https://doi.org/10.1007/s10340-014-0639-6>
- Rassati, D., Faccoli, M., Petrucco Toffolo, E., Battisti, A., & Marini, L. (2015). Improving the early detection of alien wood-boring beetles in ports and surrounding forests. *Journal of Applied Ecology*, 52, 50-58. <https://doi.org/10.1111/1365-2664.12347>
- Rassati, D., Haack, R.A., Knížek, M., & Faccoli, M. (2018). National trade can drive range expansion of bark-and wood-boring beetles. *Journal of Economic Entomology*, 111(1), 260-268. <https://doi.org/10.1093/jee/tox308>
- Rassati, D., Petrucco Toffolo, E., Roques, A., Battisti, A., & Faccoli, M. (2014). Trapping wood boring beetles in Italian ports: A pilot study. *Journal of Pest Science*, 87(1), 61-69. <https://doi.org/10.1007/s10340-013-0499-5>
- Ryan, J.A., & Ulrich, J.M. (2018). *xts: Extensible time series*. Version 0.10-2. <https://CRAN.R-project.org/package=xts>
- Skarpaas, O., & Økland, B. (2009). Timber import and the risk of forest pest introductions. *Journal of Applied Ecology*, 46(1), 55-63. <https://doi.org/10.1111/j.1365-2664.2008.01561.x>
- Tobin, P.C., Kean, J.M., Suckling, D.M., McCullough, D.G., Herms, D.A., & Stringer, L.D. (2014). Determinants of successful arthropod eradication programs. *Biological Invasions*, 16(2), 401-414. <https://doi.org/10.1007/s10530-013-0529-5>
- USDA. (1992). *Pest risk assessment of the importation of Pinus radiata and Douglas-fir logs from New Zealand*. [Miscellaneous Publication No 1508]. United States Department of Agriculture Forest Service. p. 63.
- Walker, J.T.S., Suckling, D.M., & Wearing, C.H. (2017). Past, present, and future of integrated control of apple pests: The New Zealand Experience. *Annual Review of Entomology*, 62(1), 231-248. <https://doi.org/10.1146/annurev-ento-031616-035626>
- Wood, S.N. (2006). *Generalized additive models: An introduction with R*. Boca Raton, FL, USA: Chapman & Hall/CRC.
- Wylie, F.R., Griffiths, M., & King, J. (2008). Development of hazard site surveillance programs for forest invasive species: a case study from Brisbane, Australia. *Australian Forestry*, 71(3), 229-235. <https://doi.org/10.1080/00049158.2008.10675040>