Economic impact of eucalyptus tortoise beetle (*Paropsis charybdis*) in New Zealand

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An adult *Paropsis charybdis* on *Eucalyptus* foliage. Photo: Scion.

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Executive summary

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The problem

A number of tree species in the genus *Eucalyptus* L'Her are grown in New Zealand on a small scale. However, the economic value of this resource is not known. The economic impact of damage caused by a pest, the eucalyptus tortoise beetle (*Paropsis charybdis*), to *Eucalyptus* species in grown in New Zealand is also not defined.

The current approach

The standing *Eucalyptus* crop in New Zealand was valued in terms of projected yield and other ecosystem services. Also, the cost of *Paropsis charybdis* damage to *Eucalyptus* forests was estimated along with the costs and benefits of chemical and biological control of this pest.

Key results

The total planted area of *Eucalyptus* species in New Zealand was estimated to be 27,598 ha with a standing volume of 8.1 million m^3, with a conservative asset value of $671 million. This could be increased in the future if higher value products (e.g. wood flooring or ground-durable poles) are produced from the existing *Eucalyptus* estate and future plantings. *Paropsis charybdis* shows a strong feeding preference for *Eucalyptus nitens*, which is the major species grown for the production of wood chips for paper making. *Paropsis charybdis* finds many species in the eucalypt sub-genus *Symphyomyrtus* palatable but all show different susceptibility to the pest. We know the proportion of susceptible species in different stands will differ between regions. Regional forest inventory data from the Ministry for Primary Industries (MPI 2016) was examined and combined with Scion in-house species-site matching knowledge to estimate the proportion of *Eucalyptus* species in each region that might be palatable to *P. charybdis*. From this exercise, the weighted average across New Zealand of *Eucalyptus* plantations susceptible to *P. charybdis* was estimated at 60-75%. Therefore, $402-$503 million worth of *Eucalyptus* stands have a high potential of being damaged by *P. charybdis*.

Benefit : Cost of managing **Paropsis charybdis**

Damage caused by *P. charybdis* in terms of yield loss can reach $10,000 ha^{-1} in the case of low-severity, $30,000 ha^{-1} for medium-severity and $60,000 ha^{-1} following high-severity attack at the end of a 40-year rotation. The value of the damage is lower ($1,600 ha^{-1} low-severity, $4,800 ha^{-1} medium-severity, and $9,700 ha^{-1} high-severity) for shorter (15-year) rotation pulpwood plantations. However, in the absence of effective chemical control, the rotation period of a severely damaged stand will need to be extended to obtain the same volume at harvest as an unaffected stand.

There are approximately 15,300 ha of vulnerable *E. nitens* within short-rotation pulpwood plantations in New Zealand and the potential yield loss due to *P. charybdis* damage is estimated at $10 million per year. The current management method involves chemical control by aerial spraying with insecticides once or twice per year. This costs $160 ha^{-1} per year for plantations >40 ha. Chemical treatment was found to be uneconomical for small plantations or woodlots (<10 ha) at an estimated $340 ha^{-1} per year. The current chemical control costs an estimated $1.0–$2.6 million/year and the Net Present Value of the pest control of all susceptible *Eucalyptus* species is $30-$38 million in New Zealand over a 40-year rotation.

Comparison of biological control with chemical control

Effective biological control would reduce damage caused by *P. charybdis* with no on-going costs once the agent is established. In contrast, chemical control involves on-going costs that vary based on the size of the plantation. In most situations, biological control was found to be more cost effective than chemical control. Large plantations (>40 ha) will need to be protected by chemical control when damage is severe but this is an uneconomic method for plantations <10 ha, and not economically justifiable yearly when damage is light to moderate. Thus, small growers are reliant on biological control to realise the value of their woodlots. Effective biological control will prevent an average yield loss of 4.1 m^3 ha^{-1} per year in susceptible *Eucalyptus* stands, which is equivalent to $417 ha^{-1} per year in value. Effective biological control with *Eadya daenerys* could prevent $5.8-$7.2 million in losses per year for the current *Eucalyptus* spp. stands established in New Zealand.

Eucalyptus in the context of ecosystem services

Exotic planted forests in New Zealand (including *Eucalyptus* forests) provide important environmental benefits. These include carbon sequestration, habitats for taonga species, shelter, shading and avoided nitrate leaching. Such benefits are not considered in market transactions but their values can be approximated using environmental economic valuation techniques. The quantifiable environmental value of existing *Eucalyptus* plantings was estimated to be about $11 million per year. However, these environmental values should be considered as indicative only as the value of these ecosystem services can vary substantially across space and time, as well as across tree ages and forest management practices.

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Table of contents

Introduction

Planted forests cover approximately 7% of the land area in New Zealand. The forestry sector is valued at approximately NZ$5.6 billion per year, which makes it New Zealand's third largest export earner (NZ Forest Owners Association, 2017). Protection of this resource from biosecurity threats as well as biotic and abiotic risks is, therefore, a high priority for forest growers (NZ Forest Owners Association, 2017).

New Zealand's commercial plantation forests are dominated by two softwood species: radiata pine (*Pinus radiata* D.Don; 89%) followed by Douglas-fir (*Pseudotsuga menziesii*; 5%). The remaining 6% of the planted estate is comprised of various other species that have the potential to be grown commercially at a large scale. Having a diversified forest estate is important for New Zealand in terms of spreading risk should a biosecurity incursion devastate one major plantation species. A number of species of gum trees in the genus *Eucalyptus* are grown in New Zealand on a small scale and have potential to be an expanded and valuable plantation resource (Wilcox, 1993).

Eucalyptus species are native to Australia and produce hardwood rather than softwood. Some species are very fast growing (Candy, 1997) and contain high-quality wood (Miller, et al., 1992). The wood fibre also has excellent characteristics for pulp and paper making so high value is placed on hardwood chips for manufacturing specialised high-strength packaging products both in New Zealand and overseas. In 2014, the total value of chip exports originating from *Eucalyptus nitens* (H.Deane & Maiden) Maiden plantations was estimated to be approximately NZ$44 million (J. Monge, Scion, unpublished data). The timber from some *Eucalyptus* species is attractively coloured and is suitable for flooring and specialised timber applications (Bootle, 1983). Also, the wood from some species is naturally durable so does not require treatment with toxic chemicals to make it rot resistant (Millen, 2011). A regional value chain is being developed by the New Zealand Dryland Forests Initiative (NZDFI) to grow naturally durable timber on a short rotation for use directly as poles and also for the production of Laminated Veneer Lumber (LVL). Timber from these forests should be available by 2035 (Millen, et al., 2018). One integrated forestry and processing company (Juken NZ Ltd) has already identified eucalypt LVL as a promising product and is actively planting *Eucalyptus* species on the East Coast (currently several hundred hectares). Several other East Coast forest growers and farm foresters, including Landcorp Farming and the Hawke's Bay Regional Council, are also actively planting *Eucalyptus* species (Millen, et al., 2018). It is important to note that wood from some species require specialised processing to prevent growth-stress-related characteristics and/or drying distortion in sawn timber that would otherwise reduce the value of the end product (McKinley, et al., 2002).

Eucalyptus species are beneficial to New Zealand's forestry sector but there is no current consensus on their economic value. Uncertainty exists because some trees have been damaged by a number of specialist pests and pathogens that have occasionally resulted in woodlots being so unhealthy that they have had no commercial value except as firewood. Therefore, the overall objective of this study was to estimate the current economic value to New Zealand of the standing *Eucalyptus* crop.

Many eucalypt pests have invaded New Zealand from Australia, presumably due to the close proximity of the two countries (Withers, 2001). A secondary objective of this study was to determine the loss in economic value caused by defoliation of trees by the most serious pest of *Eucalyptus* species, the eucalyptus tortoise beetle, *Paropsis charybdis* Stål. (Col.: Chrysomelidae) (Bain, et al., 1989; Withers & Peters, 2017). This beetle has been a pest of eucalypt trees in New Zealand since it invaded the South Island in 1916. It causes substantial damage to *Eucalyptus* species, especially *E. nitens*. This pest is considered a high risk to the future profitability of plantations, and this concern may be limiting the development of new plantings. For instance, a similar invasive leaf-feeding pest, *Paropsisterna beata* (Newman) was subjected to an eradication campaign by the Ministry for Primary Industries (MPI) following a cost-benefit analysis that estimated it could cause $23 million in lost pulp wood production over 20 years (Yamoah, et al., 2016).

For the last two decades, forest managers growing *E. nitens* have dealt with outbreaks of *P. charybdis* in their plantations by aerial spraying with the pesticide alpha-cypermethrin (Rolando, et al., 2016). This type of operation is expensive and may also produce incidental spray drift to adjacent plantations that may invalidate spray-free certification, for example by the Forest Stewardship Council (FSC) (Withers, et al., 2013). Biological-control approaches are more environmentally sustainable alternative methods of managing pests such as *P. charybdis.* A number of biological-control agents have been introduced into New Zealand in the past with some success (Bain, et al., 1989; Withers & Peters, 2017). Scion is currently investigating the introduction of a parasitoid *Eadya daenerys* Ridenbaugh (Hym.: Braconidae) from Australia that shows excellent potential to reduce the spring generation of *P. charybdis* by attacking larvae (Ridenbaugh, et al., 2018). However, it may not be possible to establish this beneficial parasitoid if chemical control continues to be the most favoured pest-management technique. This is because broad-spectrum pesticides (such as alpha-cypermethrin) will kill the biological-control agent as well as the pest so are likely to reduce the population size and effectiveness of the beneficial insect (Loch, 2005). Furthermore, managing *P. charybdis* by chemical control is probably not economically feasible for small growers, and they need a sustainable way of ensuring they can grow their *Eucalyptus* crop for long enough to extract the full value from the timber. This would require a sustainable and cost-effective protection from pests for a much longer rotation length.

Paropsis charybdis *biology*

Paropsis charybdis is a chrysomelid leaf-feeding beetle, one of a group of “paropsines” that have evolved to feed on the foliage of the genus *Eucalyptus* from Australia. Feeding by adult beetles is largely restricted to species in the sub-genus *Symphyomyrtus*, Section Maidenaria (Pryor, et al., 1971). For instance, they prefer *Eucalyptus viminalis* La Billardière, *Eucalyptus globulus* La Billardière, *E. nitens,* and many other closely related species. These preferred species support both adult and larval feeding and are prone to severe defoliation every year. *Paropsis charybdis* lay fewer eggs on other species of *Eucalyptus* and the resultant larvae take longer to develop. They also exhibit high mortality (for instance on the monocalypt *Eucalyptus fastigata* Deane & Maiden) (Bain, et al., 1989). Both adults and larvae of *P. charybdis* are voracious feeders. Young larvae feed on new expanding fresh foliage tips, older larvae feed on fresh (but fully expanded) adult leaves and adults can feed on older leaves as long as they are not fully hardened. Trees less than two years old have glaucous (waxy), simple-shaped juvenile leaves that are not palatable. From the age of two years to five years, a transition to glossy, sickle-shaped adult leaves occurs (Brennan, et al., 2001), after which the growing tips and young adult leaves become highly palatable to *P. charybdis*. The pest completes at least two generations per year in New Zealand (A. Pugh et al., unpublished data) so damage can occur between September and May (McGregor, 1984), but peaks in January (Murphy, et al., 2000).

Heavy defoliation of *E. nitens* results in a crown devoid of current foliage and a proliferation of juvenile foliage on the main stem and larger branches (called epicormic growth). Repeated defoliation results in crown die-back and a complete lack of stem growth or height increase. Such trees are commonly referred to as “witches’ brooms”. Complete defoliation over two consecutive years can cause the death of young trees (Bain, et al., 1989). Heavily defoliated older trees may survive indefinitely in a moribund condition without producing any additional stem growth (Figure 1). A field research project in Tasmania has modelled the impact of a range of levels of defoliation on growth of *E. nitens* over a 15-year rotation for pulp logs (Elek, et al., 2017). Their findings mirror observations made in New Zealand, particularly regarding young trees suffering repeated heavy defoliation late in the season for two consecutive years. These trees had a 17% smaller MAI (mean annual increment) and their diameter was at least 21% lower compared with untreated trees over one rotation. Defoliated trees would need to grow for three to four more years to reach the same stand volume as undefoliated trees at harvest (Elek, et al., 2017).

A

B

Figure 1. (A). A *Eucalyptus nitens* plantation in the central North Island following more than 12 years of repeated defoliation from *Paropsis charybdis*. (B). A *Eucalyptus nitens* plantation in the Southland region of the South Island that is free of any insect damage. Note that the Southland trees are half the age of the central North Island trees. Photos T. Withers & S. Gous, Scion.

Methods

The approach used here involved the collection of data on the size and age class distribution of the *Eucalyptus* spp. resource in New Zealand, and the likely costs of managing *Paropsis charybdis.* These data were then analysed using appropriate models to determine the economic value of the resource and the benefit : cost of managing *Paropsis charybdis* using various types of control.

Data collection

Eucalyptus *asset value in New Zealand*

Data on size and age class of the standing *Eucalyptus* spp. resource by region in New Zealand was collected from the National Exotic Forest Description (NEFD), websites (MPI and Forest Owners Association) and industry (Southwood Export Ltd, Oji Fibre Solutions Ltd.) to inform the asset evaluation of New Zealand *Eucalyptus* stands.

Benefit : cost of managing Paropsis charybdis

Researchers at Scion and plantations managers at Timberlands Ltd, Southwood Export Ltd, Oji Fibre Solutions NZ Ltd. were asked to provide details of the costs of forest management practices in their *Eucalyptus* plantations within the last 3–8 years, especially the methods, efficacy, and expenses they have undertaken to control *P. charybdis*. This information was broken down into: application; forest surveillance; and monitoring costs.

The aerial chemical control cost of spraying eucalypt plantations against *Paropsis charybdis* has a strong negative correlation with the plantation size, and ranges from \$22–\$140 ha^{-1} because of fixed minimum aircraft costs to initiate an operation. The pesticide cost is generally lower than the cost of application but shows a positive correlation with plantation size. An almost identical spray boom set-up and flying operation is conducted for spraying pine plantations against Dothistroma needle blight caused by the anamorph form of the pathogen *Dothistroma pini* Hulbary (Ascomycota: Dothideomycetes) so relevant variable costs for 2017 were obtained from the New Zealand Dothistroma Committee (L. Bulman unpublished data) as well compared to the data obtained from plantation managers. The sensitivity of changes in chemical control cost based on plantation size was also explored.

Previously published results for the growth of *E. nitens* under various artificial defoliation treatments (Elek, 1997; Elek, et al., 2017) were used to calculate the impact of *P. charybdis* on growth loss of susceptible eucalypts in New Zealand. The ‘heavy damage’ treatment was selected to represent the current situation for *P. charybdis* damage in New Zealand (Withers & Peters, 2017) (Table 1). Damage from *P. charybdis* was set to begin at age four when susceptible species of tree exhibiting heteroblasty initiate the transition from resistant juvenile to susceptible adult foliage (Brennan, et al., 2001).

Eucalyptus *in the context of ecosystem services*

The Environmental Valuation Reference Inventory database was searched in July 2018 for available literature on the contribution of *Eucalyptus* species to other ecosystem services besides economic value in New Zealand. The search topic “"economic valuation of biological control for eucalyptus" was used. In addition, published works by Yao et al. (2013) and by Yao and Velarde (2014) that estimate market and non-market values of ecosystem services for existing and proposed forests were also consulted.

Data analysis

Eucalyptus *asset value in New Zealand*

Various *Eucalyptus* species are grown in the existing forest estate and these differ in the land area and stand volume. The 2016 National Exotic Forest Description (NEFD) was used to quantify the number of hectares in each 5- or 10-year NEFD age class by region (NZ Forest Owners Association, 2016). Scion expert opinion was used to estimate the proportion of *E. nitens* and other species per region and the yield tables produced by Berrill, et al. (2006) were applied accordingly. The NEFD does not provide estimates of stands smaller than 40 ha; thus, it does not capture standing area of small woodlots. Expert opinion was obtained from the NZ Farm Forestry Association to enable the total area of small woodlots in New Zealand to be estimated. Then, recovery rate and an average stumpage price were allocated using values from Satchell (2015) to estimate *Eucalyptus* stand asset value by age class and region. The inventory age of the forests was used to discount the end of rotation value.

The *E. nitens* growth model (Candy, 1997) and the *E. fastigata* yield model were used to calculate stand volumes for this study (Berrill, et al., 2005). Both models were used to generate average New Zealand stand yield tables for both typical pulp and sawlog regimes for these two species by age class (Berrill, et al., 2006).The assumption was made that the *E. fastigata* yield model is adequate for approximating the standing volume of all other *Eucalyptus* species growing for sawlog regimes.

Benefit : cost of controlling Paropsis charybdis *using chemical methods*

Previously published results for the growth of *E. nitens* under various artificial defoliation treatments (Elek 1997; Elek & Baker 2017) were used to calculate the impact of *P. charybdis* on growth loss of susceptible eucalypts in New Zealand. The 'heavy damage' treatment was selected to represent the current situation for *P. charybdis* damage in New Zealand (Withers & Peters, 2017). The assumptions used in the model of *P. charybdis* impact on *E. nitens* are shown in Table 1. Damage from *P. charybdis* was set to begin at age four years when susceptible species of tree exhibiting heteroblasty initiate the transition from resistant juvenile foliage to susceptible adult foliage (Brennan et al., 2001).

The calculated volume loss at age 15 years was applied to an *E. nitens* production model for short-rotation plantations (Pérez-Cruzado et al., 2011). The loss of MAI at age 40 years was applied to an *E. fastigata* production model for long-rotation plantations (Berrill, et al., 2005).

Table 1. Assumptions used to model/simulate growth and impact of *P. charybdis* on *E. nitens*

Parameter	Assumption	Implications
Growth models	For short-rotation plantations (15 years), the *E. nitens* growth model was used (Pérez-Cruzado, et al., 2011). For long-rotation plantations (40 years), the *E. fastigata* growth model was used (Berrill, et al., 2005).	*E. nitens* grows faster initially than *E. fastigata.*
Rotation length	15 years minimum for *E. nitens* for pulp; 40 years for solid wood.	Only two types of end use were modelled.
Stocking density	Assumed even initial stocking rate of 1100 stems ha^{-1}.	Solid wood regimes have a lower final stocking density after thinning.
Susceptibility	Assumed *E. nitens* is 100% susceptible to *P. charybdis* attack while *E. fastigata* is 0% susceptible.	Other *Eucalyptus* species would likely have a range of values of susceptibility between these two extremes.
Weighted stumpage price	Assumed a weighted stumpage price of \$101 m^{-3} of a *E. nitens* green log.	Depending on the end product, this is conservative.
Plantation size	Cut off between a small and large plantation was set at 40 ha.	Assumed 16% of *Eucalyptus* forests are smaller than this cut-

		off when calculating total value to NZ.
Transition to adult foliage	*E. nitens* transitions to adult foliage at a mean age of 3 years, so only is impacted by *P. charybdis* from 4 years on.	In fact, transition to adult foliage occurs at a range of ages from 2–5 years.
Light damage	50% of new season's foliage removed twice, early in December in two consecutive years, just after having transitioned to adult foliage, LE2 or HE2 (Elek, et al., 2017).	(Assume this damage level once *Paropsis charybdis* is under effective biocontrol in NZ). Stimulates height growth in the short term. At a harvest age of 15 years, trees damaged early assumed to have 2 cm lower DBH than undamaged trees, about 12% reduction in MAI or the rotation age extended by 1 year.
Moderate damage	50% of new season's foliage removed once as well as all growth buds, late in February LDLa1 (Elek & Baker, 2017).	At 15 years old, late disbud once damaged trees were 3 cm lower DBH than undamaged trees, about 14% reduction in MAI, or extended rotation by 2 years.
Heavy damage	100% of new seasons foliage removed in February, in two consecutive years, just after having transitioned to adult foliage, HLa2 (Elek, et al., 2017).	(Assume this damage is currently experienced due to *Paropsis charybdis* feeding in NZ). Over 15 years, either wood volume loss of 20% or rotation extended by another 4 years.
Control cost	\$100–\$400 ha^{-1} per year control cost was applied in the economic model to show the break-even points of chemical applications by severity.	The estimated chemical control cost relied on industry data and expert opinion.
Inflation rate	1.75% inflation in the Net Present Value (NPV) calculation based on New Zealand Treasury data (Statistics NZ, 2013).	
Discount rate	8% discount rate was considered in the NPV calculation.	The discount rate is the choice of the entity that calculates the NPV. Lower discount rates improve the economics of chemical control.

A spreadsheet model was developed to evaluate the effect of three levels of insect damage (low, moderate, or heavy) and the aerial spray application costs needed to control *P. charybdis*/prevent insect damage in plantations. The model represented one hectare of a large (defined as >40 ha) *E. nitens* plantation from age four until harvesting (for pulp at age 15 years, or alternatively for solid wood at age 40 years). A Net Present Value (NPV) calculation was applied to obtain a more realistic estimate of the future costs and effects on income from plantations.

One or two applications per year and a variable scale of aerial spraying expense (\$100–\$400 ha^{-1} per year) and control efficacy (0–100%) were applied to explore the sensitivity of changes in control cost to *P. charybdis* attack severity (light, moderate or heavy). The estimated control cost per hectare per year includes the pest-related forest management efforts such as the cost of staff time to monitor plantation health status, and chemical application costs. In all cases, break-even points were defined and noted. A benefit : cost table was generated and used as a decision-support tool to summarise all the scenarios tested.

Comparison of biological control with chemical control

Biological control is costly to implement, but when successful can create a long-term sustainable method of supressing pest populations, that require no additional costs. The successful biological control project against the gum leaf skeletoniser pest, *Uraba lugens* Walker (Lep.: Nolidae) using *Cotesia urabae* (Austin & Allen) (Hymenoptera: Braconidae) (Berndt, 2011) cost approximately NZ$1.3 million (L. Bulman, Scion, pers. comm). The current proposal to investigate the potential of releasing a new biocontrol agent against *P. charybdis* began in 2013 and is likely to cost over $1 million by the time mass rearing and releases have been completed (L. Bulman, Scion, pers. comm). The cost was not included in the benefit : cost analyses because the full costs are not yet known and the project was funded by a combination of government public-good research funding and industry co-funding. However, the return on investment for successful biological control is generally high. For instance, the return derived from using biological control against insect pests to protect the value of urban *Eucalyptus* trees in California, USA, ranged from US$428 to US$1070 per dollar expended (Paine, et al., 2015).

Biological control was considered as an alternative to chemical control for managing populations *P. charybdis* to below ‘outbreak’ level. An insect outbreak can be defined as 'an explosive increase in the abundance of a particular species that occurs over a relatively short period of time'. This was done by determining the reduction in yield loss that could be achieved by controlling *P. charybdis* populations using biological methods. Laboratory trials have shown that a proposed new larval biological control agent (*Eadya daenerys* Ridenbaugh*,* Hymenoptera: Braconidae) (Ridenbaugh, et al., 2018; Withers, Allen, et al., 2017) can reduce survival of attacked *P. charybdis* larvae from 90% to 9%, although not all pest larvae will ever be located by this natural enemy (T. Withers, unpublished data 2018). Furthermore, in Tasmania, parasitism of spring-generation *P. charybdis* larvae from *E. daenerys* ranges from 0 to 13% per site, but this is in the presence of strong competition from tachinid flies that are not present in New Zealand (Peixoto, et al., 2018). If pest population sizes in any one region are too low then the biological-control agent will either not establish or will become locally extinct. Therefore, in the long term, *P. charybdis* and *Eadya daenerys* are likely to reach a population equilibrium, i.e. the biological-control agent will never drive the pest to extinction. However, levels of the pest should settle eventually at a lower abundance than would occur without biological control.

For this study, it was assumed that, in the future, the presence of effective biological control from *Eadya daenerys* would reduce *Eucalyptus nitens* damage severity from *P. charybdis* from “heavy late season damage” to “light early damage” (see Table 1 above for assumptions) (Elek, et al., 2017). The biological reason for this is that the parasitoid attacks the first-generation of larvae that are present during spring (A. Pugh et al, unpublished data). However, those individuals continue to feed while the parasitoid develops within them. Also, the parents of the infested larvae will persist in the plantation and cause foliar damage so light, spring-season damage will still occur. However, none of the larvae parasitised by *E. daenerys* will reach adulthood so will not emerge from the ground in summer; thus late-season damage should become rarer. This benefit was compared to the on-going costs of one chemical application per year (see above). Results were summarised in a decision-support table to show under what scenarios biological control versus chemical control was the most economically viable option in relation to plantation size.

Results and Discussion

Eucalyptus spp. asset value in New Zealand

Forest inventory data obtained from MPI showed the total area of standing *Eucalyptus* spp. in New Zealand as at April 2016 was 23,182 ha out of a total exotic forest estate of 1,704,707 ha (NZ Forest Owners Association, 2017). However, these MPI data include only owners who have at least 40 hectares of forest. Smaller areas of eucalypts are known to occur as shelterbelts, small woodlots, in small groups or individual trees. MPI (2016) estimated that 16% of New Zealand forests are less than 40 ha so the **total planted *Eucalyptus* area was estimated to be 27,598 ha**. This information plus 2016 data for *Eucalyptus* spp. forest area by age class were used as inputs into the *Eucalyptus fastigata* yield model (Berrill, et al., 2005). The resulting volume of the total *Eucalyptus* estate was 8.1 million m^3. A Net Present Value calculation by age class was applied to this volume and **total asset value** of the 27,598 ha of *Eucalyptus* spp. forests currently in New Zealand was estimated to be **NZ$671 million** (land value excluded).

End products ranging from firewood to high-value timber can be produced from *Eucalyptus* species so the stumpage value can vary. The types of end use depend on the species grown, site conditions and management regime applied. There is potential for the standing *Eucalyptus* estate and future planting of *Eucalyptus* forests to produce high-value products (e.g. wood flooring or ground durable poles). The potential increase in asset value of this resource was estimated to be up to NZ$2 billion based on data from Statistics New Zealand (Statistics NZ, 2013).

Value of eucalypt wood products

Eucalypt wood has a wide range of potential end uses (Millen, et al., 2018). Prices vary from \$20 m^{-3} to \$1200 m^{-3} depending on the quality of the wood, the level of processing, and the place in the supply chain (Satchell, 2015). The weighted stumpage price was used in the current study (Table 2) except where noted otherwise. The reason for this was to provide a conservative estimate of asset value estimate for *Eucalyptus* spp. plantations in New Zealand and to focus on the benefits of pest control.

Table 2. Eucalypt wood product stumpage value from Satchell (2015)

Weighted stumpage price	$/m^3
Solid wood (40-year rotation)	101
Pulp wood (15-year rotation)	50

Benefit : cost of controlling *Paropsis charybdis* using chemical methods

According to MPI, the largest areas of *Eucalyptus* species are in Otago and Southland (12,594 ha) and central North Island (6,534 ha). The total for these two regions is 19,128 ha. These plantations are grown for wood chips for export (Southwood Export Ltd) and for manufacture of packaging products (Oji Fibre Solutions NZ Ltd). Data obtained from plantation managers were used to estimate the average stocking densities for different species: 75-80% for *E. nitens* and 20-25% for *E. fastigata* or *E. regnans*. Only the *E. nitens* plantations (i.e. 15,300 ha) are susceptible to attack by *P. charybdis.*

Eucalypt plantings have started to increase in the Marlborough, Wairarapa, Gisborne and Hawkes Bay regions, reflecting the efforts of the NZDFI (Millen, et al., 2018). Research has begun to evaluate which of the species being developed by the NZDFI are susceptible to *P. charybdis* (Lin, et al., 2017). Although this research is still preliminary, it is known that half of most promising species in terms of end use (i.e. *E. bosistoana* F. Muell., *E. quadrangulata* Deane & Maiden, *E. camaldulensis* Denhardt, and *E. argophloia* Blakely) are showing moderate to high damage caused by *P. charybdis* and other paropsine pests (Lin, et al., 2017). The NZDFI have implemented a research programme that includes selection for pest resistance within the most promising seedlots for future plantings(Millen, et al., 2018). At the present time however damage susceptibility of these species to attack by *P. charybdis* remains highly variable. To reflect this variability within these regions, it was estimated that a range of between 50-70% of the 1900 hectares of plantations would be susceptible to damage, and 30-50% resistant. These data were combined with data from the pulp-growing regions. In addition, all the remaining regions where the composition mixes of species was unknown were assigned a range of between 50% and 70% susceptibility. These data were combined to produce a range of estimated weighted averages across New Zealand of *Eucalyptus* species susceptible to *P. charybdis* of 60-75%. **Therefore, existing *Eucalyptus* stands, worth approximately $402-$503 million are currently vulnerable to yield loss caused by *P. charybdis*.**

A range of scenarios involving one of three levels of insect damage (low, moderate, or heavy) was assessed using the spreadsheet model to determine the cost of *P. charybdis* control for one hectare of a large (defined as >40 ha) *E. nitens* plantation from age four until harvesting (for pulp at age 15 years, or alternatively for solid wood at age 40 years). The current management method of chemical control (Rolando, et al., 2016) **costs an estimated $1.0–$2.6 million/year and the Net Present Value of the pest control of all susceptible *Eucalyptus*** species **is $30-$38 million in New Zealand over a 40-year rotation**. An average application cost of $160 ha^{-1} per year was used. However, the cost of chemical control, if applied, would be at least $340 ha^{-1} per year for small plantations (<10 ha).

Short rotation

In large (>40 ha) eucalypt plantations managed under a short (15-year) rotation for a pulpwood end use, damage caused by *P. charybdis* can reach a NPV $1,600 ha^{-1} in the case of a low-severity attack, $4,800 ha^{-1} from a moderate-severity attack and $9,700 ha^{-1} after high-severity attacks at the end of a 15-year rotation. The benefit : cost ratios of chemical control are summarised in Table 3 and Figure 2. The green cells in the tables indicate those situations where the present values of the avoided yield loss are higher than the present values of chemical application, i.e. it is profitable to apply chemical control. The red cells indicate those situations where using chemical control will not provide enough benefit (i.e. won't reduce growth yield loss sufficiently) to justify application.

Table 3. Benefit : cost ratios of chemical control to reduce yield loss in an *E. nitens* plantation grown for pulpwood on a 15-year rotation under various scenarios. A. one insecticide application per year, and B. two insecticide applications per year

A. One application per year

Plantation type	Size (ha)	Cost (NZ$/ha/application)	Benefit : cost ratio for a given *P. charybdis* damage severity		
			Heavy	Moderate	Low
Large plantation	>40	100	3.4	1.8	0.7
Large wood lot	30-40	200	2.1	1.1	0.4
Medium wood lot	10-20	300	1.1	0.6	0.2
Very small wood lot	<10	400	0.9	0.4	0.2

B. Two applications per year

Plantation type	Size (ha)	Cost (NZ$/ha/application)	Benefit : cost ratio for a given *P. charybdis* damage severity		
			Heavy	Moderate	Low
Large plantation	>40	100	1.7	0.9	0.3
Large wood lot	30-40	200	1.1	0.6	0.2
Medium wood lot	10-20	300	0.6	0.3	0.1
Very small wood lot	<10	400	0.4	0.2	0.1

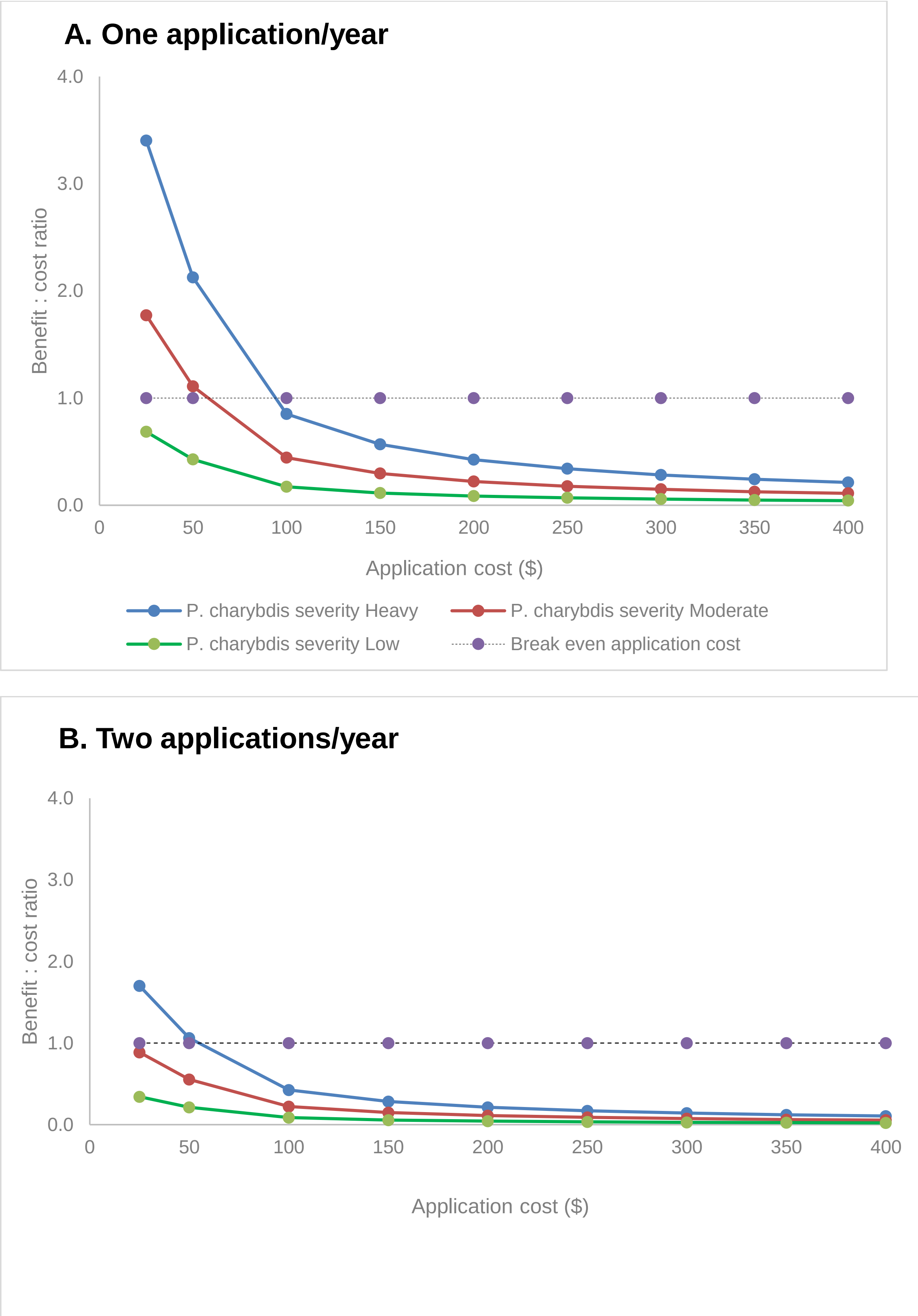

Figure 2. Impact of aerial chemical application cost against *P. charybdis* on the benefit : cost ratio for an *E. nitens* plantation (>40 ha) grown for pulpwood on a 15-year rotation (A. one application per year; B. two applications per year)

Long rotation

Some eucalypt plantations are managed under a long (40-year) rotation for solid wood end uses. No studies on the effect of *P. charybdis* over this time frame are available so it is not known whether chemical control would be needed every year, or whether the loss of MAI that is modelled up to 15 years old would continue to be realised up to 40 years old (Elek, et al., 2017). Candy (1999) made the assumption that all trees stabilise to the same growth rate as undefoliated trees within four years of defoliation ceasing. Applying this assumption means that smaller trees never regain the growth that they had lost in previous years. However, Elek and Baker (2017) found that more heavily defoliated trees continued to show reduced growth rates compared to undefoliated trees at harvest, which suggests they continue to generate a lower MAI, and the variation between treatments increases over time. The benefit : cost ratios of chemical control for a long rotation are summarised in Table 4 and Figure 3.

Table 4: Benefit : cost ratio of chemical control to reduce yield loss in a solid wood 40-year rotation plantation according to damage severity caused by *Paropsis charybdis*, and plantation size, when undertaking: A. one insecticide application per year; and B. two insecticide applications per year

A. One application per year

Plantation type	Size (ha)	Cost (NZ$/ha/application)	Benefit : cost ratio for a given *P. charybdis* damage severity		
			Heavy	Moderate	Low
Large plantation	>40	100	4.1	2.0	0.7
Large wood lot	30-40	200	2.6	1.3	0.4
Medium wood lot	10-20	300	1.4	0.7	0.2
Very small wood lot	<10	400	1.0	0.5	0.2

B. Two applications per year

Plantation type	Size (ha)	Cost (NZ$/ha/application)	Benefit : cost ratio for a given *P. charybdis* damage severity		
			Heavy	Moderate	Low
Large plantation	>40	100	2.0	1.0	0.3
Large wood lot	30-40	200	1.3	0.6	0.2
Medium wood lot	10-20	300	0.7	0.3	0.1
Very small wood lot	<10	400	0.5	0.3	0.1

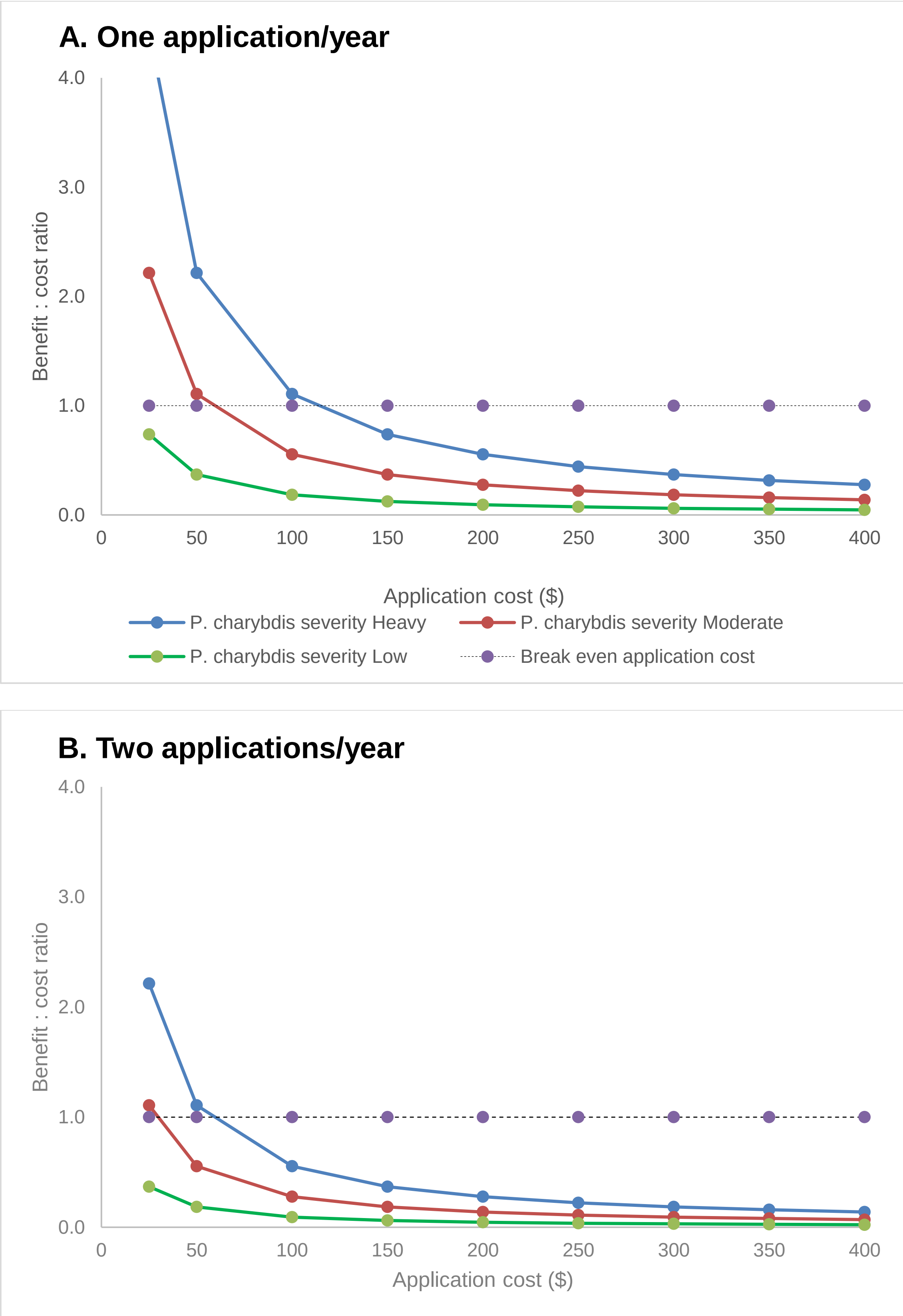

Figure 3. Impact of aerial chemical application cost against *P. charybdis* on the benefit : cost ratio for an *E. nitens* plantation grown for solid wood in a 40-year rotation (>40ha). (A: one application per year; B two applications per year).

Damage caused by *P. charybdis* in terms of yield loss can reach \$10,000 ha^{-1} in the case of low-severity, \$30,000 ha^{-1} for medium-severity and \$60,000 ha^{-1} following high-severity attack at the end of a 40-year rotation. With the cost of chemical control for plantations >10 ha found to be NZ\$160 ha^{-1} per year, chemical pest control is **not economically viable when damage severity is low**. For medium-severity damage, chemical pest control is economical only if the prevented yield loss is >65%. In the case of high severity, chemical control is viable if the avoided yield loss is >34% (Figure 4).

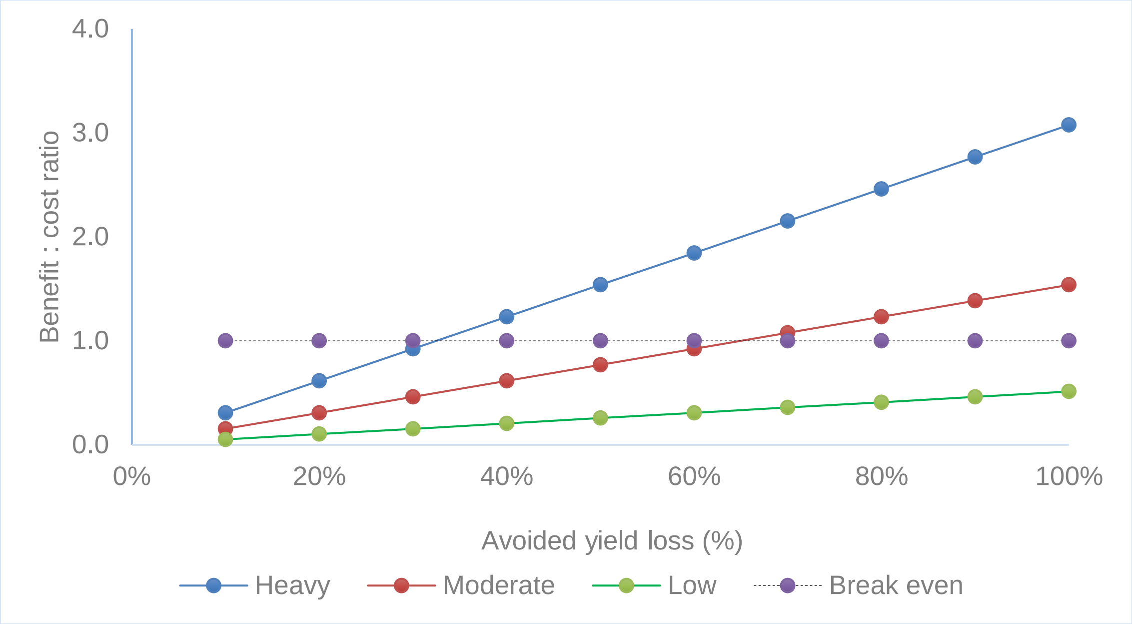

Figure 4. Benefit : cost ratio of the percent avoided yield loss in *E. nitens* plantations from *P. charybdis* damage at various degrees of severity assuming an average total chemical application cost of $160/ha in large plantations (>40ha).

The chemical control cost for very small plantations (≤10 ha) is NZ$340 ha^{-1} per year due to higher fixed costs of operating aircraft over smaller areas. At this cost, chemical pest control is not economically viable when damage from *P. charybdis* is of low or medium severity. For high-severity damage, chemical control is beneficial only if the avoided yield loss is more than 70% (Figure 5).

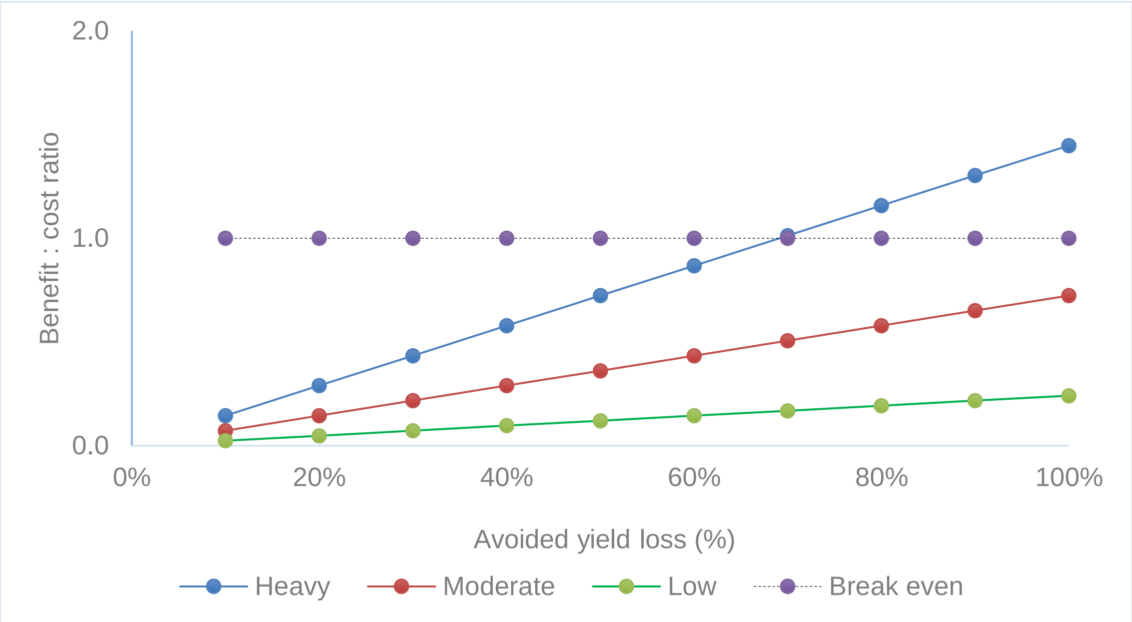

Figure 5. Benefit : cost ratio of percent avoided yield loss from *P. charybdis* at various severities according to average chemical application costs of $340 ha^{-1} in very small plantations (≤10 ha)

Comparison of biological control with chemical control

The economic benefit of preventable yield loss by reducing *P. charybdis* populations using biological control was estimated. It was assumed that, in the future, the presence of effective biological control from *Eadya daenerys* would reduce *Eucalyptus nitens* damage severity from *P. charybdis* from "heavy late-season damage" to "light early-season damage" (Table 1). The analyses were conducted in relation to plantation size. The following assumptions were applied:

- zero chemical application cost when the biological-control agent was used in all years
- first pest attack occurs at year 3,
- 95% avoided yield loss by aerial chemical control insecticide application
- 45% yield loss prevented by effective biological control (Table 1)
- one chemical application per year

The results of the analysis are shown in Table 5.

Table 5. Benefit : cost ratios of utilising biological control compared to chemical control on *Eucalyptus nitens* yield loss under either: A. short rotation of 15 years; or B. long rotation of 40 years.

A. Short rotation

Plantation type	Size (ha)	Benefit : cost ratio for a given *P. charybdis* damage severity		
		Heavy	Moderate	Low
Large plantation	>40	0.69	1.11	X
Large wood lot	30-40	0.89	3.64	X
Medium wood lot	10-20	3.04	X	X
Very small wood lot	<10	X	X	X

B. Long rotation

Plantation type	Size (ha)	Benefit : cost ratio for a given *P. charybdis* damage severity		
		Heavy	Moderate	Low
Large plantation	>40	0.74	0.83	X
Large wood lot	30-40	0.88	1.50	X
Medium wood lot	10-20	1.62	X	X
Very small wood lot	<10	4.01	X	X

X= chemical control costs exceed the prevented yield loss benefits based on Table 3 A and B even without using a biological-control agent

The green cells in Table 5A and B show the situations when the net present values of the avoided yield loss from biological control are higher than those of chemical application, i.e. it is profitable to rely on biological control. The red cells indicate that biological control will not provide sufficient benefit (i.e. reduce growth yield loss) so application of chemical control will be required to maintain the profitable growth of the plantation. *Eadya daenerys* will be more economically beneficial for small and medium wood lots, which would require unrealistically costly chemical control applications. No clear net monetary benefit of biological control would occur compared to chemical control in the case of large plantations experiencing very high- or medium-severity of defoliation by *Paropsis charybdis*. The advantage of biological control is greater for a short, 15-year rotation than for a long, 40-year rotation.

Using *Eadya daenerys* to reduce damage from *Paropsis charybdis* provides an average NPV of \$1,245 ha^{-1} over a 40-year rotation period of a *Eucalyptus* spp. stand. Assuming a 60-75% susceptibility rate across New Zealand of eucalypt woodlots and plantations, the total NPV of using biological control instead of chemical control is \$17.4-\$21.8 million.

Effective biological control will prevent an average yield loss of 4.1 m^3 ha^{-1} per year in susceptible *Eucalyptus* stands, which is equivalent to \$417 ha^{-1} per year in value. Effective biological control with *Eadya daenerys* could prevent \$5.8-\$7.2 million in losses per year for the current *Eucalyptus* spp. stands established in New Zealand.

Eucalyptus in the context of ecosystem services

The Millennium Ecosystem Assessment (MEA, 2005) provides a framework for demonstrating the full range of direct and indirect benefits provided by an ecosystem (e.g. a *Eucalyptus* forest ecosystem) to society. This framework enables the assessment and accounting of market (e.g. timber) and non-market (e.g. biological control, recreation and habitat provision) values in policy discussions. Under this framework, the *biological control* service is classified as one of the regulating services (i.e. an ecosystem process usually mostly taken for granted as it indirectly benefits society). However, this section focuses on describing the potential benefits of using biological control as an eco-friendly pest control method over chemical control of *P. charybdis* in New Zealand's *Eucalyptus* forests based on related economic valuation studies.

New Zealand's 1.7 million hectare exotic planted forest estate is mainly recognised for timber values but it is also being increasingly regarded for the provision of non-market ecosystem services such as carbon sequestration, avoided erosion, recreation, biodiversity conservation and improved water quality (Yao, et al., 2013). Timber has a market value and, therefore, it is easily accounted for in decision making. Non-market ecosystem services are also important and they can be estimated using economic valuation techniques based on actual behaviour of forest users (e.g. travel cost), hypothetical behaviour under simulated market scenarios (e.g. stated preference) and other environmental economic valuation approaches (Barry, et al., 2014; Yao, Scarpa, et al., 2014) (Dhakal, et al., 2012). In the estimation of non-market benefits, a monetary value is assigned based on the fact that the benefit is defined as a change in human well-being generated by the change in provision of an environmental good (Bateman, et al., 2011). For example, in the estimation of willingness to pay for species conservation in planted forests, respondents of a stated preference survey are asked if they would be willing to financially support a proposed programme that would increase the abundance of iconic species in planted forests (Yao, Scarpa, et al., 2014). Bateman, et al. (2011) described the major non-market valuation techniques and recommended practices (e.g. avoiding double counting, reducing biases) used to ensure that estimated values are robust and that such values can be aggregated accordingly.

Chemical control reduces numbers of many insect species in a forest but biological control only reduces populations of the target insect. Therefore, there should be more food for insect-eating birds (e.g. piwakawaka (fantail), riroriro (grey warbler) and tui) in *Eucalyptus* stands under biological control. Yao, et al. (2010) used a survey-based stated-preference approach called 'contingent valuation' to test how a sample of more than 700 New Zealand households would value the enhancement of biodiversity on private land. Their results showed that a typical household would be willing to financially support the planting and growing of native trees on private land to provide habitats for native birds at the rate of NZ\$42 per household per year for a five-year programme. Similarly, a stated preference study by Yao, Scarpa, et al. (2014) found that a sample of 209 New Zealand households would pay for a five-year programme that would conserve key native species (e.g. North Island brown kiwi, a taonga species) in planted forests (Holzapfel, et al., 2008). An older study by Jetter, et al. (2004) also used the contingent valuation method to estimate the willingness to pay of a sample of 522 households in Southern California for proposed biological control of an insect pest of *Eucalyptus* in the urban landscape. They found the release of natural enemies was overwhelmingly the most preferred option while chemical insecticide was least preferred. All pest control options were valued by a typical household respondent and each would be prepared to pay on an annual basis US\$485 for natural enemy, US\$131 for bacterial spray and US\$23 for the chemical pesticide option.

Use of chemical pesticides in plantation forests can pollute or contaminate waterways, which can negatively impact on human health and freshwater-related recreational activities (e.g. fishing, swimming, and boating). Clinch (1999) estimated the reduction on angling value due to water pollution from forestry in the UK to be approximately £20 ha^{-1}. In 2016, a large majority (73%) of New Zealand's planted forests had environmental certification (i.e. FSC) (NZ Forest Owners Association, 2017). *FSC Criterion 6.6* states that "Management systems shall promote the development and adoption of environmentally-friendly non-chemical methods of pest management and strive to avoid the use of chemical pesticides" (FSC (Forest Stewardship Council), 2013). These examples provide a strong case for the use of biological control to ensure that waterways are safe for recreation while ensuring the forest itself is compliant with environmental certification requirements.

Various ecosystem services such as timber, recreation, avoided erosion, carbon sequestration and avoided nitrate leaching have already been quantified in New Zealand forests using the Forest Investment Framework and economic valuation techniques (Barry, et al., 2014; Yao, et al., 2013; Yao, et al., 2016; Yao & Velarde, 2014)). Yao and Velarde (2014) approximated the value of ecosystem services provided by planted forests in the Ōhiwa catchment in the Bay of Plenty (on a per hectare basis; Table 6). Not all of the non-market ecosystem service values identified for Ōhiwa would be applicable for the existing 27,598 hectares of *Eucalyptus* plantings estimated above nor for any new plantings. For example, the recreation value described in Yao and Velarde (2014) only applies to publicly accessible planted forests. The NZDFI have stated their aim is to increase the area of *Eucalyptus* forest by 100,000 ha by 2030, which is five times more than the current *Eucalyptus* estate (Millen, February 2018). These new *Eucalyptus* plantings would likely be set on private farmlands; therefore, recreational access will be limited. In terms of species conservation value, the study by Yao, Scarpa, et al. (2014) specifically applies to planted forests that are sufficiently large i.e. at least 5000 hectares in a contiguous area so may not be applicable to new *Eucalyptus* plantings. Also, it is not possible to apply values for nutrient cycling and soil formation as those services fall under supporting services (which underpin the provision of the final ecosystem services), which could lead to double counting (Fu, et al., 2011). However, approximate values for carbon sequestration, avoided erosion and some of the other services listed in Table 6 can be applied to these new plantings if they fit the conditions stated in New Zealand's Emissions Trading Scheme (ETS). The ETS defines a forest as an area covering at least one hectare of forest species and has more than 30% tree crown-cover on each hectare, and an average crown-cover width of at least 30 metres. In this exercise, it was assumed that half of the new plantings will have the characteristics that allow them to be classified as 'forests'.

It was assumed that half of the identified 27,598 ha of existing eucalypt plantings could be classified as forests, i.e. 13,799 ha. This latter value was multiplied by the average annual value of applicable ecosystem services of \$812 ha^{-1}. This results in a conservative, aggregate non-market ecosystem service value estimate of approximately NZ\$11 million per year or a total of approximately \$NZ440 million for a 40-year rotation. These values should be considered as indicative only and should be treated with caution as the value of these services can significantly vary across space and time as well as across tree ages and forest management practices.

Table 6. Forest ecosystem services quantified on a per-hectare basis.

Ecosystem service	**Ecosystem service value of exotic forestry in Bay of Plenty's Ōhiwa catchment ($/ha/year)**	**Applicable values for existing *Eucalyptus* plantings in New Zealand ($/ha/year)**
Recreation	900	na
Species conservation	257	na
Carbon sequestration	48	48
Avoided sedimentation	121	121
Avoided nitrate leaching	168	168
Pollination	206	206
Water regulation	6	6
Waste treatment	244	244
Pest and disease regulation	11	11
Water supply	8	8
Nutrient cycling	994	na
Soil formation	14	na
TOTAL	2,977	812

Source: Yao and Velarde (2014). na means this particular value is not applicable to *Eucalyptus* forests that are closed to public access, or no data exists.

Eucalyptus forests also provide other important services such as shelter, shading, amenity trees, floral resources, species-diverse plantations, wind breaks and firewood (Paine, et al., 2015; Taranaki Regional Council, undated) in addition to those listed above. New Zealand city dwellers and residents (as well as local councils) have recognised the importance of the establishment and maintenance of street and park trees (Meurisse, et al., 2016), which do potentially include certain species of *Eucalyptus*. For example, Vesely (2007) found that New Zealand urban households would be willing to financially support a proposed programme that would increase the number of amenity trees in urban areas. Since biological control of would effectively and efficiently control *P. charybdis*, it could help in maintaining and sustaining the environmental and social benefits provide by *Eucalyptus* species in both rural and urban settings.

The NZDFI is also encouraging the creation of smaller-size durable eucalypt plantations (woodlots and shelterbelts) due to the diversity of benefits these species offer if planted in farm environments, including:

- On-farm production of posts, poles and timber for farm infrastructure with no treatment required
- Excellent firewood
- Nectar and pollen production
- Shelter and shade for stock
- Remediation of waste water (Some eucalypt species have been proven to remediate waste water through the use of spray irrigation in plantations and could have the potential to strip nitrates from ground water if planted and harvested with care in riparian margins).
- Erosion control and carbon sequestration (*Eucalyptus* spp. can live hundreds of years so could also be established as permanent forests on steep unproductive land for erosion control and to sequester carbon. The trees could be spaced widely to allow native planting or regeneration to also form a long-term forest canopy. Forest ecosystem services such as avoided erosion and carbon sequestration have already been quantified using the Forest Investment Framework (Yao, et al., 2016)).

These benefits are likely to extend to the billion-tree programme announced recently by the Labour government (Millen, et al., 2018)

The above values of biological control in planted forests provide some positive non-market values for planted forests in New Zealand. However, these values were generated for different locations and were undertaken at a different scale to the current study so were not to incorporate into the economic evaluation conducted here. Little published literature exists that compares valuation studies on conservation biological control. One review paper by (Naranjo, et al., 2015) included two New Zealand based economic valuation studies but focused on agricultural crops such as tomato, soybeans and cacao rather than forest. Therefore, estimating the economic value of introduced biological control in forestry is an area for future study. Also, there are insufficient data at present to show how the provision of ecosystem services vary between a biologically controlled versus chemically controlled *Eucalyptus* forests.

Conclusion

Existing plantings of *Eucalyptus* species in New Zealand have a substantial economic asset value. This value is expected to increase in the next decade with additional investment in new plantings. Forest growers need to invest in pest management to prevent yield loss from *P. charybdis*. The economic analysis undertaken here shows that either chemical- or biological-control methods can be the most cost effective in different situations depending on the severity of the pest outbreak, plantation size, (and associated aerial spraying cost) and rotation length.

The following trade-offs exist:

1.) Biological control of *P. charybdis* becomes more cost effective as the cost of chemical control increases. This information is most relevant for small (<10 ha) *Eucalyptus* woodlots where the cost of aerial spraying is unjustifiable when higher than \$300 ha^{-1}.

2.) The average value of the harvested timber is lower for short-rotation pulp plantations than for long-rotation solid wood plantations. Biological control of *P. charybdis* is more cost effective than chemical control for short rotations.

3.) Only long-term yield losses following severe damage to large plantations are sufficiently high to justify chemical treatment rather than biological control.

Chemical control can be disadvantageous to the environment, society and sustainability certification, and could reduce the value of the wood or product. *Eucalyptus* trees grown in New Zealand may provide a range of direct and indirect ecosystem service benefits. The aggregate non-market ecosystem service value of 13,799 ha of existing *Eucalyptus* forest was estimated to be approximately NZ\$11 million per year.

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