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Analysis

Economic Outcome of Classical Biological Control: A Case Study on the *Eucalyptus* Snout Beetle, *Gonipterus platensis*, and the Parasitoid *Anaphes nitens*

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ABSTRACT

Despite the importance of invasive pests, few studies address the costs and benefits of the strategies used to control them. The present work assesses the economic impact of the *Eucalyptus* snout beetle, *Gonipterus platensis*, and the benefits resulting from its biological control with *Anaphes nitens* in Portugal, over a 20-year period. Comparisons were made between the real situation (with *A. nitens*) and three scenarios without biological control: 1) replacement of *Eucalyptus globulus* by resistant eucalypts; 2) insecticide use; and 3) offset of yield losses by imported wood. A cost-benefit analysis was performed to evaluate a programme that aimed to accelerate *A. nitens* establishment. Although *A. nitens* provides adequate pest control in several regions, 46% of the area planted with eucalypts is affected by the beetle, causing wood losses of 648 M euros over 20 years. Losses in the three hypothetical scenarios were estimated at 2451 M-7164 M euros, resulting in benefits from biological control of 1803 M–6516 M euros, despite the fact that only partial success was achieved. Anticipating biological control by just one, two, or three years resulted in benefit-cost ratios of 67, 190, and 347, respectively. Because nonmarket values were not accounted for, these figures are likely underestimated.

1. Introduction

Invasive alien species pose a major threat to natural and managed ecosystems, and can have substantial ecological and economic impacts. Biological invasions by insects alone cost at least 70 billion US dollars per year globally, but this value is greatly underestimated due to the lack of reliable cost assessments (Bradshaw et al., 2016). Classical biological control (CBC) is a particularly useful strategy to manage non-native species that attain pest status in their introduced range due to the absence of natural enemies (Kenis et al., 2017). Between 1870 and 2010, 2384 species of natural enemies have been introduced for CBC of insect pests worldwide, leading to the control of 172 of 588 target pests (Cock et al., 2016). Despite the high number of programmes undertaken, analyses weighing economic costs and benefits of CBC have hardly been assessed (Greathead, 2003; Kenis and Branco, 2010; Naranjo et al., 2015). The scarcity of economic studies arises from many causes, including lack of funding for post-release monitoring, long periods from release until full field establishment of the biological control agent, difficulty in assessing impacts of CBC programmes, or difficulty in assigning monetary values to externalities (Cock et al., 2015; McFayden, 2008). In addition, when successful control is achieved the problem disappears and the focus shifts to other problems (Paine et al., 2015).

Gonipterus platensis (Marelli) (Coleoptera: Curculionidae) is one of three species from the Australian genus *Gonipterus* that were accidentally introduced in other parts of the world, where they became pests of eucalypts (Hurley et al., 2016; Mapondera et al., 2012). CBC with the egg parasitoid *Anaphes nitens* (Girault) (Hymenoptera: Mymaridae) has been the strategy most commonly used to reduce *Gonipterus* spp. populations. This natural enemy was first used in South Africa, in 1926 (Tooke, 1955). It was also introduced in New Zealand, North and South America, and Europe (Arzone and Vidano, 1978; Hanks et al., 2000; Tooke, 1955). Good results were obtained with *A. nitens* in many countries, but complete success was not always achieved, especially in

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the case of *G. platensis* in some regions in South America, Western Australia, and Southwestern Europe (Loch, 2008; Mapondera et al., 2012; Reis et al., 2012; Valente et al., 2004).

The present work was conducted in Portugal, which is a relevant country for eucalypt wood production. The Tasmanian blue gum, *Eucalyptus globulus* Labill., is the most extensively planted forest species in the country, covering ca. 812,000 ha (ICNF, 2013). This value represents over 50% of the total area occupied by *E. globulus* in Europe and over one fourth of the area planted with this species worldwide (Cerasoli et al., 2016; Harwood, 2015). *Eucalyptus globulus* plantations are the main source of raw material for pulp and paper production, one of the most important industries in the country. Despite the high socio-economic importance of eucalypt stands, the vast area occupied by monocultures of this exotic species may be perceived as having negative ecological effects (Veiras and Soto, 2011). Similarly to other managed forest plantations, eucalypt stands may be the source of ecosystem disservices and can generate negative externalities, such as competition with other plant species and soil erosion. However, such negative impacts can be effectively avoided by adopting adequate forest design and management practices (Branco et al., 2015). One aspect that has generated much controversy is the invasive potential of eucalypts. Even though a few species have been listed as invasive, eucalypts seldom spread considerable distances from planting sites (see Rejmánek and Richardson, 2011). In recent studies, Fernandes et al. (2016, 2017) showed that *E. globulus* does not display invasive behaviour in Portugal. On the other hand, eucalypt stands can provide many ecosystem services, which have been summarised by Branco et al. (2015).

Prior to the detection of the snout beetle in Portugal, in 1995 (Valente et al., 2004), *A. nitens* had already been introduced in Spain, in 1994 (Pérez Otero et al., 2003). Natural dispersion of *A. nitens* from Spain would probably have been enough to promote the establishment of the parasitoid in Portugal, as there are no relevant geographical barriers between the two neighbouring countries. Nevertheless, a programme to rear and release *A. nitens* in Portugal was launched in 1997, aiming to accelerate the benefits from this biological control agent. Around 300,000 parasitoids were released over a period of four years (1997–2000), after which *A. nitens* rapidly established. Within one year, parasitism rates in some plantations reached up to 80% (Valente et al., 2004). Currently, i.e. 20 years later, *A. nitens* is widely distributed across the country and successful control of *G. platensis* populations has been achieved in several areas. However, in some inland regions of northern and central Portugal, with cooler climate than the southern and coastal areas, the parasitoid remains ineffective (Reis et al., 2012; Valente et al., 2004).

Despite the high economic importance of eucalypts worldwide and the vast distribution of *Gonipterus* spp., little information is currently available on either the economic impact of these insects or the economic benefits resulting from their control. In California, Jetter and Paine (2004) assessed the benefits of controlling *G. platensis* attacking urban trees as the average amount that a household would be willing to pay (sensu Boardman et al., 1996) for a public pest control programme. The authors concluded that each household would pay about 21 times more to import and release *A. nitens* than for the implementation of a chemical control programme. Paine et al. (2015) reported complete control of *G. platensis* by *A. nitens* in California, with a benefit-cost ratio ranging from 428 to 1070 for a total investment of 2.6 M US dollars in CBC programmes that targeted the snout beetle and seven other eucalypt pests. In Portugal, Reis et al. (2012) found that defoliation by *G. platensis* severely affects the yield of *E. globulus* plantations, causing up to 86% wood loss in some areas. However, to date, neither the effect of *G. platensis* nor of the parasitoid has been economically assessed.

By assessing the economic impact of this key forest pest and the economics of its biological control, the present case study aims to discuss the importance of weighing costs and benefits of CBC on pest management decision making. The specific objectives of this study were to assess: i) the economic impact of *G. platensis* in *E. globulus* plantations in Portugal; ii) the economic benefits resulting from partial control of *G. platensis* by *A. nitens*, by comparing expected losses of eucalypt wood under three hypothetical scenarios without biological control, over a period of 20 years; and iii) the economic outcome of the biological control programme conducted in Portugal with the aim of anticipating the expected benefits of *A. nitens* natural dispersion.

2. Material and Methods

2.1. Economic Impact of G. platensis in Portugal

2.1.1. Area Affected During the Spreading Phase

During the dispersion phase of *G. platensis* in Portugal (1996–2003), field surveys were conducted annually to assess the area affected by the snout beetle (as described in Appendix 1).

2.1.2. Damage by G. platensis

To assess the area currently affected by the snout beetle, a survey was conducted between 2011 and 2014 over an area of ca. 85,000 ha of *E. globulus* plantations (managed by The Navigator Company) that extended to all Territorial Units of Continental Portugal (as described in Appendix 2 and Fig. S1). The distribution of *G. platensis* attacks in 2011–2014 was extrapolated per NUTS3 region (Nomenclature of Territorial Units for Statistics, version 2010; EUROSTAT, 2016) for the period between 2004 and 2016, using the available national forest inventories (ICNF, 2013). According to these inventories, the area planted with eucalypts in Continental Portugal was 717,246 ha in 1995, 785,762 ha in 2005, and 811,943 ha in 2010. Based on these numbers, the total area planted with eucalypts was assumed to be 717,246 ha from 1996 to 2004, 785,762 ha from 2005 to 2009, and 811,943 ha from 2010 to 2016. Because *G. platensis* populations were still establishing between 1996 and 2003 (see Section 2.1.1 and Appendix 1), the economic impact in a given year during this period was assumed to have occurred only in areas already occupied by the insect in the previous year.

2.1.3. Wood Loss Estimates

The percentage of tradeable wood production loss (*WPL*) was assessed for each defoliation level (see Section 2.1.2) using Eq. (1) (Reis et al., 2012), where *D* is percent defoliation by *G. platensis*:

$$WPL = 5.428e^{0.0027}.\ D \tag{1}$$

This equation was developed for conditions similar to those of the present study and is, to the best of our knowledge, the most adequate model available, even though it probably underestimates wood loss, as stated by its authors. For plantations having Very high defoliation, *WPL* was assumed to be 100% rather than the 72% given by Eq. (1), because even if some biomass is produced it will not have commercial use for pulping (C. Valente, personal observation). Based on this assumption and on the class marks of the defoliation intervals for each level of attack, the following categories of *WPL* were obtained: 100% (Very high defoliation); 42% (High defoliation); 16% (Moderate defoliation); 7% (Low defoliation); and 0% (No damage). Tradeable wood volume lost per year (*WVL*; m^3ob·year^{-1}, where ob means over bark) per NUTS3 region was estimated with Eq. (2) by applying *WPL* to the potential annual productivity (*PAP*; m^3ob·year^{-1}) for *E. globulus* without defoliation:

$$\mathrm{WVL} = \mathrm{WPL.\ PAP} \tag{2}$$

PAP was assessed for NUTS3 using 3PG model (Landsberg and Waring, 1997) parametrised with unpublished data from The Navigator Company for *E. globulus*. The model ran with soil data collected in each plantation [stoniness, soil texture, soil depth, and suitability class for *E. globulus* according to Sousa et al., 2013] and climate data (average monthly rainfall, average monthly minimum temperature and average monthly maximum temperature, from the climate normal of

1961–2000; average annual radiation and average number of days with rainfall, from the climate normal of 1941–1970) provided by the Portuguese Meteorological Institute (Instituto Português do Mar e da Atmosfera). Model outputs were obtained from 10,669 records, corresponding to ca. 120,000 ha distributed throughout the country. Mean annual tradeable wood increment (*MAI*; $m^3ob{\cdot}ha^{-1}{\cdot}year^{-1}$) estimated by 3PG for each soil-climate combination was used to determine the average potential *MAI* for NUTS3 in a scenario without defoliation. Total *PAP* per NUTS3 region was calculated by multiplying *MAI* in each region by the corresponding number of hectares planted with eucalypts.

2.1.4. Economic Loss Estimates

To assess the annual economic impact of *G. platensis*, *WVL* estimates for each year were converted into monetary units (euros) using stumpage prices (i.e. wood prices before harvesting and transportation to the mill; $euros{\cdot}m^{-3}ob$). Because the domestic price of eucalypt wood is usually lower than the f.o.b. price ("free on board", i.e. the price of an imported good at the border) and higher than the c.i.f. price ("cost, insurance and freight", i.e. the price of an exported good at the border), wood was considered to be a non-tradeable commodity and was therefore valued at domestic prices in the analyses, as recommended by Campbell and Brown (2003). Annual stumpage prices from 1997 to 2016 (Table S1) were provided by L. Sarabando (Baixo Vouga Forestry Association).

All calculations were discounted to present values (2016) in euros using a 4% discount factor, which is the value currently recommended by the European Commission for the cost-benefit assessment of publicly funded projects (Sartori et al., 2014). Because calculations were based on uncertain assumptions, sensitivity analyses were performed for the stumpage price (−20% versus + 20%) and for the discount rate (3% versus 5%).

2.2. Economic Benefit of A. nitens in Portugal

The economic benefit resulting from biological control was assessed for the 1996–2016 period by comparing current losses (with biological control, Scenario 0), estimated in Section 2.1, with losses that would have occurred in the absence of *A. nitens*. Considering a hypothetical situation without parasitism, total yield loss by *G. platensis* could have occurred. This assumption is based on observations of total wood loss in Portugal, when parasitism rates are extremely low (Reis et al., 2012; Valente et al., 2004), and in South Africa, when the snout beetle was free from biological control (Tooke, 1955). Even though 100% wood production loss would be expected without *A. nitens* or other control methods, a more conservative value of 75% was assumed in our analysis.

Three scenarios without parasitism by *A. nitens* were considered. In Scenario 1, forest owners were assumed to have replaced *E. globulus* with eucalypt species less susceptible to *G. platensis*. This replacement would only have been possible if adequate alternatives were available, but species with wood quality for pulping similar to *E. globulus* and simultaneously well adapted to Portuguese environmental conditions would be hard to find, if they exist at all. Still, examples of species that are generally less attacked by the snout beetle and could be used for this purpose are mentioned by Cordero-Rivera and Santolamazza-Carbone (2000). *Eucalyptus globulus* plantations would then be replaced at a rate of 25 thousand ha per year. This rate was estimated from data referring to new plantations of *Eucalyptus* spp., conducted by the pulp and paper companies operating in Portugal. Between 2010 and 2015, these companies managed 154,861 ha and planted 4772 ha per year, on average (CELPA, 2016). The same rate of planting was then applied to 811,943 ha, the total area of eucalypt plantations in Portugal, according to the latest national forest inventory (ICNF, 2013). Replacement of *E. globulus* stands would only have started in 2000, so that a four year time interval would have allowed for the identification of alternative tree species and for the production of the plants needed. New plantations were not considered as an additional investment, but rather as the standard practice of replacing *E. globulus* plantations at cutting age. For simplification, new plantations were assumed to have the same productivity and market value as *E. globulus*, even though wood from resistant eucalypts would predictably have a lower market value.

In Scenario 2, insecticides would be used to control *G. platensis* populations. It seems likely that only part of the area affected by the snout beetle would then be treated, mostly due to legal and forest certification restrictions to pesticide use (e.g. distance to water sources). Insecticides were therefore assumed to have been used annually in half of the area attacked. Insecticide applications would have started in 2000, so that adequate insecticides could be identified and legally authorised. Based on the results of efficacy studies performed for several insecticides under laboratory and field conditions (Echeverri-Molina and Santolamazza-Carbone, 2010; Loch, 2005; Pérez Otero et al., 2003; Santolamazza-Carbone and Ana-Magán, 2004), chemical treatments were assumed to be 100% effective in controlling the snout beetle. A single insecticide application would prevent wood losses in the treated areas during one year, as shown by Loch (2005) for alpha-cypermethrin treatments in Western Australia. The cost of treating 1 ha with insecticide (one application per year) was considered to be 45 euros, based on current average market prices (C. Valente, personal observation).

In Scenario 3, no replacement of the planted *Eucalyptus* species would take place and insecticides would not be applied, implying that replacement wood would have to be imported to supply the pulp and paper industry. Because in the study area eucalypts are normally harvested when plantations reach 12 years, the amount of wood that would have to be imported in a given year *y* (IMP_y; $m^3ob{\cdot}year^{-1}$) was assessed using Eq. (3), where *WVL* ($m^3ob{\cdot}year^{-1}$) is wood loss due to *G. platensis* in the previous years:

$$IMP_y = \sum_{i=1}^{12} \frac{1}{12} .\ WVL_{y-i} \tag{3}$$

Annual economic losses in this scenario were calculated by multiplying the wood volume imported each year by the corresponding price of imported wood. Annual prices of wood imports between 1997 and 2016 (Table S1) were provided by F. Goes (CELPA, Portuguese Paper Industry Association).

Due to uncertainty linked to some parameters, sensitivity analyses were performed for all scenarios for: i) percentage of wood loss caused by *G. platensis* in the absence of parasitism (50% versus 100%); ii) wood price (−20% versus + 20%); and iii) discount rate (3% versus 5%).

2.3. Cost-Benefit Analysis of the CBC Programme with A. nitens in Portugal

A posthoc analysis was performed to determine the benefit-cost ratio of the biological control programme started in 1997, which aimed to accelerate *A. nitens* establishment in Portugal. Costs and benefits were discounted to present (2016) values in euros using a 4% discount rate. Programme costs were assessed through the sum of the expenses involved in the acquisition, mass rearing, releasing, and monitoring of *A. nitens*, namely costs with personnel, parasitoid purchase, facilities and equipment, maintenance, electricity, water, materials, and travel expenses (Table S2). These costs were obtained by consulting internal documentation available at RAIZ (Forestry and Paper Research Institute), the institution that carried out most of the programme activities, in collaboration with other organisations (see Valente et al., 2004).

If the mentioned biological control programme had not been implemented, *A. nitens* would still have spread naturally from Spain, where it was first released in 1994 (Pérez Otero et al., 2003). Yet, this would have resulted in a delay in the establishment of the parasitoid between one and three years, assuming dispersal rates observed in other regions (Pinet, 1986; Tooke, 1955). To assess the benefits of releasing

A. nitens in the study area in order to anticipate its establishment, three alternative scenarios without releases were considered, assuming that the outcome of biological control would have been delayed by one, two, or three years. Economic losses were estimated as in Section 2.1. Sensitivity analyses were performed for: i) percentage of wood loss caused by *G. platensis* in the absence of parasitism (50% versus 100%); ii) wood price (−20% versus + 20%); and iii) discount rate (3% versus 5%).

3. Results

3.1. Economic Impact of G. platensis in Portugal

Results of the survey conducted between 2011 and 2014 showed that 46% of the area planted with eucalypts in Portugal was attacked by *G. platensis*, with 17% having Low defoliation, 17% having Moderate defoliation, and 12% having High to Very high defoliation (Table S3). High or Very high defoliation levels were detected in 14 of the 28 NUTS3 regions, all located in the northern half of the country. Despite the partial success attained with CBC with *A. nitens*, up to about 1 M m^3ob of tradeable eucalypt wood have been lost annually due to *G. platensis* (Table S3). This wood volume corresponds to an economic loss of about 27 M euros per year, considering the stumpage wood price in 2016 (26 euros·m^{-3}ob). For the entire study period (1996–2016), losses are estimated to accumulate to 648 M euros, at a 4% discount rate relative to the base year, 2016 (Table S4; Table 1). By varying the parameters used in the calculations (yield reduction by *G. platensis* without parasitism, wood price, and discount rate), estimated total losses ranged from 518 M to 777 M euros (Table 1).

3.2. Economic Benefit of A. nitens in Portugal

Economic losses calculated annually for the study period (1996–2016), considering the three scenarios without *A. nitens*, are shown in Table 1. Accumulated losses over 20 years would have reached 2546 M euros in Scenario 1, 2451 M euros in Scenario 2, and 7164 M euros in Scenario 3. By subtracting the economic loss in the real situation (with *A. nitens*; 648 M euros) from the minimum loss value for the three scenarios without *A. nitens* (2451 M euros in Scenario 2), a benefit of at least 1803 M euros would have resulted from biological control.

By varying the parameters used in sensitivity analyses, economic losses without *A. nitens* would have ranged between 1354 and 3739 M euros in Scenario 1, between 1767 M and 3683 M euros in Scenario 2, and between 4776 M and 9552 M euros in Scenario 3. Regardless of the variations in parameters used in the sensitivity analyses, partial biological control under the current circumstances (Scenario 0) is by far the most favourable scenario. The worst outcome was obtained for wood imports (Scenario 3). Both eucalypt replacement (Scenario 1) and insecticide application (Scenario 2) would account for economic losses about two to four times higher than with *A. nitens*. Despite the very similar economic outcomes in Scenarios 1 and 2, it is interesting to note that, for a yield reduction by *G. platensis* of 50%, eucalypt replacement would be preferable to insecticide application, whereas for 100% of yield reduction the more immediate effect of insecticides would be more cost-effective. Variations in the valuation of wood also lead to differences in the outcomes of Scenarios 1 and 2. For a higher (+20%) wood price, the fact that only half of the affected area could be treated with insecticides leads to higher economic losses, and eucalypt replacement would be the best management option in the long run.

3.3. Cost-Benefit Analysis of the CBC Programme with A. nitens in Portugal

The cost of the CBC programme, carried out from 1997 to 2003, was estimated at ca. 1.1 M euros at present values (details in supplementary Table S2). Assuming that biological control of *G. platensis* would have been delayed by one to three years if the programme had not been executed, the net benefit resulting from parasitoid releases would range from 75 M to 389 M euros for a delay of one and three years, respectively (Table 2). Benefit-cost ratios would be 67, 190, and 347 for one, two, or three years without successful biological control by *A. nitens*, respectively. By varying the parameters in sensitivity analyses, benefit-cost ratios ranged from 39 to 489 (Table 2).

Table 1
Economic value of wood lost due to *Gonipterus platensis* in Continental Portugal, between 1996 and 2016, in the real situation with parasitism by *Anaphes nitens* (Scenario 0) and three hypothetical scenarios without biological control (Scenarios 1–3). The parameters varied in the sensitivity analyses were the percentage of yield reduction by *G. platensis* in the absence of biological control (50% and 100%), wood price (−20% and +20%; applied to import prices in Scenario 3 and to stumpage prices in the remaining calculations), and discount rate (3% and 5%).

Scenario	Base scenario (million euros)[a]	Sensitivity analyses (million euros)					
		Yield reduction by *G. platensis*		Wood price		Discount rate	
		50%	100%	-20%	+20%	3%	5%
0: Real situation[b]	648	642	654	518	777	592	710
1: Eucalypt replacement[c]	2546	1354	3739	2145	3218	2298	2825
2: Insecticide application[d]	2451	1767	3136	2041	3683	2242	2685
3: Wood imports[e]	7164	4776	9552	5730	8603	6732	7632

[a] Base scenario assuming 75% yield reduction by *G. platensis*, wood prices at annual stumpage prices (Scenarios 0, 1, and 2) or import prices (Scenario 3), and values discounted at 4% relative to the base year 2016.

[b] Scenario 0- Current circumstances, with *A. nitens* present in Portugal since 1997.

[c] Scenario 1- *Eucalyptus globulus* plantations replaced by resistant eucalypts from 2000 onward, at a rate of 25 thousand ha·$year^{-1}$.

[d] Scenario 2- Insecticides applied once a year, from 2000 onward, in 50% of the area affected by *Gonipterus platensis*.

[e] Scenario 3- Wood lost replaced by imported wood and losses valued at import prices.

4. Discussion

According to the present assessment, defoliation by *G. platensis* resulted in wood losses of 648 M euros in the study area over the past 20 years. The most severe attacks occurred in the north of the country, in cool and mountainous regions, as suggested by previous studies (Reis et al., 2012; Valente et al., 2004). Such economic losses happened in spite of partial success of biological control by *A. nitens*. Without parasitism, losses would predictably have ranged from 2451 M euros, in a scenario where *G. platensis* populations were controlled with insecticides, to almost 7200 M euros if wood losses were offset by imported wood. Therefore, the benefit of biological control with *A. nitens* in the study area during the last two decades amounted to at least 1803 M euros (2451 M minus 648 M euros). By varying the parameters in the sensitivity analyses, economic losses without biological control would have ranged from 1354 M to 9552 M euros, for Scenarios 2 and 3, respectively. These extreme values were obtained by varying the percentage of wood loss (50% and 100%) caused by *G. platensis*.

Our results underestimate the impact of both the damage caused by *G. platensis* and the benefit from *A. nitens*, since calculations were based exclusively on the effects on wood production. Even though pulpwood is regarded as the key provisioning service provided by eucalypt plantations, other ecosystem services and socio-economic benefits are also provided (Branco et al., 2015). Other possible impacts resulting from *G. platensis* defoliation, which are summarised in Table 3, can be as important as those on wood production itself (Holmes et al., 2009). Socio-economic impacts in particular may be of great relevance, since the activities related to the pulp and paper production assume an important

Table 2
Costs, benefits, and benefit-cost ratios of the biological control programme with *Anaphes nitens* in Continental Portugal versus three scenarios of no release with varying delay times in parasitoid establishment (one, two, and three years). The parameters varied in the sensitivity analyses were the percentage of yield reduction by *Gonipterus platensis* in the absence of biological control (50% and 100%), wood price (−20% and +20%; applied to import prices in Scenario 3 and to stumpage prices in the remaining calculations), and discount rate (3% and 5%).

	Delay in *A. nitens* establishment	Base scenario[a]	Sensitivity analyses					
			Yield reduction by *G. platensis*		Wood price		Discount rate	
			50%	100%	-20%	+20%	3%	5%
Costs (million euros)	n.a.	1.1	1.1	1.1	1.1	1.1	1.0	1.3
Benefits (million euros)	1 year	75.1	43.8	106.3	60.1	90.1	63.1	89.2
	2 years	213.2	125.9	300.6	170.6	255.9	180.3	251.8
	3 years	389.1	229.9	549.4	311.3	466.9	331.0	456.7
Benefit-cost ratio	1 year	67	39	94	54	80	65	68
	2 years	190	112	268	152	228	189	191
	3 years	347	205	489	277	416	346	347

[a] Base scenario assuming 75% yield reduction by *G. platensis*, wood prices at annual stumpage prices, and values discounted at 4% relative to the base year 2016.

role for the economy and the social sector, mainly regarding employment. In Portugal, the manufacture of paper and paper products assures 17,800 direct jobs, and forestry and logging activities are estimated to generate 13,500 direct jobs (EUROSTAT, 2017) (see socio-economic activities in Table 3). Indirectly, this impact would extend to hundreds of thousands of small land owners that depend on forestry activities as a supplementary source of income, mostly in underprivileged rural areas (Sarmento and Dores, 2013). Even if unemployment resulting from *G. platensis* attacks would reallocate to other activities, the negative impact would not be negligible, particularly in the forestry sector.

Despite our attempt to use realistic scenarios, it is doubtful that the three scenarios without parasitism by *A. nitens* considered here would be sustainable. In Scenario 1, eucalypt species both resistant to *G. platensis* and endowed with characteristics similar to *E. globulus* would have to be available. Due to the favourable adaptation of *E. globulus* to the Portuguese environmental conditions and to the high quality of this species' wood for pulp production, such a replacement would be difficult. Regarding Scenario 2, the use of insecticides in forests poses several disadvantages in comparison to biological control, since ecological, environmental, and economic impacts may occur. Additionally, insecticide use is constrained by legal and forest certification restrictions, and public concern over pesticide use is an important issue (Jetter and Paine, 2004; Pimentel et al., 1992; Sexton et al., 2007). Due to such difficulties, repeatedly treating half of the area affected by the snout beetle, as predicted in Scenario 2, might be impracticable. As for Scenario 3, it is possible that the large amount of wood needed would not be readily available for import from external markets. Furthermore, the higher costs of wood in this scenario (compared to the costs of wood produced locally) would reduce the market competitiveness of the pulp and paper companies in Portugal.

A more realistic scenario should assume the simultaneous implementation of the three options identified (replacement of *E. globulus* by less susceptible species, use of insecticides, and wood import), but the analysis of such scenario would be very complex and higher levels of uncertainty would be introduced. Yet, these three strategies have in fact been implemented simultaneously. In cooler northern regions of Portugal and Spain where severe defoliation by *G. platensis* occurs regularly, a less susceptible species, *Eucalyptus nitens* Maiden, has been planted as an alternative to *E. globulus* (Pérez-Cruzado et al., 2011). However, *E. nitens* has important disadvantages when compared to *E. globulus*, such as poor coppicing ability (Little et al., 2002) and lower pulpwood quality (Kibblewhite et al., 2000). Two commercial insecticides, Calypso (active ingredient thiacloprid) and Epik (active ingredient acetamiprid), are currently authorised in Portugal against *G. platensis* (ICNF, 2015). Epik is also authorised in Spain (MAPAMA, 2017). In Portugal, chemical control has been carried out with Calypso since 2011 and with Epik since 2012, with good results (C. Valente, unpublished data). Based on data gathered from statistical reports

Table 3
Impacts of defoliation by *Gonipterus platensis* on socioeconomic activities and ecosystem services.

Type of impact	Impact on services	References
Provisioning ecosystem services	Reduced pulpwood yield.	Branco et al. (2015), Reis et al. (2012), present study
	Negative impact on honey production, since eucalypts are major sources of pollen and nectar for honeybees.	Daners and Tellería (1998), Feás et al. (2010)
	Reduced aesthetic value of eucalypts used as ornamental trees (e.g. parks and roadsides).	Paine et al. (2015)
	Increased management costs and environmental risks due to the use of insecticides to control the pest.	Pimentel et al. (1992), Sexton et al. (2007)
Socio-economic activities	Negative impact on the Portuguese economy (the pulp and paper industry contributes with 4.4% to the gross domestic product and represents 5% of the country's exports, valued at ca. 2500 M euros in 2015).	CELPA (2016), INE (2016)
	Reduction in employment (forestry and logging activities[a] are estimated to generate 13,500 direct jobs, particularly in rural areas; the manufacture of paper and paper products[b] assures about 17,800 jobs, 3000 of which directly by the Portuguese pulp and paper industry).	CELPA (2016), EUROSTAT (2017)
	Decreased economic return leads forest owners to reduce forest management, leading to changes in land use and value.	Kenis and Branco (2010)
Other relevant ecosystem services	Decreased carbon sequestration.	Pinkard et al. (2014)
	Decreased water retention and increased nutrient leaching.	Fernández et al. (2006), Lovett et al. (2002)
	Lower ability of weakened eucalypt plantations to compete with invasive plant species, such as wattles (*Acacia* spp.), leading to severe changes in ecosystem structure and functioning.	Fernández et al. (2006), Lorenzo et al. (2010)

[a] NACE A02, according to the European Classification of Economic Activities (EUROSTAT, 2008).
[b] NACE A17, according to the European Classification of Economic Activities (EUROSTAT, 2008).

published by the Portuguese Paper Industry Association (CELPA, 2007, 2016), ca. 22.8 M m^3ob of eucalypt wood were imported between 1997 and 2015, 56% of which in the last five years. Although damage by *G. platensis* might not be the sole reason for the sharp increase in imports, it is likely a major driver, as our estimate of wood loss due to defoliation for the same period equals 75% of these imports (17.4 M m^3ob).

The biological control programme planned to accelerate the establishment of *A. nitens* in Portugal had a positive return on investment. Its minimum benefit-cost ratio was estimated at 67, when the benefits of releasing *A. nitens* were considered to have occurred in one year only, and accrued to 190 or 347 if benefits for two or three years, respectively, were taken into account. The most extreme values of benefit-cost ratios were obtained in sensitivity analyses, by varying yield reduction (50 or 100%) due to *G. platensis* in the absence of parasitism. Unlike the trade-offs revealed by sensitivity analyses for other pest management practices (Table 1), biological control leads to benefits that increase consistently with the degree of anticipation of its effects, regardless of variations in pest defoliation, wood price, or discount rate (Table 2). The time delay in biological control of one to three years, predicted in our study for a situation without a CBC programme, is based on observations by Tooke (1955) and by Pinet (1986). Tooke (1955) reported limited dispersion of *A. nitens* during the first two seasons after its introduction in South Africa, but recorded a fast spreading rate (> 100 km year^{-1}) once the parasitoid populations became well established. Nevertheless, a spreading delay of three years may be underestimated, as a longer period might have been needed for the parasitoid to spread naturally from Galicia (Spain) to central/southern Portugal, covering ca. 300–400 km. In fact, Pinet (1986) recorded slow dispersal of *A. nitens* in France, after its introduction in Italy, near the border between the two countries. In three years (1978–1981), *A. nitens* had spread only about 40 km in France, and in 1981 the parasitoid had to be released in several locations that remained without parasitism (Pinet, 1986).

The benefit-cost ratios obtained in the present study are positive, similarly to what was found for other CBC programmes that were evaluated economically (Naranjo et al., 2015). The ratios found in our study are conservative, as only 75% yield loss caused by *G. platensis* was assumed, instead of the more likely 100% loss. Furthermore, the cost-benefit analyses performed here included post-release monitoring costs between 2001 and 2003, which were valued at about 20% of the total costs. As a result, the costs directly contributing to the benefits are overestimated in the analyses. Inversely, by using a well-known natural enemy, the costs of this programme were lower than if a new CBC agent had to be identified in the pest's native range. This will likely be the case for other parasitoids that have recently been evaluated as alternative CBC agents, such as the Tasmanian *Anaphes inexpectatus* Huber and Prinsloo (Valente et al., 2017a, 2017b) and *Anaphes tasmaniae* Huber and Prinsloo (Ide et al., 2013).

5. Conclusions

The present study highlights the importance of prompting pest management immediately following invasion, as anticipating control by even a single year may have a positive economic impact. This result should encourage decision makers and stakeholders to rapidly implement control measures against important invasive alien species. Even considering some unfavourable assumptions, as we did in the sensitivity analyses, the CBC programme with *A. nitens* remains cost-effective. Our results further suggest that even partially successful CBC programmes may provide economic benefit. As shown by McFayden (2008) for two programmes against the weeds *Lantana camara* L. and *Rubus fruticosus* L. in Australia, economic benefits can be attained even from CBC projects that are ultimately considered failures. Positive outcomes from apparent failures, or low success actions, can occur when the target species has high economic impact, as even a small reduction in losses is economically relevant. Our findings emphasize the importance of measuring the success of CBC programmes on the basis of their economic impact, rather than by merely quantifying technical and/or biological parameters, such as parasitism rates. However, because gathering the information necessary to perform an economic analysis might be a laborious, expensive, and long-term task, such an assessment will remain a challenge for biological control practitioners.

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Appendix 1. Procedures Used in Section 2.1.1 to Assess the Area Affected by *Gonipterus platensis* in Portugal During its Spreading Phase (1996–2003)

The first sampling point was located at the edge of the snout beetle's known distribution from the previous year, where the insect was assumed to be present. From there, observations were made every 4 km in the most likely direction of dispersal, typically south and east, until neither signs of damage nor insects were detected. At each sampling point, the canopy of every eucalypt in the observer's field of vision was carefully examined with binoculars, in order to detect *G. platensis*. Absence of *G. platensis* in a given sampling point was confirmed by checking two more points with eucalypts located in the same direction. Once a point of no detection was reached, the survey would resume in a new direction from the last sampling point where the snout beetle was detected. In order to construct a comprehensive map, presence or absence of *G. platensis* was assigned to “Freguesia”, the smallest Portuguese administrative territorial unit.

Appendix 2. Procedures Used in Section 2.1.2 to Assess the Area Affected by *Gonipterus platensis* in Portugal Between 2011 and 2014

Defoliation data was collected annually (between June and October) after the annual defoliation peak by *G. platensis*, which normally occurs in May. Only plantations older than 1.5 years were evaluated in order to assure that trees had adult foliage, which is in general more susceptible to *Gonipterus* attack than juvenile foliage (Tooke, 1955). Defoliation was categorised into the following five damage categories, based on the leaf area loss in the upper third of each tree canopy: 1) No damage (no defoliation); 2) Low (1–20% defoliation); 3) Moderate (21–60% defoliation); 4) High (61–90% defoliation); and 5) Very high ($> 90\%$ defoliation). A total of ca. 1400 plantations were surveyed, ranging from 1 ha to about 3000 ha. Depending on plantation size and heterogeneity (defoliation, topography, stand age, and eucalypt provenance or clone), 1 to 30 sampling points were inspected per plantation. At each sampling point, the trees in the observer's field of vision were inspected with binoculars and overall defoliation, corresponding to the most frequent attack level observed, was estimated. Annual geographical layers produced on the four years of sampling were overlapped using QGIS 2.2.0 software. Plantation areas were broken down into single-part polygons and the highest attack level recorded during the four-year period was assigned to each polygon. Plantations were then grouped into 28 territorial units (NUTS3, Nomenclature of Territorial Units for Statistics, version 2010; Fig. S1) (EUROSTAT, 2016) and the total area per defoliation level and NUTS3 region was calculated.

Appendix 3. Supplementary Data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolecon.2018.03.001.

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