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Cost–Benefit Analysis of Monitoring Insect Pests and Aerial Spraying of Insecticides: The Case of Protecting Pine Forests against *Dendrolimus pini* in Brandenburg (Germany)

Oliver Maaß * and Hella Kehlenbeck

Julius Kühn Institute (JKI)—Federal Research Centre for Cultivated Plants, Institute for Strategies and Technology Assessment, Stahnsdorfer Damm 81, 14532 Kleinmachnow, Germany; hella.kehlenbeck@julius-kuehn.de
* Correspondence: oliver.maass@julius-kuehn.de; Tel.: +49-(0)-3946-47-5214

Abstract: Monitoring of insect pests and aerial spraying of insecticides have proven to be effective in protecting forests against needle-feeding insect pests. However, the literature on the economic viability of insect monitoring and aerial spraying of insecticides is scant. This research conducts a cost–benefit analysis of monitoring insect pests and use of insecticides for 5600 ha of managed pine forests. The case studied is the mass outbreak of the pine tree lappet moth (*Dendrolimus pini* L.) in Brandenburg (Germany) in 2014. Costs were estimated based on information from standardized questionnaires and semi-structured expert interviews. Benefits were analyzed by comparing the loss of revenue due to *D. pini* with the costs of insect monitoring and insecticide spraying in two scenarios of pine production (with protection vs. without protection). The results show that monitoring *D. pini* and aerial spraying of insecticides are economically beneficial to forest owners. The total net present value (*NPV*) of protection was about EUR 1965 ha^{-1} at a discount rate of 0% and the benefit–cost ratio (*BCR*) was about 22.14. *NPVs* and *BCRs* per hectare were highest for protecting stands with high site index and stands in the age class of 20–39 years. Sensitivity analyses revealed that *NPV* results are more sensitive to changes in timber prices than to changes in protection costs. The authors conclude that monitoring insect pests and aerial spraying of insecticides are economically viable options to protect forests against needle-feeding insect pests.

Keywords: insect pests; forest protection; monitoring; aerial spraying; insecticides; pine; costs; benefits; net present value; benefit–cost ratio

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1. Introduction

Forest insects play an important role in the physical and biological processes of forest ecosystems [1]. They pollinate plants, convert nutrients, and decompose dead plant and animal tissue. They aerate the soil, provide food and habitat for animals, and contribute to biological diversity [2]. However, uncontrolled mass propagations of insect pests can pose a serious threat to the vitality and productivity of forests. For instance, mass outbreaks of needle-feeding insect pests like the spruce budworm (*Choristoneura fumiferana Clem.*), the nun moth (*Lymantria monacha*), or the pine-tree lappet moth (*Dendrolimus pini* L.) have the potential to destroy large areas of natural or managed forests and to cause considerable economic and environmental losses and costs [3,4].

Economic losses through insect pests in commercial forestry are mainly caused by the reduction of harvest volumes and timber quality as a result of reduced growth rates, increased mortality, and tree defects [5–8]. Another cause is the potential decrease in raw timber exports due to phytosanitary regulations and trade bans [5,9]. Further losses can arise from reduced tourism revenues [5] and from the loss of ecosystem services provided by forests [10,11].

Potential costs can accrue from measures for controlling insect pests and for mitigating impacts on forest growth (e.g., changes in silvicultural practices) [5,12]. Salvage logging and restoring damaged stands are other potential costs [13–15]. In addition, costs can arise from potential risks to human health [10] and from untapped economic opportunities, for instance, if forest owners forgo the planting of susceptible tree species [5].

Strategies for protecting forests against insect pests have become increasingly important since outbreaks are predicted to occur more frequently and widely spread as a result of climate warming [16–18]. Existing strategies include, among others, (i) promoting biodiversity in forests [19], (ii) altering species composition by planting non-susceptible tree species [20,21], (iii) re-planning harvest schedules to retain less vulnerable species and age classes [22], (iv) conducting salvage harvesting of dying or dead trees [23], and (v) conserving natural bio-controls (i.e., predators, parasitoids, pathogens) [12]. However, the only method which can effectively prevent impending stand losses by leaf- and needle-feeding insect pests in the short term is pest monitoring and aerial spraying of insecticides [24,25].

Pest monitoring involves "the process of measuring the variables required for the development and use of forecasts to predict pest outbreaks" [26] (p. 12). The results of monitoring help to understand the impact of insect pests on the forest ecosystem, to decide on counteracting the infestation, and to select suitable control methods such as aerial spraying of insecticides [27]. In forestry, aerial sprayings are generally "foliar applied sprays, intended to control feeding larvae on crop trees" [28] (p. 1). The main advantage of aerial spraying over land-based spraying is the ability to treat large areas relatively quickly. Furthermore, a better coverage of target surfaces is possible, and costs are usually lower [28,29]. Concerns about aerial spraying of insecticides include applications in urban and environmentally sensitive areas [29] and the potential impact of insecticides on non-target organisms [30]. Other issues are associated with the spray drift which poses a threat to human health and the environment if the spraying is improperly executed [31].

Aerial spraying of insecticides has proven to be effective in controlling insect pests [32,33]. However, many countries have restricted or banned aerial applications of insecticides due to environmental and human health concerns. The Directive 2009/128/EC, which regulates the use of pesticides in the European Union, claims that "Member States shall ensure that aerial spraying is prohibited" [34] (p. 77). Aerial spraying may only be allowed in exceptional cases if there are "no viable alternatives", or if aerial spraying offers "clear advantages in terms of reduced impacts on human health and the environment as compared with land-based application of pesticides" [34] (p. 77). A consequence of the restrictive conditions for aerial spraying of pesticides in Europe is that the area treated by air is relatively small [35]. In Germany, for instance, a total area of 45,000 ha of pine forests was treated by aerial spraying of insecticides between 2008 and 2018 [36]. This area represents less than 1.86% of the total area forested with pine in Germany [37].

The literature on forest pest management contains numerous studies that have analyzed the economic impact of insect pests and their management on forestry [6–8,38–40]. However, studies on the economic costs and benefits of aerial spraying of insecticides are rather scant [12,41,42]. In one of the few studies conducted, Aimi et al. [11] used cost–benefit analysis to assess the private and social profitability of controlling the processionary moth (*Thaumetopoea pityocampa*) in Italian pine forests. The authors found that aerial spraying of insecticides is unprofitable for private forest owners since costs are not covered by sufficient monetary benefits. Aerial spraying is only profitable in the case studied if the possible loss of forest ecosystem services and the costs for treating diseases caused by *T. pityocampa* (e.g., contact dermatitis) are taken into account. These findings are confirmed by the case analysis of Gatto et al. [10] who studied the costs and benefits of protecting pine forests against the processionary moth in Portugal. In contrast, cost–benefit analyses of controlling spruce budworm (*Choristoneura fumiferana* Clem.) in Canada showed that the monetary benefits of spraying insecticides outweigh the costs of protection [3,12,41]. A further shortcoming of the economic literature is that very few studies have considered the costs of insect monitoring when evaluating aerial sprayings of insecticides [3].

In this research, we take the costs of monitoring into account. Based on a case study in Germany, we aim to assess the monetary costs and benefits of monitoring insect pests and aerial spraying of insecticides in managed forests. We will analyze the economic viability of these measures and contribute to enhancing the empirical basis for economic assessments of aerial spraying of insecticides in forests.

2. Materials and Methods

2.1. Case Study

The case study selected for analyzing the costs and benefits of monitoring insect pests and aerial spraying of insecticides is the mass outbreak event of the pine tree lappet moth, *Dendrolimus pini* L. (Lepidoptera, Lasiocampidae), in the German Federal State of Brandenburg in 2014.

Brandenburg is located in northeast Germany and has an area of about 2.9 M hectares of which 1.1 M hectares (37%) are classified as forestland [43]. The average annual rainfall in the region is low and soils are mostly sandy and poor in nutrients. The predominate tree species is Scots pine (*Pinus sylvestris* L.) which was mainly cultivated in large even-aged monocultures until the late 1980s. Currently, Scots pine accounts for 77% of the forested area in Brandenburg [43]. These characteristics facilitate mass propagations of *D. pini* in the region [18].

D. pini is a large moth (Figure 1) with a wingspan of about 50–70 mm (males) and 70–90 mm (females) [44]. Its needle-feeding caterpillars are considered one of the most destructive defoliators of pine forests in Europe [45,46]. The species is widely distributed between western Europe and Middle Asia but until recently frequent and damaging outbreaks of *D. pini* have been mainly observed in the lowlands of northeast Germany and northern Poland [47]. Latest studies suggest that *D. pini* is spreading to the north and south of Europe [47–49] and outbreaks may become more frequent and widespread as a result of climate warming [18]. Another indication of the increasing threat by *D. pini* is the significant shortening of the period between outbreaks in central Europe [47].

(**a**) (**b**) (**c**) (**d**)

Figure 1. Developmental stages of *D. pini*: (**a**) Moth, (**b**) eggs, (**c**) caterpillar, and (**d**) cocoons (pictures: Katrin Möller).

The preferred host tree of *D. pini* is Scots pine (*Pinus sylvestris* L.) but caterpillars can also feed on the needles of other coniferous trees and species of pine. Adult moths, which live for 9–10 days, emerge from pupae between late June and mid-August. The flight period usually lasts from July until the middle of August, depending on the weather conditions. After mating, the female deposits between 150 and 300 eggs on the twigs, needles, and the bark of the host tree. The caterpillars hatch within 16 to 25 days and feed on pine needles until the first winter frost. Then, the caterpillars move down the tree to hibernate in the leaf litter and soil. In spring, the caterpillars return to the canopy, where they continue feeding on needles, but also on buds, young shoots, and green bark [44,50]. Studies suggested that one caterpillar of *D. pini* feeds on approximately 900 needles and 97% of the needles are consumed during spring feeding [51]. The development of the caterpillars is completed after 6–7 instars. Pupation starts from May–June and lasts four to five weeks. It occurs inside semi-transparent cocoons which are spun loosely on the trunk, in the canopy, and in bark crevices [44,50].

Serious damage including large-scale tree death due to feeding by *D. pini* has frequently occurred in Brandenburg and other regions of northeast Germany [4,52]. The forestry authorities in Brandenburg monitor the population density of *D. pini* to predict the site-specific risk of defoliation in the region. The results of the monitoring are used to decide on proper control methods including aerial spraying of insecticides. The monitoring is based on a multiple-step procedure which starts in winter by investigating soils for caterpillars of *D. pini* on a rough sampling raster throughout pine forests in Brandenburg. Further monitoring steps proceed in spring if the number of vital caterpillars exceeds specific threshold values. The steps take place on a smaller raster in the infested areas. First, the number of caterpillars per tree is estimated based on the number of caterpillars captured by sticky bands. Another method used to estimate the number of caterpillars is to fell sample trees. Next, the risk of defoliation is assessed by comparing the number of caterpillars found with species-specific threshold values under consideration of the site index, age, and foliage intactness of the infested stands [53]. The forestry authorities consider the spraying of insecticides, if the assessment predicts needle loss of more than 90% and no viable alternatives (e.g., silvicultural practices) exist to prevent impending tree death. Actors involved in the monitoring of *D. pini* include the local forest districts that conduct the monitoring in their territory and the State Forestry Research Centre Eberswalde (*LFE*) which belongs to the Public Forest Enterprise of the German Federal State of Brandenburg (*LFB*). The *LFE* guides the work of the forest districts, carries out the laboratory analyses, and ultimately predicts the risk of defoliation based on the data collected.

The main actors involved in the spraying of insecticides are the *LFB*, the local forest districts, and the *LFE* who jointly prepare, conduct, and follow up the application. The *LFB* is mainly responsible for tendering and officially announcing the spraying. Furthermore, it acts as an intermediary which supports the forest districts in creating flight maps and coordinating the application. The forest districts are also in charge of informing public authorities (e.g., water and nature conservation authorities) and consulting with the forest owners regarding the spraying. Other tasks include the closing of stands for public access during the spraying and documenting the treatment. The *LFE* mainly serves as a superordinate coordinator which advises, among others, the forest districts and checks whether the spraying complies with the legal provisions for applying insecticides in forests. Another actor is the local road authority and the police who are, if required, responsible for road closures during the treatment. Further actors include the service provider who conducts the aerial spraying, the public authorities which approve and regulate the spraying (e.g., nature conservation authorities, plant protection service), and the forest owners.

In 2014, the monitoring program predicted the total defoliation (i.e., >90% needle loss) of 7782 ha of pine stands in the region due to feeding by *D. pini*. The majority of the infested stands were owned by the State of Brandenburg and managed by the *LFB*. The stands were located in the Cottbus forest district and the Lieberose forest district, where a total area of 53,000 ha is forested with Scots pine. In order to protect the stands, 5600 ha of susceptible area were treated with insecticides (i.e., *lambda-cyhalothrin* and *diflubenzuron*) via helicopter. The actual treated area was smaller than the area at risk since some of the infested stands were left unsprayed due to their location in protected areas and buffer zones (Figure 2).

The stands were treated once via Hughes 500 and AS 350 helicopters with mounted air-assisted sprayers with a swath width of 25–30 m and size five injector nozzles. Table 1 provides information about the application rate of the active substances used for the treatment.

Table 1. Application rate of the active substances.

Active Substance	Application Rate	Volume of Water Sprayed	Area Treated with the Active Substance
			(ha)
Lambda-Cyhalothrin	75 mL ha^{-1}	35 L ha^{-1}	5320
Diflubenzuron	75 g ha^{-1}	35 L ha^{-1}	280

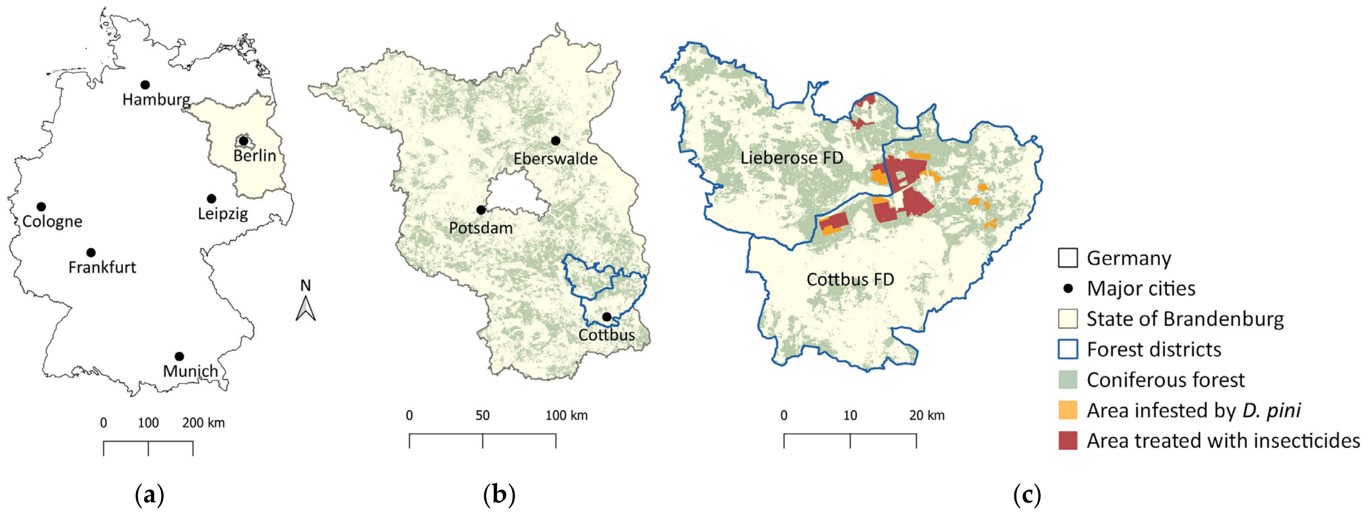

Figure 2. Study area maps showing (**a**) Germany with the Federal State of Brandenburg, (**b**) Brandenburg with the Cottbus and Lieberose forest districts, and (**c**) the forest districts (FDs) with the spatial location of the area infested by *D. pini* and the area treated with insecticides in 2014.

The treated stands were even-aged monocultures at ages between 5 and 165 years and with site indices ranging from −1.0 (highest site productivity) to 5.0 (lowest site productivity). Tables 2 and 3 provide an overview of the site index and age class distribution of the treated pine stands based on information from the *LFB*.

Table 2. Site index distribution of the treated pine stands in 2014 (with a site index (SI) from −1.0 (highest site productivity) to 5.0 (lowest site productivity)).

Site Index	Site Productivity	Area	Share in the Total Area
		(ha)	(%)
$-1 \leq SI < 1$	High	688	12
$1 \leq SI < 3$	Medium	3797	68
$3 \leq SI \leq 5$	Low	1115	20
$-1 \leq SI \leq 5$		5600	100

Table 3. Age class distribution of the treated pine stands in 2014.

Age Class	Area	Share in the Total Area
(Years)	(ha)	(%)
0–19	72	1
20–39	1994	36
40–59	1341	24
60–79	1014	18
80–99	294	5
100–119	132	2
120–139	618	11
140–159	100	2
160–179	34	1
0–179	5600	100

The aerial spraying of insecticides proved to be highly effective in protecting the studied stands against *D. pini*. The sample trees felled by the forest authorities after the spraying showed that about 99% of the feeding caterpillars were killed by the treatment [54].

2.2. Data Collection

Primary data about the case study were collected between 2020 and 2022 by written questionnaires and semi-structured face-to-face interviews with experts involved in the control of forest insect pests in Brandenburg. In total, we sent three questionnaires to the *LFE* and the Cottbus and Lieberose forest districts to collect information about the costs of monitoring *D. pini* in 2014. Furthermore, we sent four questionnaires to the *LFB*, the *LFE*, and the forest districts to ascertain the costs of the aerial spraying of insecticides included in this study. The costs determined on the basis of the questionnaires were used as input data for the cost–benefit analysis.

The interviews complemented the questionnaires. They were used to accumulate general information on controlling forest insect pests in Brandenburg as well as detailed information on controlling *D. pini* in 2014. The interviewees were selected according to their roles and expertise in controlling insect pests. In sum, we conducted six interviews with eight different experts. Two interviews were with one expert from the *LFE* about the monitoring program and the spraying of insecticides. We interviewed four foresters from the Cottbus and Lieberose forest districts who prepared the spraying in the study area, the employee of the *LFB* who coordinated the spraying, and the service provider who conducted the spraying. The interviews mainly dealt with the work steps for controlling *D. pini* in the study area and the associated costs and benefits. Other topics included the specific site and stand characteristics of the study area and the institutional setting for controlling insect pests (e.g., rules for applying insecticides in forests). The interviews were guided by semi-structured guidelines and lasted between 55 and 160 min. All interviews were digitally recorded and transcribed. The questionnaires and the guidelines are presented in the Supplementary Materials.

In addition to the information obtained from the questionnaires and interviews, we used a dataset about the treated pine stands. The dataset was provided by the *LFB* and included economically relevant information on the age, the site index, the stand density, and the area size of the studied stands. Furthermore, it included information about the standing timber volume in the reference year 2014 and the expected timber volume at the end of the rotation period. The dataset provided information on the characteristics of about 85% of the stands treated with insecticides. We assumed that the stands which were not covered by the dataset show the same characteristics regarding age, site index, stand density, and timber volume as the stands for which information was available.

The results of the cost–benefit analysis were presented to seven experts to discuss the findings from a practical point of view. The experts participating in the discussion were the employee of the *LFB* who is in charge of coordinating aerial sprayings of insecticides in Brandenburg, two foresters from the *LFE*, and four employees from the Cottbus and Lieberose forest districts including the heads of the districts and two forest rangers. All participants had profound expertise and long-term experiences in monitoring insect pests and aerial spraying of insecticides. In the first step, a written summary of the results was sent to each expert. In the second step, the results were presented in four face-to-face meetings and then discussed with the experts in terms of their significance for controlling insect pests in practice. The expert discussions lasted between 46 and 144 min. All discussions were digitally recorded and transcribed. Table 4 presents an overview of the questionnaires, expert interviews, and discussions conducted in this study. It provides information about the methods and main topics of the data collection, the number and affiliation of the experts interviewed, and the duration of the interviews and discussions.

Table 4. Description of questionnaires, expert interviews, and discussions.

Method	Main Topic	Interviewees	Number of Experts Interviewed	Duration
Questionaire	Costs of monitoring *D. pini* in the Cottbus FD/Lieberose FD	LFE	-	-
Questionaire	Costs of monitoring *D. pini* in the Cottbus FD	Cottbus FD	-	-
Questionaire	Costs of monitoring *D. pini* in the Lieberose FD	Lieberose FD	-	-
Questionaire	Costs of aerial spraying of insecticides in the Cottbus FD/Lieberose FD	LFB	-	-
Questionaire	Costs of aerial spraying of insecticides in the Cottbus FD/Lieberose FD	LFE	-	-
Questionaire	Costs of aerial spraying of insecticides in the Cottbus FD	Cottbus FD	-	-
Questionaire	Costs of aerial spraying of insecticides in the Lieberose FD	Lieberose FD	-	-
Expert interview	Monitoring of forest insect pests in Brandenburg	LFE	1	111 min
Expert interview	Aerial spraying of insecticides in Brandenburg	LFE	1	160 min
Expert interview	Aerial spraying of insecticides in Brandenburg	LFB	1	123 min
Expert interview	Aerial spraying of insecticides in Brandenburg	Service provider	1	108 min
Expert interview	Aerial spraying of insecticides in the Cottbus FD	Cottbus FD	3	68 min
Expert interview	Aerial spraying of insecticides in the Lieberose FD	Lieberose FD	1	55 min
Expert discussion	Discussion of results	LFB	1	80 min
Expert discussion	Discussion of results	LFE	2	144 min
Expert discussion	Discussion of results	Cottbus FD	3	62 min
Expert discussion	Discussion of results	Lieberose FD	1	46 min

2.3. Data Analysis

The study focuses on analyzing the monetary costs and benefits of protecting pine stands against *D. pini* in the Cottbus and Lieberose forest districts in 2014. It concentrates on the area actually treated with insecticides (i.e., 5600 ha), i.e., infested stands which were left unsprayed were not considered in the analysis.

2.3.1. Scenarios

The benefits of protecting pine stands against *D. pini* in the studied case were analyzed by comparing the potential loss of revenue due to feeding by *D. pini* with the costs of monitoring *D. pini* and the aerial spraying of insecticides in two different scenarios of pine production.

The scenario "*without protection*" represents the baseline scenario in which no protection of pine stands through monitoring and aerial spraying of insecticides takes place. In this scenario, we assume that feeding by *D. pini* completely defoliates infested stands. Empirical studies on tree mortality due to insect feeding in the region have shown a high mortality rate of Scots pine after complete defoliation by *D. pini* [52,55,56]. In addition, these studies have stated that continued management of regenerated pine trees is often unprofitable [55]. Based on the findings regarding tree mortality, we assume that complete defoliation results in the death of stands. Furthermore, we assume that defoliated stands are logged in the year of infestation, i.e., in most cases before the end of the rotation period. A consequence of the defoliation and premature logging is a loss of revenue for forest owners. The loss of revenue results from the difference in value between the expected stand value at the end of the rotation period and the stand value in the year of infestation. It was used as a baseline for comparison with the scenario "*with protection*" to determine the monetary benefits of monitoring *D. pini* and spraying insecticides.

The scenario "*with protection*" refers to the real case in which monitoring and spraying of insecticides are used to protect pine stands against feeding by *D. pini*. Based on the verified efficacy of the treatment [54], it is assumed that monitoring *D. pini* and spraying of insecticides prevent any feeding damage. Furthermore, it is assumed that stands can grow optimally until the end of the rotation period. Forest owners experience no loss of revenue in the scenario "*with protection*" but have to bear the costs of the monitoring and the aerial spraying.

2.3.2. Cost–Benefit Analysis

The loss of revenue in the scenario "*without protection*" was analyzed based on methods proposed in the official guideline for evaluating forests in Brandenburg [57]. The guideline was developed by the regional forestry authority (*LFB*) to assist practitioners in assessing the economic value of forests. It provides region-specific values of forest production (e.g., planting costs, harvesting costs, timber prices) which have been collected by the *LFB*. Following this guideline, we ascertained the loss of revenue (L) in the scenario "*without protection*" by calculating the difference between the expectation value of the studied stands (E) and their felling value (F) at the age of infestation (a):

$$L = E_a - F_a. \quad (1)$$

The expectation value of a stand is a present value which takes into account the current value of the stand and the expected future revenues until the end of the rotation period [58,59]. The expectation value of the studied stands was calculated based on the age constants method and the BLUME-Formula [60]. The age constants method with application of the BLUME-Formula has been applied as an approximation method for evaluating the monetary value of forests at stand, firm, national, and international levels [4,61,62].

Age constants (A) can be used for estimating the relative value development of a stand from its establishment until the end of the rotation period. They indicate for different tree species at any age (a) the ratio between the stand value (SV) at the age a reduced by the stand costs (c) and the felling value (F_r) at the end of the rotation period (r) reduced by the stand costs (c) [63]:

$$A_a = \frac{SV_a - c}{F_r - c}. \quad (2)$$

Age constants are derived from standard stands with given rotation periods and are based on average timber volumes, growth rates, and values of production (e.g., average yields from thinning, average management costs, species-specific production risks) [63]. Dependent on the age, the age constants range between the value of 0 at the beginning of the rotation period and the value of 1 at the end of the rotation period. Age constants are usually listed in tabular form showing for each age of a specific tree species the corresponding age constant. The age constants used in this study were obtained from the Institute for Federal Real Estate (*BIMA*) [64], which is the official authority for the publication of age constants in Germany. They are presented in the Supplementary Materials (Table S1). A detailed theoretical foundation of the age constants method is set out in the studies of Sekot [65] and Sagl [60].

The expectation value of the studied stands was calculated according to the BLUME-Formula [57,66] as a function of the age constant (A_a) at the age of infestation (a), the felling value of the stand (F_r) at the end of the rotation period (r), the stand costs (c), the stand density index (d), and the area size (s) of the stand:

$$E_a = [(F_r - c) \times A_a + c] \times d \times s. \quad (3)$$

The stand costs comprise the costs of all measures required to establish the stand (e.g., soil preparation, planting, tending of young growth) and to protect the young growth against damage (e.g., fencing). The stand costs represent the minimum value of the expectation value, while the felling value at the end of the rotation period represents the maximum value. The stand costs of the studied pine stands were assumed to be EUR 1200 ha^{-1} based on information from the guideline [57]. The stand density and the area of the stands were taken from the dataset of the *LFB*.

The age constants presented in the Supplementary Materials (Table S1) refer to the standard rotation period of Scots pine which is 120 years in Germany. However, the rotation periods assumed in our study case were between 90 and 130 years, depending on the site index (Table 5). If the planned rotation period of a stand differs from the standard, the stand age must be adjusted before selecting the appropriate age constant [57,59].

Table 5. Assumed rotation periods of Scots pine in the study area (based on information from *LFB*).

Site Index	Rotation Period
	(Years)
$-1 \leq$ SI < 0	90
$0 \leq$ SI < 1	100
$1 \leq$ SI < 2	110
$2 \leq$ SI < 3	120
$3 \leq$ SI < 4	130
$4 \leq$ SI ≤ 5	130

The age of the stands concerned was adjusted by multiplying the stand age in the year of infestation with the ratio between the standard rotation period ($RP_{standard}$) and the assumed rotation period ($RP_{assumed}$):

$$a_{adjusted} = a \times \frac{RP_{standard}}{RP_{assumed}}. \tag{4}$$

The adjusted stand age, calculated according to the Equation (4), was then used as the basis for selecting the appropriate age constant.

The felling value of the stands at the age of the infestation (F_a) was calculated by multiplying the timber volume at the age of the infestation (V_a) with the difference between timber price (p_a) and harvesting costs (h_a):

$$F_a = V_a \times (p_a - h_a). \tag{5}$$

The felling value of the stands at the end of the rotation period (F_r) was calculated by multiplying the expected timber volume at the end of the rotation period (V_r) with the difference between timber price (p_r) and harvesting costs (h_r):

$$F_r = V_r \times (p_r - h_r). \tag{6}$$

The standing timber volume of the stands in the year of the infestation and the expected timber volume at the end of the rotation period were taken from the dataset of the *LFB*. Bark and harvest losses were taken into account by converting the standing timber volume into cubic meters of timber harvested. Table 6 presents the age-dependent factors used for the conversion.

The harvesting costs and timber prices used for calculating the felling value of the studied stands represent region-specific average values, which were taken from the guideline [57]. The harvesting costs presented in the guideline refer to the average costs of harvesting pine stands by *LFB* workers in the period 2011–2013. The timber prices presented in the guideline were collected from pine timber sales in Brandenburg between 2011 and 2013. The harvesting costs and timber prices in 2014 were assumed to be equivalent to the average costs and prices in the period of 2011–2013, since no information was available for the reference year.

The harvesting costs and timber prices presented in the guideline are graded in half decimal points (i.e., 0.5, 1.0, 1.5, 2.0., etc.). In the *LFB* dataset, however, the site indices of the studied pine stands were graded in tenths (e.g., 0.5, 0.6, 0.7, 0.8., etc.). Therefore, we used interpolation to estimate the harvesting costs and timber prices for tenths of the site index. The interpolated timber prices and harvesting costs ranged from EUR 55–74 m^{-3} and EUR 16–17 m^{-3}, respectively, depending on the site index (Table S2). Since forecasting future timber prices and harvesting costs involves uncertainties, we assumed that timber prices and harvesting costs are identical at the time of infestation and at the end of the rotation period.

Table 6. Factors used for converting standing timber volume into cubic meters of timber harvested [57].

Age Class (Years)	Conversion Factor
0–19	0.77
20–39	0.77
40–59	0.80
60–79	0.82
80–99	0.84
100–119	0.85
120–139	0.86
140–159	0.86
160–179	0.86

After calculating the expectation value and the felling value of the studied stands, we calculated the loss of revenue in the scenario "*without protection*" according to Equation (1). The loss of revenue in the scenario "*without protection*" was compared to the costs of the monitoring and the spraying of insecticides in the scenario "*with protection*" to determine the net benefits of protecting the studied pine stands against *D. pini*.

The economic criteria used for evaluating the studied costs and benefits included net present value (*NPV*) and benefit–cost ratio (*BCR*). The *NPV* of an investment is the value of the difference between all future revenues and costs discounted to the present:

$$NPV = \sum_{t=0}^{N} \frac{(revenues_t - costs_t)}{(1+i)^t}, \quad (7)$$

where (N) denotes the total number of periods, (t) describes the time of the cash flow, and (i) is the discount rate. According to this general equation, the investment will be profitable in absolute terms when $NPV > 0$ and unprofitable when $NPV < 0$. In the studied case, the *NPV* indicates the difference between the benefits of protection (i.e., averted loss of revenue at the end of the rotation period) discounted to the reference year and the costs of protection (i.e., cost of monitoring and aerial spraying of insecticides) in the reference year:

$$NPV = \sum_{x=1}^{S} \left[\frac{benefits_x}{(1+i)^{r-a}} - costs_x \right], \quad (8)$$

where (S) denotes the total number of individual stands protected; (x) identifies the individual stand protected; (r) is the age of the individual stand at the end of the rotation period; (a) is the age of the individual stand in the year of the infestation; and (i) is the discount rate. No discounting of the costs was needed since the costs of the monitoring and insecticides spraying accrued in the reference year.

The discount rates used for discounting the benefits of protection to the reference year were 0%, 1.5%, and 3.0%. The discount rate of 1.5% corresponds to the specific interest rate of the *LFB* [57] which commercially managed the treated stands in the study year. The discount rates of 0% and 3.0% were chosen to consider a discount rate in the analysis that is higher and lower, respectively, than the interest rate of the *LFB*.

The benefit–cost ratio of an investment is the ratio of the discounted benefits to the discounted costs:

$$BCR = \sum_{t=0}^{N} \frac{benefits_t}{(1+i)^t} \Bigg/ \sum_{t=0}^{N} \frac{costs_t}{(1+i)^t}. \quad (9)$$

Referring to the study case, the *BCR* indicates the ratio between the discounted benefits of protection and the costs of protection in the reference year:

$$BCR = \sum_{x=1}^{S} \frac{benefits_x}{(1+i)^{r-a}} \Bigg/ \sum_{x=1}^{S} costs_x \quad (10)$$

The monitoring and insecticide spraying will be cost-efficient when *BCR* > 1 and inefficient when *BCR* < 1. The *NPV* and *BCR* of protection were calculated for the different site indices and age classes of the studied stands. The *NPV* was used to determine the protection of stands which provided the highest net benefit. The *BCR* was used to determine the most cost-efficient protection of stands, i.e., the protection with the highest benefit per unit of cost.

All costs and benefits were calculated with an accuracy of four decimal places. However, the results and area sizes presented in this study were rounded to the nearest whole number when appropriate.

2.3.3. Sensitivity Analysis

A sensitivity analysis was performed to assess how changes in protection costs and timber prices affect the *NPV* and *BCR* results. For this purpose, protection costs and timber prices were increased from +10% to +100% and decreased from −10% to −100%. In addition, we gradually increased the protection costs and decreased the timber prices until the total *NPV* of protecting all stands was zero (i.e., *NPV* = 0). In this way, we explored to what extent an increase in costs and decrease in timber prices the benefits cover the costs. The protections costs and the timber prices were varied separately while all other determinants of the *NPV* and *BCR* (e.g., stand costs, harvesting costs, interest rate) were kept constant.

2.3.4. Analysis of the Expert Interviews and Discussions

The information obtained from the interviews and expert discussions was analyzed by MAXQDA software (version 2018.2, Cleverbridge AG, Cologne, Germany). First, we developed a scheme of thematic categories to structure the information systematically. The categories were derived deductively from the main topics of the interview guidelines. The main categories were: (i) stand and site characteristics; (ii) damage through insect pests; (iii) monitoring; (iv) insecticide spraying; (v) actors and responsibilities; (vi) benefits; (vii) costs; (viii) rules; and (ix) implications for practice. In the next step, we went through the transcripts and assigned all relevant text sequences to the matching categories. In the last step, we identified the information that was relevant for the analysis and summarized this material.

3. Results

3.1. Costs

The total costs of protecting the studied pine stands were about EUR 520,500, including the cost for monitoring *D. pini* (EUR 58,200) and the costs for spraying insecticides (EUR 462,300). In reference to the total area treated with insecticides (i.e., 5600 ha), the specific costs of protection were EUR 92.95 ha^{-1}. The costs of monitoring were EUR 10.39 ha^{-1} and the costs of the aerial spraying of insecticides were EUR 82.55 ha^{-1} (Table 7).

The costs of monitoring *D. pini* incorporated the costs for materials (e.g., satellite imagery, sticky bands, detectors, rakes, gloves, chainsaws, microscopes), labor (e.g., investigating soils for caterpillars, mounting and checking of sticky bands, felling of sample trees, analyzing data), car use, and others (e.g., costs for postage and telephone calls).

The costs of spraying insecticides involved the costs for materials (e.g., satellite imagery) and the costs for helicopter services, insecticides, and water. Further costs comprised the labor costs for preparing and conducting the application (e.g., consultation with relevant authorities, creation of flight maps, consulting with forest owners, coordination of workers, public closure of treated areas, data management, mail processing, press and public relations), the costs for car use, and others (e.g., costs for approving and announcing the application).

Table 7. Costs of protecting pine stands against *D. pini* in the Cottbus and Lieberose forest districts in 2014.

Costs of Protection		Costs	Costs per Hectare Treated	Share in the Total Costs of Monitoring/Spraying Insecticides	Share in the Total Costs of Protection
		(EUR)	(EUR ha^{-1})	(%)	(%)
Costs of monitoring *D. pini*	Materials	8000	1.43	13.75	1.54
	Labor	44,200	7.89	75.95	8.49
	Car use	5900	1.05	10.14	1.13
	Other costs	100	0.02	0.17	0.02
	Total costs	58,200	10.39	100	11.18
Costs of spraying insecticides	Materials	5900	1.05	1.28	1.13
	Helicopter services	339,700	60.66	73.48	65.26
	Insecticides	65,400	11.68	14.15	12.56
	Water	1900	0.34	0.41	0.37
	Labor	46,100	8.23	9.97	8.86
	Car use	3000	0.54	0.65	0.58
	Other costs	300	0.05	0.06	0.06
	Total costs	462,300	82.55	100	88.82
Total costs of protection		520,500	92.95		100

The largest share in the total costs of protection was for the spraying of insecticides via helicopter (78%), followed by the costs for labor (17%), materials (3%), car use (2%), and water and others (<1%). The largest share in the costs of monitoring was for labor (76%), while the largest share in the costs of spraying insecticides was for payment of helicopter services (73%).

3.2. Benefits

The total standing timber volume protected by monitoring *D. pini* and the aerial spraying of insecticides was 1.12 M m^3 with bark. The felling value of the standing timber in the year of infestation was about EUR 44.35 M and the expectation value was EUR 55.87 M in total. Accordingly, the premature logging of the stands in the scenario "*without protection*" resulted in a revenue loss of about EUR 11.52 M. The loss was averted in the scenario "*with protection*" and represents the monetary benefits of monitoring *D. pini* and the spraying of insecticides in the study area and study year. The present value of the benefits was EUR 4.68 M at the discount rate of 1.5% and EUR 2.05 M at the discount rate of 3%. Henceforth, all results presented in the text refer to the discount rate of 0%, if not specified otherwise.

Table 8 shows the standing timber volume of the treated stands at the age of infestation (V_a) and the expected timber volume at the end of the rotation period (V_r) for different site indices. Furthermore, the table shows the associated felling values (F_a; F_r), the expectation value (E_a), as well as the undiscounted (i.e., i = 0) and discounted benefits (i.e., i = 0.015; i = 0.03) from monitoring *D. pini* and spraying of insecticides. Table 9 presents the results for different age classes.

The largest share of the benefits in absolute terms (EUR 9.11 M) was found for protecting the stands on sites with medium productivity ($1 \leq$ SI < 3). The standing timber volume of these stands was about 0.75 M m^3 in total and accounted for 67% of the total timber volume protected. By contrast, the highest benefits per hectare treated (EUR 2767 ha^{-1}) were found for protecting the stands on sites with high productivity ($-1 \leq$ SI < 1). The standing timber volume of these stands was about 0.15 M m^3 and made up 13% of the total timber volume protected. Protecting the stands with high site index exhibited a benefit of about EUR 368 ha^{-1} higher than the EUR 2399 ha^{-1} resulting from protecting the stands with medium site index. The lowest benefits (EUR 0.51 M and EUR 459 ha^{-1}) were found for protecting the stands on sites with low productivity ($3 \leq$ SI ≤ 5). The standing timber volume of these stands totaled 0.22 M m^3 and constituted 20% of the total standing timber volume protected.

Table 8. Timber volumes, stand values, and monetary benefits from monitoring *D. pini* and spraying of insecticides in the Cottbus and Lieberose forest districts in 2014 (presented for different site indices).

Site Index	Area Treated	V_a	V_r	F_a	F_r	E_a	Present Value of Benefits at Different Discount Rates		
							i = 0	i = 0.015	i = 0.03
	(ha)	(m^3)	(m^3)	(EUR)	(EUR)	(EUR)	(EUR)	(EUR)	(EUR)
$-1 \leq SI < 1$	688	154,631	342,930	6,781,354	16,173,641	8,684,349	1,902,996	851,525	392,926
$1 \leq SI < 3$	3797	746,389	1,508,009	29,778,199	63,769,037	38,886,642	9,108,443	3,607,948	1,530,265
$3 \leq SI \leq 5$	1115	220,148	256,482	7,788,456	9,158,212	8,300,745	512,289	223,393	126,289
$-1 \leq SI \leq 5$	5600	1,121,168	2,107,421	44,348,009	89,100,890	55,871,736	11,523,727	4,682,866	2,049,480
	(ha)	(m^3 ha^{-1})	(m^3 ha^{-1})	(EUR ha^{-1})	(EUR ha^{-1})	(EUR ha^{-1})	(EUR ha^{-1})	(EUR ha^{-1})	(EUR ha^{-1})
$-1 \leq SI < 1$	688	225	499	9859	23,513	12,625	2767	1238	571
$1 \leq SI < 3$	3797	197	397	7842	16,794	10,241	2399	950	403
$3 \leq SI \leq 5$	1115	197	230	6985	8213	7444	459	200	113
$-1 \leq SI \leq 5$	5600	200	376	7919	15,911	9977	2058	836	366

V_a: Timber volume at the age of infestation; V_r: Expected timber volume at the end of the rotation period; F_a: Felling value at the age of infestation; F_r: Felling value at the end of the rotation period; E_a: Expectation value at the age of infestation.

Table 9. Stand values and monetary benefits from monitoring *D. pini* and spraying of insecticides in the Cottbus and Lieberose forest districts in 2014 (presented for different age classes).

Age Class	Area Treated	V_a	V_r	F_a	F_r	E_a	Present Value of Benefits at Different Discount Rates		
							i = 0	i = 0.015	i = 0.03
(Years)	(ha)	(m^3)	(m^3)	(EUR)	(EUR)	(EUR)	(EUR)	(EUR)	(EUR)
0–19	72	18	19,424	698	752,514	172,547	171,849	41,663	10,689
20–39	1994	237,857	842,315	9,775,347	37,177,205	16,566,930	6,791,584	2,365,401	858,330
40–59	1341	315,031	554,945	12,829,050	23,911,933	15,404,938	2,575,888	1,168,302	543,957
60–79	1014	295,466	406,377	11,824,721	16,848,044	13,550,052	1,725,332	921,514	499,909
80–99	294	80,496	90,864	2,919,920	3,363,224	3,119,017	199,096	133,834	91,025
100–119	132	35,806	36,761	1,349,269	1,390,873	1,408,212	58,943	51,177	44,649
120–139	618	132,237	132,479	4,784,743	4,792,835	4,785,778	1035	975	920
140–159	100	17,983	17,983	643,887	643,887	643,887	0	0	0
160–179	34	6275	6275	220,374	220,374	220,374	0	0	0
0–179	5600	1,121,168	2,107,421	44,348,009	89,100,890	55,871,736	11,523,727	4,682,866	2,049,480
(Years)	(ha)	(m^3 ha^{-1})	(m^3 ha^{-1})	(EUR ha^{-1})	(EUR ha^{-1})	(EUR ha^{-1})	(EUR ha^{-1})	(EUR ha^{-1})	(EUR ha^{-1})
0–19	72	0	271	10	10,498	2407	2397	581	149
20–39	1994	119	422	4903	18,646	8309	3406	1186	430
40–59	1341	235	414	9565	17,829	11,486	1921	871	406
60–79	1014	291	401	11,656	16,608	13,357	1701	908	493
80–99	294	274	309	9930	11,438	10,607	677	455	310
100–119	132	271	278	10,213	10,528	10,659	446	387	338
120–139	618	214	214	7740	7753	7742	2	2	2
140–159	100	179	179	6424	6424	6424	0	0	0
160–179	34	183	183	6427	6427	6427	0	0	0
0–179	5600	200	376	7919	15,911	9977	2058	836	366

V_a: Timber volume at the age of infestation; V_r: Expected timber volume at the end of the rotation period; F_a: Felling value at the age of infestation; F_r: Felling value at the end of the rotation period; E_a: Expectation value at the age of infestation.

The highest benefits in terms of age (EUR 6.79 M and EUR 3406 ha^{-1}) were found for protecting the stands in the age class of 20–39 years. The standing timber volume of these stands was 0.24 M m^3 in total and accounted for 21% of the total timber volume protected. The lowest benefits (EUR 0.001 M and EUR 2 ha^{-1}) resulted from protecting the stands in the age class of 120–139 years. Protecting the stands in the age class of 140–179 years provided no monetary benefits since the stands had passed the end of the rotation period and were ready for harvesting. When discussing stands that have reached harvest maturity, they will hereafter be referred to as "mature stands".

3.3. Net Present Value

The total *NPV* of protecting the studied pine stands against *D. pini* was about EUR 11.0 M in absolute terms and EUR 1965 ha^{-1} in relative terms (Table 10). The highest *NPV* in absolute terms (EUR 8.76 M) was found for protecting the stands on sites with medium productivity. By contrast, the highest *NPV* per hectare treated (EUR 2674 ha^{-1}) was found for protecting the stands on sites with high productivity. The *NPV* of protecting the stands with high site index was about EUR 368 ha^{-1} higher than the *NPV* of protecting the stands with medium site index, which was EUR 2.306 ha^{-1}. The lowest *NPVs* (EUR 0.41 M and EUR 366 ha^{-1}) were found for protecting the stands on sites with low productivity.

Table 10. Costs, benefits, *NPV*, and *BCR* of protecting pine stands against *D. pini* in the Cottbus and Lieberose forest districts in 2014 (presented for different site indices).

Site Index	Area Treated	PV [1] of Costs	Present Value of Benefits at Different Discount Rates			*NPV* [2] of Protection at Different Discount Rates			*BCR* [3] of Protection at Different Discount Rates		
			i = 0	i = 0.015	i = 0.03	i = 0	i = 0.015	i = 0.03	i = 0	i = 0.015	i = 0.03
	(ha)	(EUR)	(EUR)	(EUR)	(EUR)	(EUR)	(EUR)	(EUR)			
$-1 \le SI < 1$	688	63,935	1,902,996	851,525	392,926	1,839,061	787,590	328,991	29.76	13.32	6.15
$1 \le SI < 3$	3797	352,923	9,108,443	3,607,948	1,530,265	8,755,520	3,255,025	1,177,341	25.81	10.22	4.34
$3 \le SI \le 5$	1115	103,642	512,289	223,393	126,289	408,647	119,752	22,647	4.94	2.16	1.22
$-1 \le SI \le 5$	5600	520,500	11,523,727	4,682,866	2,049,480	11,003,227	4,162,366	1,528,980	22.14	9.00	3.94
	(ha)	(EUR ha^{-1})	(EUR ha^{-1})	(EUR ha^{-1})	(EUR ha^{-1})	(EUR ha^{-1})	(EUR ha^{-1})	(EUR ha^{-1})			
$-1 \le SI < 1$	688	93	2767	1238	571	2674	1145	478	29.76	13.32	6.15
$1 \le SI < 3$	3797	93	2399	950	403	2306	857	310	25.81	10.22	4.34
$3 \le SI \le 5$	1115	93	459	200	113	366	107	20	4.94	2.16	1.22
$-1 \le SI \le 5$	5600	93	2058	836	366	1965	743	273	22.14	9.00	3.94

[1] PV = present value; [2] *NPV* = net present value (=PV benefits - PV costs); [3] *BCR* = benefit-cost ratio (=PV benefits/PV costs).

The highest *NPVs* with respect to age (EUR 6.61 M and EUR 3313 ha^{-1}) were observed for protecting the stands in the age class of 20–39 years (Table 11). The lowest *NPV*, which showed a positive value, was found for protecting the stands in the age class of 100–119 years. The *NPV* of protecting the stands in the age classes of 120–139, 140–159, and 160–179 years showed negative values, which indicates that the monetary benefits of protecting these stands were not sufficient to offset the costs. Table 10 presents the *NPV* and *BCR* results for different site indices. Table 11 presents the *NPV* and *BCR* results for different age classes.

Table 11. Costs, benefits, *NPV*, and *BCR* of protecting pine stands against *D. pini* in the Cottbus and Lieberose forest districts in 2014 (presented for different age classes).

Age Class	Area Treated	PV [1] of Costs	PV [1] of Benefits at Different Discount Rates			*NPV* [2] of Protection at Different Discount Rates			*BCR* [3] of Protection at Different Discount Rates		
			i = 0	i = 0.015	i = 0.03	i = 0	i = 0.015	i = 0.03	i = 0	i = 0.015	i = 0.03
(Years)	(ha)	(EUR)	(EUR)	(EUR)	(EUR)	(EUR)	(EUR)	(EUR)			
0–19	72	6663	171,849	41,663	10,689	165,187	35,000	4026	25.79	6.25	1.60
20–39	1994	185,320	6,791,584	2,365,401	858,330	6,606,264	2,180,081	673,011	36.65	12.76	4.63
40–59	1341	124,660	2,575,888	1,168,302	543,957	2,451,228	1,043,642	419,298	20.66	9.37	4.36
60–79	1014	94,289	1,725,332	921,514	499,909	1,631,043	827,225	405,620	18.30	9.77	5.30
80–99	294	27,331	199,096	133,834	91,025	171,766	106,504	63,694	7.28	4.90	3.33
100–119	132	12,279	58,943	51,177	44,649	46,664	38,898	32,370	4.80	4.17	3.64
120–139	618	57,455	1035	975	920	−56,420	−56,480	−56,535	0.02	0.02	0.02
140–159	100	9317	0	0	0	−9317	−9317	−9317	0	0	0
160–179	34	3187	0	0	0	−3187	−3187	−3187	0	0	0
0–179	5600	520,500	11,523,727	4,682,866	2,049,480	11,003,227	4,162,366	1,528,980	22.14	9.00	3.94
(Years)	(ha)	(EUR ha^{-1})	(EUR ha^{-1})	(EUR ha^{-1})	(EUR ha^{-1})	(EUR ha^{-1})	(EUR ha^{-1})	(EUR ha^{-1})			
0–19	72	93	2397	581	149	2304	488	56	25.79	6.25	1.60
20–39	1994	93	3406	1186	430	3313	1093	338	36.65	12.76	4.63
40–59	1341	93	1921	871	406	1828	778	313	20.66	9.37	4.36
60–79	1014	93	1701	908	493	1608	815	400	18.30	9.77	5.30
80–99	294	93	677	455	310	584	362	217	7.28	4.90	3.33
100–119	132	93	446	387	338	353	294	245	4.80	4.17	3.64
120–139	618	93	2	2	2	−91	−91	−91	0.02	0.02	0.02
140–159	100	93	0	0	0	−93	−93	−93	0	0	0
160–179	34	93	0	0	0	−93	−93	−93	0	0	0
0–179	5600	93	2058	836	366	1965	743	273	22.14	9.00	3.94

[1] PV = present value; [2] *NPV* = net present value (=PV benefits - PV costs); [3] *BCR* = benefit-cost ratio (=PV benefits/PV costs).

3.4. Benefit–Cost Ratio

The total BCR of protection was about 22.14, which indicates that the total benefits from monitoring *D. pini* and the aerial spraying exceeded the total costs by more than 22 times (Table 10). The highest *BCR* (29.76), i.e., the most cost-efficient protection, was found, like in the case of the *NPV* estimates, when protecting the stands on sites with high productivity. The lowest *BCR* (4.94) was observed for protecting the stands on sites with low productivity.

The highest *BCR* regarding age (36.65) was found for protecting the stands at the age of 20–39 years (Table 11). The lowest *BCR* (4.80) with a value greater than one occurred when protecting the stands at the age of 100–119 years. The *BCR* of protecting the stands which had reached harvest maturity was zero, indicating that their protection was not cost-efficient.

The comparison of the total *NPV* and the total *BCR* at the different discount rates showed that the monitoring of *D. pini* and the aerial spraying of insecticides is also economically viable at the discount rates of 1.5% and 3.0%. The total *NPV* of protecting all stands was about EUR 743 ha^{-1} at the discount rate of 1.5% and about EUR 273 ha^{-1} at the discount rate of 3.0%. The total *BCR* of protection was 9.00 at the discount rate of 1.5% and 3.94 at the discount rate of 3.0% (Tables 10 and 11).

3.5. Sensitivity Analysis

The sensitivity analysis showed that the total benefits of protection were sufficient to cover the total costs until a 2114% increase in the costs and a 92% decrease in the prices of timber. In addition, the analysis revealed that the total *NPV* of protecting all stands reacts more elastically towards changes in the price of timber than to changes in the costs of protection. For instance, increasing the price of timber by 20% increased the total *NPV* by 22%. In contrast, increasing the costs of protection by 20% decreased the total *NPV* by only 1%. Figure 3 illustrates this finding by the solid yellow curve showing the change in *NPV* in response to changes in timber prices and the solid red curve showing the change in *NPV* in response to changes in protection costs. The slope of the yellow curve is steeper than the slope of the red curve. The analysis further showed that the *BCR* responds more elastically to the decrease in protection costs than to the increase in timber prices and, conversely, more elastically to the decrease in timber prices than to the increase in protection costs. For instance, the 50% reduction in protection costs increased the BCR by 100%, while the 50% increase in timber prices increased the *BCR* by 52%. Conversely, the 50% decrease in timber prices reduced the *BCR* by 52%, while the 50% increase in protection costs reduced the *BCR* by 33%. The green dashed curve, which indicates the change in *BCR* in response to changes in protection costs, and the black dashed curve, which indicates the change in *BCR* in response to changes in timber prices, illustrate this finding (Figure 3). The slope of the green dashed curve is steeper than the slope of the black dashed curve if costs and prices decrease and flatter if costs and prices increase.

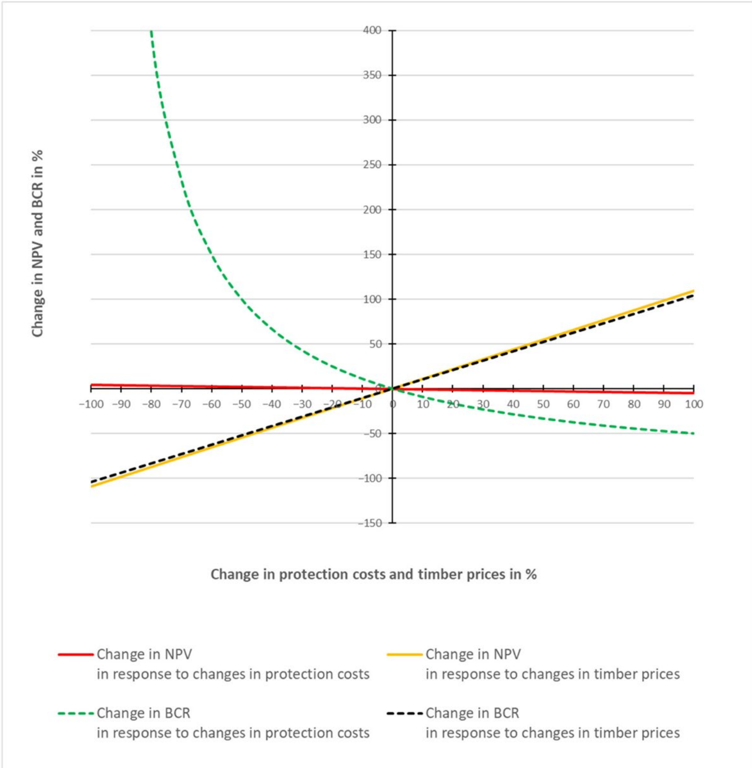

Figure 3. Change in *NPV* and *BCR* in response to changes in protection costs and timber prices.

4. Discussion

4.1. Empirical Findings

Assessment studies, like the study at hand, can provide pest managers and forest owners with important information about the costs and benefits of monitoring insect pests and aerial spraying of insecticides. They can assist in decision making on forest protection and offer a basis for reflecting on the monetary consequences of decisions. The present study contributes to the literature on forest pest management by adding empirical evidence about the economic viability of monitoring insect pests and aerial sprayings of insecticides in managed forests. To our knowledge, this is the first cost–benefit analysis of monitoring *D. pini* and aerial spraying of insecticides against mass propagations of *D. pini*.

The results showed that monitoring insect pests and aerial spraying of insecticides are economically viable options to protect forests from needle-feeding insect pests such as *D. pini*. The *NPV* of protecting pine stands in the study case was positive which indicates that the total benefits of protection exceeded the total costs. The comparison of our results with those of other case studies revealed that there is no consensus in the literature about the economic viability of aerial spraying of insecticides. Our results corroborate the findings of Chang et al. [41], Liu et al. [3], and Slaney et al. [12] who found that the monetary benefits of aerial sprayings of insecticides against *Choristoneura fumiferana* in Canada outweigh the costs. Our results are in contrast to the findings of Aimi et al. [11] and Gatto et al. [10] who showed that the market benefits of spraying insecticides against *Thaumetopoea pityocampa* in Italy and Portugal are insufficient to cover the costs of protection. The studies highlight that aerial spraying of insecticides against processionary moth caterpillars is only economically viable if the reduced risk to human health and the protection of the social and environmental service values provided by forests are considered in the assessment.

Previous assessment studies analyzed how different severities of outbreaks and intensities of control influence the economic viability of aerial sprayings of insecticides [3,12]. Our study revealed how differences in site index and age of stands affect the benefits of protection. The *NPV* and *BCR* results indicate that protecting stands with high site index is more beneficial and cost-efficient than protecting stands with medium and low site index.

Furthermore, the results show that the protection of young stands is more beneficial and cost-efficient than the protection of old stands. The findings suggest that pest managers can increase the benefits and the cost-efficiency of insecticide spraying by focusing on protecting stands characterized by a high site index and young age. However, from a practical point of view, this approach can result in a large number of small and disjointed treatment plots, which, according to the interviewees, are more costly to spray than spraying a large, coherent area. Furthermore, this procedure means accepting damage to unprotected stands, which may exceed the benefits of spraying insecticides in protected stands.

The forestry authorities in the study case do not seek to maximize the benefits of protection by spraying only those stands with a high site index or young age. Instead, they aim to protect all stands at risk independent of their site index and age. Preserving forests in their entirety, including the integrity of their economic (e.g., wood provisioning), ecological (e.g., wildlife habitat, biodiversity, carbon storage, air purification, soil and water protection), and social functions (e.g., recreation, tourism), is more important for the forestry authorities in the study area than maximizing the monetary benefits and cost-efficiency of aerial spraying of insecticides. This is particularly evident in the case of protecting stands that had passed the end of the rotation period. The results show that the protection of stands that have reached harvest maturity is not economically justified since no monetary benefits result from the protection to offset the costs. This finding raises the question, why should mature stands be protected? One reason which can justify the protection of mature stands is the value of the social and environmental services they provide (e.g., recreation, soil and water protection, wildlife habitat) [67]. Another reason is the role of older trees in converting monocultures into more mixed-species, multi-aged stands. Several studies showed that the presence of higher age class trees can be a decisive factor in successfully establishing young stands [68,69]. They provide shade and protect young growth against extreme weather conditions such as heat, freezing, and wind. Moreover, the shady light conditions under the canopy of old trees keep the competing vegetation low and may help the planted tree species to gain a growth advantage over pioneer tree species [68]. A further aspect, expressed by the interviewees, is the desire of profit-driven forest owners to be flexible in deciding when to harvest. Profit-driven forest owners prefer to harvest when timber prices are high. Uncontrolled insect feeding in unprotected stands increases the risk of tree damage and may force forest owners to harvest mature stands when timber prices are low. Insect monitoring and aerial spraying of insecticides can contribute to keeping harvest timing flexible. The value of flexible harvest timing and the ecosystem services provided by mature stands seem sufficient to compensate the forestry authorities in the study area for the costs of protecting mature stands.

The monetary benefits of monitoring insect pests and aerial spraying of insecticides depend not only on the site index and age of stands but also on the prices of timber and the costs of protection. The comparison of the wood prices in Germany over the years revealed that the producer prices of pine wood were not stable between 2000 and 2022. Instead, the prices were subjected to volatilities ranging from −46% to +3% compared to the prices in the statistical reference year 2015 [70]. The interviewees reported that the costs of monitoring *D. pini* and the costs of aerial spraying of insecticides have steadily increased in the study area due to increased labor costs and higher prices for fuels, helicopter services, and insecticides. The market price of the active agent *diflubenzuron* increased from EUR 266 kg^{-1} to EUR 408 kg^{-1} in the period 2006–2014 [71]. The price of *lambda-cyhalothrin* increased from EUR 137 L^{-1} to EUR 167 L^{-1} in the period 2012–2022 [71]. Decreasing timber prices and increasing costs reduce the economic viability of monitoring insect pests and aerial spraying of insecticides. The results of the sensitivity analysis showed that the *NPV* of the studied measures is more sensitive to changes in the prices of timber than to changes in the cost of protection. In addition, we found that there is a great scope for increases in protection costs (+2114%) and decreases in timber prices (−92%) that would not jeopardize the economic viability of monitoring *D. pini* and aerial spraying of insecticides in the study area. This finding suggests that insect control by monitoring and aerial spraying of insecticides are an economically viable option in Brandenburg, even if future costs were to increase and timber prices were to decrease.

Our results are specific to the case of protecting pine forests against *D. pini* in Brandenburg and may not be simply generalized or transferred to other regions, tree species, and insect pests without critical reflection upon the value of the timber protected and the costs of protection. We assume that similar results to the study case can be expected for regions where *D. pini* is naturally distributed and where stand characteristics and protection costs are similar to those observed in Brandenburg. Further statements on the transferability of our results to other tree species and insect pests require detailed information about the monetary value of the stands at risk and the specific costs of protection. The costs of monitoring insect pests and aerial spraying of insecticides may not be covered by sufficient benefits if the timber of the tree species protected has a low market value. Moreover, the costs of monitoring and aerial spraying of insecticides vary by region, tree species, and insect pest [3,72,73]. We acknowledge that further empirical work is needed to prove whether the findings remain valid in other cases of monitoring insect pests and aerial sprayings of insecticides.

4.2. Limitations

Our methodological approach of coupling cost–benefit analysis with the age constant method and application of the BLUME-Formula proved to be expedient for evaluating the monetary costs and benefits of monitoring insect pests and aerial spraying of insecticides. We believe that the proposed approach can be easily applied in other case studies to assess the monetary costs and benefits of measures for controlling insect pests in forests. However, some limitations remain in our study, which could be improved by future research. Our study was designed to assess the monetary costs and benefits of monitoring insect pests and aerial spraying of insecticides which accrue for forest owners. Yet, forest protection by aerial spraying of insecticides may also create a number of costs and benefits to society and the environment. The research design presented here could be improved by incorporating externalities into the cost–benefit analysis. Recent studies have shown that external benefits can significantly influence the economic viability of aerial sprayings of insecticides [3,10,41]. For instance, Chang et al. [41] found that including social values like the preservation of opportunities for recreation into cost–benefit analysis generally increases the *BCR* and *NPV* of aerial spraying of insecticides. Similarly, Aimi et al. [11] and Gatto et al. [10] showed that the economic viability of aerial spraying increases when environmental services like soil protection and carbon fixation are included in the analysis. Incorporating such non-market service values and potential risks (e.g., effects on non-target organisms) into our analysis may provide decision makers with additional information that can contribute to a more all-round assessment of monitoring insect pests and aerial spraying of insecticides. In this context, it would also be interesting to analyze the economic viability of spraying biological insecticides which are generally considered less risky to the environment than chemical plant protection products [74].

5. Conclusions

In this study, we assessed the monetary costs and benefits of monitoring insect pests and aerial sprayings of insecticides in managed pine forests. The findings highlight the economic value of insect control and provide stakeholders with practical information and knowledge about the economic consequences of pest monitoring and insecticide spraying. The results show that the monetary benefits of monitoring insect pests and aerial spraying of insecticides are much greater than the costs, provided that the protected stands have not yet passed the end of the rotation period. Referring to the study case, we conclude that monitoring insect pests and aerial spraying of insecticides are economically viable options to protect forests against needle-feeding insect pests. However, the benefits and the cost-efficiency of protection vary with the site index and age of stands. Aerial spraying of insecticides is more beneficial and cost-efficient in stands with a high site index and in young stands than in stands with a low site index and in old stands. The protection of stands that have reached harvest maturity provides no monetary benefits, but the preservation of ecosystem services and the role of older trees in forest conversion may justify their protection. Future studies should contribute to a more holistic assessment of aerial sprayings of insecticides by integrating ecological risks as well as the environmental and social ecosystem services of forests into cost–benefit analysis.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f15010104/s1, S1: Questionnaires for collecting information on the costs of monitoring insect pests and aerial spraying of insecticides; S2: Guidelines for expert interviews; Table S1: Age constants for evaluating the monetary value of pine stands in Germany; Table S2: Harvesting costs and timber prices of Scots pine for different site indices in Brandenburg.

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