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Report on the economic impacts of the Norwegian contingency plan for Pine Wood Nematode (PWN) *Bursaphelenchus xylophilus*

Even Bergseng[1], Bjørn Økland[2], Terje Gobakken[1], Christer Magnusson[3], Trond Rafoss[3] and Birger Solberg[1]

[1] Dep. of Ecology and Natural Resource Management, Norwegian Uni. of Life Sciences, Ås, Norway

[2] Norwegian Forest and Landscape Institute, Ås, Norway

[3] Norwegian Institute for Agricultural and Environmental Research, Ås, Norway

Preface

This report is produced for Bioforsk as specified in contract nos.1110402 between Bioforsk and the Department of Ecology and Natural Resource Management (INA) at the Norwegian University of Life Sciences. The report is made in cooperation by a team of researchers from Bioforsk (Christer Magnusson, Trond Rafoss), INA (Even Bergseng, Terje Gobakken, Birger Solberg) and Skog & Landskap (Bjørn Økland), with Birger Solberg as project leader. Bjørn Økland has provided the biological calculations, Even Bergseng has done the economic calculations and most of the initial writings, Trond Rafoss has provided the climate change scenario, and the other authors have contributed mainly in discussions of outline, assumptions, results and final formulations.

The study has not been externally evaluated, and should be kept restricted until main parts of it have been published in a peer reviewed international journal.

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Contents

Summary

The pinewood nematode (PWN) causes Pine Wilt Disease (PWD), which is an important forest pest in countries where it is introduced. The first European discover of PWN was in Portugal in 1999. Large-scale control measures have been taken to eradicate it, but despite these efforts, PWN has spread. The likelihood of PWN entering Norway via wood packaging material is high, but the risk of epidemic pine wilt is low under current climate due to low summer temperatures. The Norwegian Food Safety Authority has commissioned a pest risk assessment on the effects and costs of abatement strategies against PWN in Norway. With two main scenarios, we analyse (i) the impact on forest production and associated costs of a introduction of PNW in Norway under different climate conditions, (ii) the effect of the risk management measures proposed in the preliminary contingency plan for PWN and (iii) the economic consequences of these risk management measures. The first scenario (A) assumes that no measures are taken, neither to detect nor to eradicate PWN, and is run under both current climate conditions and according to climate change assumptions. The second (B) assumes implementation of the proposed contingency measures when PWN is detected, with complete removal of host conifer trees within a 3 km radius eradication zone around detection points and a surrounding observation zone of 17 km. Eradication zones are kept clear of host trees and all forest management measures are banned in the observation zone for 20 years. The analysis utilises forest and land inventory data from the National Forest Inventory to run a biological model for the dispersal of PWN and an economic model for forest valuation. The results are combined to assess the economic impact of PWD in Norway.

We find that if no contingency measures are introduced under present climate conditions, the economic consequences of PWN in Norway are zero, as no pine trees will develop PWD. If future climate changes, we estimate that less than 300 trees will die per year over the first 50 years, i.e. the costs are negligible. Furthermore, the present contingency plan is not be able to stop PWN from spreading. The net present value of accumulated costs of the contingency plan over a 50 year period is ~2 billion NOK depending on interest rates. These costs are caused by reduced income from industrial timber production and the costs of the eradication measures. Costs related to e.g. reduced recreation or biodiversity, are not included in the above estimates, but would without doubt be very high. Many of the factors in the analysis are burdened with high uncertainty, but sensitivity analyses indicate that the results are rather robust even for drastic changes in assumptions.

1 Introduction

The pinewood nematode (PWN) causes Pine Wilt Disease (PWD) which is the most important forest pest of Japan (Mamiya, 1984) and in other countries where it is introduced (China, Taiwan and Portugal). PWN is vectored by longhorn beetles in the genus *Monochamus* (Togashi & Shigesada, 2006). The first European infestation by PWN was discovered in Portugal in 1999 (Mota et al., 1999), whereupon a demarcated area was set up in the infested area of Setubal south of Lisbon. Since then, large-scale control measures have been taken in and around the infested area, aiming to stop further spreading of the nematode and to finally eradicate it from the EU territory (Rodrigues, 2008). The measures include felling and destruction of weakened pines within the infested area and the establishment of a surrounding host-free containment zone. Despite these efforts, new infestations were detected in various areas in Portugal, far outside the containment area, and also in Spain in 2008 (INRA 2009, (Robinet et al., 2009) and Madeira. The outbreak of PWN in Portugal has triggered surveys for PWN in several other European countries, (e.g., EC, 2000; Jordbruksverket, 2008a; Magnusson et al., 2007), and outlines of contingency plans prescribe strong risk management measures for eradication if PWN should be detected (e.g., EPPO_PM9/1(2); Jordbruksverket, 2008a; Mattilsynet, 2007). The likelihood of PWN entering Norway by the pathway of coniferous wood packaging material is high (VKM, 2008). However, the risk from the nematode causing epidemic pine wilt is strongly linked to the average summer temperature, which makes it difficult to detect PWN in a Nordic climate due to the lack of symptoms. According to the ForestETP model (Evans, Evans, & Ikegami, 2008), the presence of PWN in the Nordic countries will under current climate rarely lead to PWD due to low summer temperatures (Jordbruksverket, 2008a).

Once alien pest species have become established in new habitats, they may be extremely difficult to eradicate (Genovesi, 2005), and the costs of damage and control programs may be very high (Hulme, Pysek, Nentwig, & Vila, 2009; Haack, Herard, Sun, & Turgeon, 2010; Pimentel, 2002). Despite extensive efforts in monitoring and stopping the spread of introduced species, several examples show that the range expansions continue to take place, e.g. Gypsy Moth in North America (Liebhold, Sharov, & Tobin, 2007), Brown Spruce Longhorn Beetle *Tetropium fuscum* in Canada (Sweeney, Gutowski, Price, & De Groot, 2006, www.inspection.gc.ca), and the Pine Wood Nematode (PWN) *Bursaphelenchus xylophilus* in Japan, Portugal and Spain (Naves, Camacho, de Sousa, & Quartau, 2007). The studies illustrates that due considerations have to be given to the costs of risk management measures, and these costs have to be evaluated against the probability of eradication for alien pests.

On this background, the Norwegian Food Safety Authority in 2008 commissioned the Norwegian Scientific Committee for Food Safety to do a pest risk assessment on the effects and costs of abatement strategies against PWN in Norway (www.vkm.no/dav/b81ba7bc37.pdf). Specifically, the main objectives of the assessment were to analyze:

(i) the impact on forest production/volume and the associated costs of a future introduction and spread in Norway of PNW, under (a) current climate conditions and (b) under a predefined future climate change scenario;
(ii) the effect of the risk management measures proposed in the preliminary contingency plan (Mattilsynet, 2007) developed to stop the spread of eventual PWN introductions to Norwegian forests;
(iii) the economic consequences of these risk management measures.

This report describes the methodology (chapter 2) and results (chapter 3) of the study, and discusses the main findings in chapter 4.

2 Material and methods

2.1 Specification of the contingency measures analysed

In this section we define the risk management measures which are analysed to fulfil the objectives specified in chapter 1. As the measures are connected to assumptions regarding climate change and size of abatement areas and detection sampling, we have used the term scenario. Two main scenarios (A, B) are analysed.

Scenario A assumes that no measures are taken, neither to detect nor to eradicate PWN. It is divided in two sub-scenarios, A1 and A2 according to climate change assumptions.

Scenario A1 assumes that the current climate prevails in Norway – i.e. it is assumed that no significant climate change occurs during the coming 50 years. As Pine Wilt Disease (PWD) will most likely not be expressed in Norway under the current climate, scenario A1 is the ”business as usual”- scenario – i.e. it assumes that we get the present harvest level and investments in forestry. The costs estimated in the other scenarios defined below are thus the costs relative to the outcome of scenario A1.

Scenario A2 is the same as scenario A1 except that we assume a climate change corresponding to a temperature increase of ~2°C by the end of the coming 50 year period and PWD outbreaks as defined in section 2.5.

Scenario B assumes implementation of the proposed Norwegian contingency measures when PWN is detected, as described in paragraph 6.2 in Mattilsynet (2007). It assumes complete logging and destruction of all host conifer trees (all conifer trees except *Thuja plicata*) within a circle of 3 km around each detection point (hereafter referred to as the eradication zone) and an observation zone of 17 km around this zone for intensive monitoring (3000 samples). In the eradication zone all host trees are immediately cut and then destroyed by burning at the site or, if economically feasible, utilized for chips or lumber production under conditions that prevent spread of PWN (sealed container transport or heating to 56 degrees C for minimum 30 minutes (Jordbruksverket, 2008a)). The eradication zone will be kept clear of host trees for a 20 year period, and a ban on all forest management measures is imposed in the observation zone during the same time period. The measures and assumptions underlying scenario B are described in more detail in sections 2.3 and 2.4. If additional infestations are found, new zones of logging (3 km radius) and intensive monitoring (17 km) should be established around the new infestation points. This scenario is run under current climate conditions. It also serves as a low estimate of the costs under climate change (cf. section 3.2 and 4.2).

2.2 Data

All land and forest data are collected from the National Forest Inventory (NFI, 2010). We use the counties Østfold, Oslo, Akershus, Hedmark, Oppland, Buskerud, Vestfold and Telemark, because the biological model for PWN dispersal and spread is based on harvesting data for these counties (Økland et al., 2010). The relative distribution of NFI sample plots on land use classes and counties is shown in Figure 1 and Table 1. Approximately 2/3 of the sample plots are classified as forest land.

Table 1 Relative distribution of sample plots in the data set distributed on county and land use class, and total number of plots in each county and land use class.

	Land use classes							Total	
	Agri-cultural land	Prod-uctive forest	Other forest land	Grazing land	Other	Settle-ments	Wetland/ mire	%	N
Østfold	20.2	58.9	6.3	0.2	2.0	6.1	6.5	6.5	496
Akershus	15.0	61.4	2.5	0.8	0	10.5	9.8	7.9	601
Oslo	0	60.7	1.8	0	0	33.9	3.6	0.7	56
Hedmark	5.3	67.6	8.4	0.2	1.4	4.2	13.0	31.7	2 411
Oppland	8.3	62.0	8.5	0.6	2.2	5.3	13.2	19.2	1 460
Buskerud	5.2	63.6	10.7	0.7	1.6	7.3	10.7	14.6	1 108
Vestfold	16.9	58.8	3.0	0.0	2.6	12.7	6.0	3.5	267
Telemark	2.5	56.0	16.2	0.5	5.9	5.0	14.0	15.9	1 212
Total %	7.5	62.69	9.16	0.43	2.26	6.1	11.86		
Total N	571	4771	697	33	172	464	903		7611

Land use classes "Agricultural land" and "Settlements" show the most notable differences between counties. The same information is presented graphically in Figure 1.

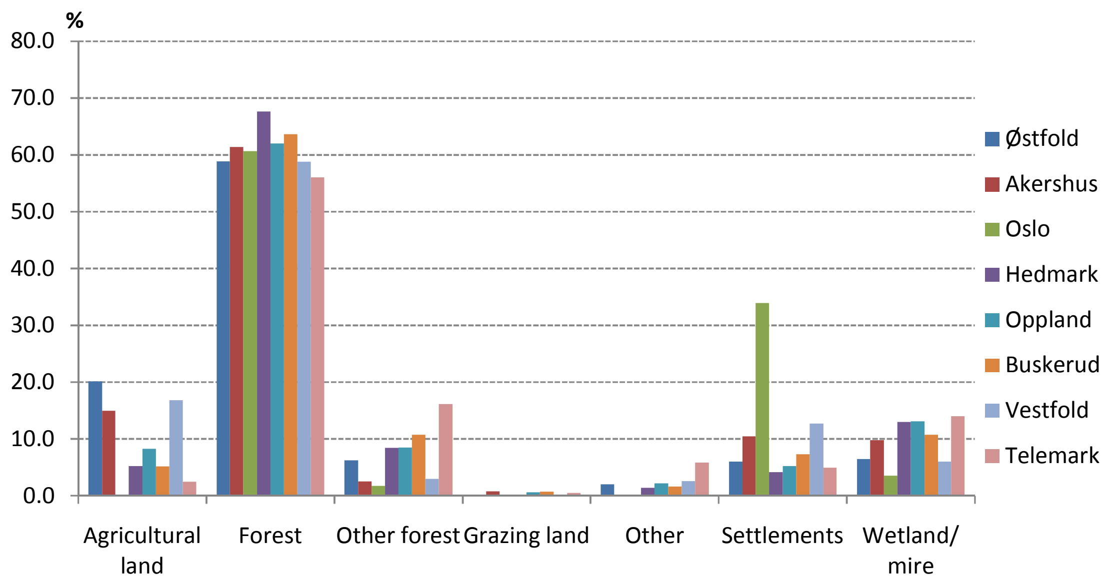

Figure 1 Relative distribution of sample plots in the data set distributed on county and land use class.

Using sample plot information from the National Forest Inventory implies that weighting is unnecessary when calculating average number.

2.3 A model for the dispersal of Bursaphelenchus xylophilus

2.3.1 Basic system descriptions and model assumptions

Økland et al. (2010) developed a model for the dispersal of PWN. The model makes use of the information available in literature for potential *Monochamus* vectors in combination with biological and climatic information from Scandinavian forest systems (Økland et al., 2010), including information from experimental studies (L.M. Schroeder & Magnusson, 1992) and PWN surveys in Scandinavia (Jordbruksverket, 2008b).

Local and regional spread of PWN is related primarily to dispersal by insect vectors of the genus *Monochamus* (Togashi & Shigesada, 2006). The principal vector in Portugal *M. galloprovincialis* is present in the south-eastern part of Norway. However, the most widely distributed PWN vector species in Norway is *Monochamus sutor*, which has a univoltine life cycle (one generation per year) in southern lowland districts of Norway (Bakke & Kvamme, 1992; Ehnström & Holmer, 2007). This species is also assumed to be a suitable vector for PWN (VKM, 2008). It has been demonstrated to transmit the native species *Bursaphelenchus mucronatus* a close relative to PWN, to dead wood via oviposition (laying of eggs) and to fresh branches of Scots pine and Norway spruce via maturation feeding (Magnusson & Schroeder, 1989; L.M. Schroeder & Magnusson, 1992). *B. xylophilus* appears to be a superior competitor compared to *B. mucronatus*, and it cannot be stated that *B. mucronatus* will be efficient as a factor to decrease propagation of this invasive species *B. xylophilus* (Vincent et al., 2008). There is abundant supply of host trees in Norway (NFI, 2010), the most important species being Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) H. Karst.). *P. sylvestris* belongs to the group of pines that are highly susceptible to PWD, while PWN can live in *P. abies* but probably without causing PWD (VKM, 2008). In Scandinavia, the vector *M. sutor* can oviposit and develop in recently dead wood of both tree species, while *M. galloprovincialis* is limited to recently dead pine trees (Ehnström & Axelsson, 2002; Ehnström & Holmer, 2007).

The transmission of PWN between the beetle generations can either be from parents to offspring via the larval habitat (i.e. dead wood), or through maturation feeding on new shoots and branches of living conifers that later die, and become larval habitat of *Monochamus* (Togashi & Shigesada, 2006). The latter option is important in areas with outbreaks of PWD, while the chance of transmission of nematodes from living trees to *Monochamus* beetles is considered to be low in the Scandinavian forests where temperatures usually are likely to be too low for development of PWD (Jordbruksverket, 2008a). Bergdahl and Halik (2004) documented that living pine trees can host PWN infestations for at least 14 years without showing symptoms of PWD. In temperate climates, healthy trees are normally not damaged by PWN and the maximum time for latent infections to persist in living trees is not known (VKM, 2008). Application of the ForestETP-model to Swedish forests (Evans et al., 2008) under current climatic conditions showed that the likelihood of PWD development is small and limited to small incidences of PWD, in southern Sweden in years with summer temperatures higher than normal (Jordbruksverket, 2008a). Thus, the current model of initial spread is limited to transmission of PWN through the larval habitat in dead conifers, the so-called saprophytic life cycle (VKM, 2008). The model keeps track of the living trees infested through maturation feeding; however, it is not assumed that further spread of PWN takes place from these trees. The likelihood that non-infested beetles become infested during copulation with PWN-infested beetles is set to zero as the density of infested beetles will be low in the early spread of PWN. As long as PWD trees are rare or absent, trees infected during maturation feeding will not be a significant breeding habitat for vector beetles.

2.3.2 Model description

A simulation model built in R (R, 2009) estimates how PWN spreads if it enters in SE Norway. The model assumes that introduction of one PWN infested object - i.e. one PWN-infested beetle, e.g. *M. galloprovincialis* or *M. alternatus* or a piece of PWN-infested dead wood - leads to PWN-infection of dead wood objects utilized by the local *Monochamus* populations in the lowlands of SE Norway (*M. sutor* and *M. galloprovincialis*), which in turn starts a spread of PWN to an increasing proportion of the existing *Monochamus* population and its habitat objects. As the vector has a univoltine life cycle, the model uses annual time steps in the risk areas for import in SE Norway. The model keeps track of PWN-infested objects of Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*) of suitable category and exposition for *M. sutor*. According to field and survey experiences, the main habitat for oviposition is logging residues (tops, larger branches etc) and dead trees, when they are sun-exposed, e.g. on clear-cut areas or along forest roads and margins of clear-cut areas (L. M. Schroeder & Lindelow, 2003; L. M. Schroeder, Weslien, Lindelow, & Lindhe, 1999;

Trägårdh, 1929). The density of suitable deadwood objects was estimated from the PWN survey and the NFI (see details in Økland et al., 2010).

The high abundance of *M. sutor* in newly burnt forests far away from source habitats for these beetles implies that many beetle individuals can undertake long-distance dispersal over several kilometers in Scandinavian forests (Forsslund, 1934; Trägårdh, 1929). Several individuals may fly short distances when suitable breeding material (newly wind-felled trees) is found within or at the edges to the same area where they have developed (typical a 1-2 year old clear-cut area). A dispersal kernel based on a mark-recapture study is described for short-distance flight of *M. alternatus* (Takasu et al., 2000). The flight distances of this kernel (mean 14 meter and maximum about 60 meter) are below typical distances within Scandinavian clear-cut areas. Mean of the distance across 63525 clear-cut areas in SE Norway (Fritzøe property and Løvenskiold property) and mid Sweden (Dalarna län and Värmland län) was 157 meter, and 95% of the distances were within the interval 58 – 437 meter. However, when all suitable breeding material becomes occupied or too old, several beetles must fly long distances to next suitable clear-cut area (a clear-cut area with fresh logging residues or newly wind-felled trees), which indicates that a significant proportion of the vector beetles fly long distances. Considering the shortest distance between clear-cut areas of suitable age for *Monochamus sutor* in SE Norway (Fritzøe and Løvenskiold) and mid Sweden (Dalarna and Värmland), the mean distance was 1170 meter, with 95% of the shortest distances being within the interval 66 – 5112 meter. This is about the same scale as the flight distances in the mark-recapture study of *M. alternatus* (mean 1820 meters), which was used in the long-distance part of the two-component dispersal kernel described by Takasu *et al.* (2000). As mark-recapture studies are lacking for *M. sutor*, we assumed the two-component dispersal kernel described by Takasu *et al.* (2000) in the present simulation model. Between objects, each individual of vector beetles were assumed to spread isotropically (uniform in all directions) with randomized direction θ of

Eq. 1 $$\theta \sim uniform(0 - 2\Pi)$$

We let the flight distance *z* of each individual be randomly drawn from a dispersal distribution kernel *F* corresponding to the annual mark-recapture-based dispersal functions and parameterizations described by Takasu *et al.* (2000), which includes a balance between short- and long-distance dispersal:

Eq. 2 $F(z) = \sigma_L \cdot f_L + (1 - \sigma_L) \cdot f_S$

where f_L is the function of long-distance dispersal, f_S is the function of short-distance dispersal, and σ_L is the proportion of individuals dispersing according to the long-distance dispersal component. σ_L is set to 0.35, reflecting that a large proportion of the beetle population must fly long distances to find other suitable clear-cut areas for breeding. The long-distance dispersal component is an exponential function:

Eq. 3 $f_L(z) = 0.000275 \cdot e^{-0.00055 \cdot z}$

Among the short-distance dispersal beetles (1-σ_L), a fraction (1-σ_S) remains in the same place, while the rest σ_S disperse a short distance according to the following function:

Eq. 4 $f_S(z) = \frac{0.0358}{\tau(0.3915)} \cdot e^{-\left(\frac{z}{35.69}\right)^{2.554}}$

where τ is the Gamma function.

All biological parameter values were derived from the literature, recent research (PHRAME, 2007), expert opinions, data from the NFI and the PWN survey in Norway (Magnusson et al., 2007) and Sweden (Jordbruksverket, 2008b). The selected estimates were based on the species and forest systems being closest to that of the model system. Further model details can be found in Økland et al. (2010).

2.3.3 The detection survey and its implementation in the model

PWN surveys were started in the Nordic countries in the year after the first detection in Portugal (1999) and have continued up to date. The surveys in Norway and Sweden are based upon the EC Pinewood Nematode Survey Protocol 2000 and the document Nordic Pine Wood Nematode Survey, Draft Manual 2000-02-11 by Magnusson et al. (2000). The sampling is not dependent on PWD-symptoms, but each sample requires extraction of nematodes and nematode identification by microscopy and often PCR-methods to verify the presence or absence of PWN. Sampling is stratified to risk areas, which are defined as circular zones of 50 km radius around locations with high likelihood of entry (e.g. ports). Within each circle, most samples are taken from selected types of logging residues in clear-cut areas, which is the most important breeding habitat of *Monochamus* species in

Scandinavia. Among the residuals, samples are taken selectively from tops and thick branches (< 5 cm diameter) with signs of *Monochamus* activity (e.g. exit holes, galleries or typical saw dust). The Swedish PWN survey yielded 3146 samples in the period 2000-2007 (Jordbruksverket, 2008b), while the Norwegian PWN survey treated 3165 samples in the period 2000-2006 (Magnusson et al., 2007). This level of about 420 samples per year (representing 0.02 % of the estimated number of suitable objects with *Monochamus* marks in the total sampling area of the detection survey) was used in the simulation model. Furthermore, the management parameters of the model were based on the Norwegian survey, where the survey included ten zones of 50 km radius (total area 78 540 km^2) and samples from both coniferous hosts of *M. sutor*, Scots pine (*Pinus sylvestris* L.) and Norway spruce [*Picea abies* (L.) Karst.]. Every year of the model simulation, 420 samples were drawn randomly from the estimated total number of objects with signs of *Monochamus* breeding within the total survey area (78 540 km^2), among which the PWN-infested objects were distributed during the simulated spread. Using estimates of the number of tops and large branches per pine and spruce in different diameter classes, we deployed the statistics of the average volume of logged spruce and pine per km^2 per year in SE Norway to estimate the total number of suitable residual objects for *Monochamus* breeding per km^2. To this number, we added the number of sun-exposed recently dead pines and spruces per km^2 in SE Norway (see details in Økland et al., 2010), to get the total number of suitable objects for *Monochamus* breeding per km^2. This total number was multiplied with a factor representing the fraction of suitable object that actually showed signs of *Monochamus* activities (estimated from the PWN survey data), leading to an estimate of 28.8 objects per km^2. When infested objects were found by the detection sampling in the simulation script, measures in the contingency plan were applied around each detection point.

2.3.4 The contingency plan and its implementation in the model

A draft contingency plan for Norway prescribes complete logging and destruction of all host conifer trees within a circular zone of 3 km radius around each detection point and an external 17 km observation zone for intensive monitoring (3000 samples) and pre-emptive measures. If additional infestations are found, new zones of logging (3 km) and intensive monitoring (17 km) should be established around the new infestation points (Mattilsynet, 2007). Similar draft plans for large-scale eradication have been developed for other Nordic countries (Evira, 2007; Jordbruksverket, 2008a), and are also included by the European and

Mediterranean Plant Protection Organization (EPPO) in a standard for official control of PWN and its vectors (EPPO_PM9/1(2)).

Similar to the Norwegian contingency plan (Mattilsynet, 2007), the model used in this study removes all infections and suitable host tree objects in a radius of 3 km around detection points before next time step of the 50 year long simulation. Furthermore, an intensive sampling with 3000 samples is implemented in a 17 km wide zone around the zones of tree removal, using the same estimates of sampling objects densities as described above. For each new point of detection, a new zone of tree removal was executed before the next time step of the simulation.

2.3.5 Tree mortality due to PWD

We used the mortality percentages data of pines which were estimated by the ForestETP for Sweden (Jordbruksverket, 2008a) to estimate percent mortality as a function of mean temperature for June to September, using the Generalised Logistic Function (http://en.wikipedia.org/wiki/Generalised_logistic_function):

Eq. 5 $$Y(t) = \mathrm{A} + \frac{\mathrm{K-A}}{\left(1+\mathrm{Q}\cdot \mathrm{e}^{-\mathrm{B(t-M)}}\right)^{1/\mathrm{v}}}$$

where *A* is lower asymptote, *K* is upper asymptote, *B* is growth rate, *Q* is a parameter depending on Y_0, *v* affects near which asymptote maximum growth occurs, *M* is the temperature value for maximum growth. We set *A* = 0, *K* = 75, *B* = -0.6074067 (estimated), *Q* = 30, *v* = 0.04 and *M* = 7.35642 (estimated). The parameter values were partly chosen to adapt a suitable shape. Estimation was done with the function for Nonlinear Least Squares (nl) in Stata (www.stata.com). This yields the following relation between temperature and tree mortality rate,

Eq. 6 $$Y(t) = \frac{75}{\left(1+30\cdot \mathrm{e}^{-0.6074067\cdot(\mathrm{t}-7.35642)}\right)^{25}}$$

Figure 2 shows data points and fitted function for the relationship between temperature and the share of trees that develop PWD. Clearly, there is a threshold temperature somewhere between 15 and 16°C below which PWD does not develop. In our function, mortality levels out at 75 % (upper asymptote). Under conditions favourable to the nematode, tree mortality would definitely be higher and in some situations as high as 100 %. However, the function form and level at the right end temperature scale is not very relevant in the Nordic climate. Furthermore, it is important to note that tree mortality likely also depends on such factors as tree species, tree age, tree size and soil moisture to mention a few.

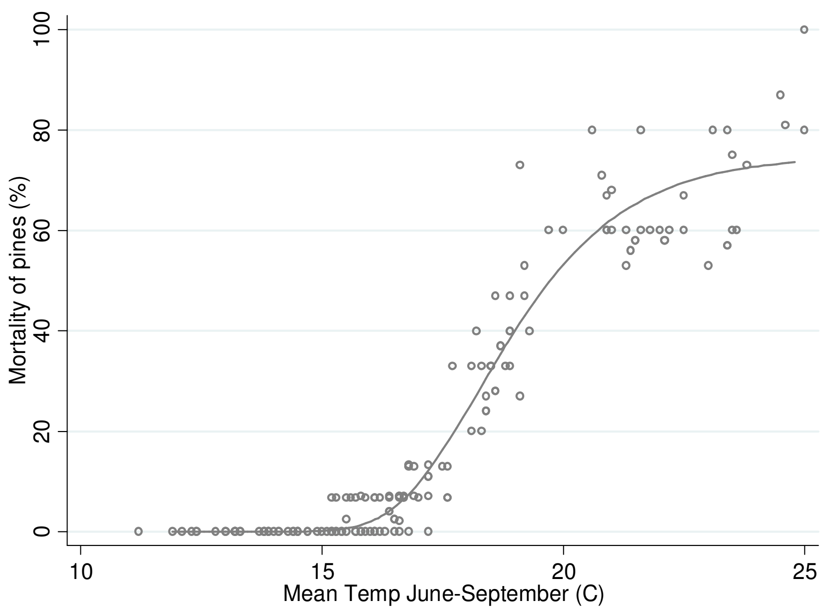

Figure 2 Data points and fitted function for the relative share of infested trees that develop Pine Wilting Disease. Data source: Jordbruksverket. 2008. Konsekvensanalys av angrepp av tallvedsnematod i svensk skog. Rapport 2008.

2.3.6 Simulation repetitions and statistical treatments

Each simulation starts from an entry infestation of PWN , and runs for 50 years to record accumulated area in the eradication and observation zones, as well as eradication success when applying the PWN survey (Magnusson et al., 2007) and the contingency plan (Jordbruksverket, 2008a). The stochastic 50-year simulations were repeated 250 times, and average values for relevant variables were calculated. All results presented in later sections are based on averages from the simulations.

Due to matrix size limitations in R, only 185 simulations succeeded, and these were restricted to a time period of 31 years. Results for the 31 first years have been extrapolated to reach 2050, using the following function

Eq. 7 $Y(x) = e^{a \cdot x^b}$

where *x* is years and *a* and *b* are parameters to be estimated. Estimated coefficients for *a* and *b* are shown in Table 2.

Table 2 Parameters for extrapolation of results.

Variable	parameter	coefficient	SD	t-value
N of trees	a	0.526	0.008	69.1
	b	1.409	0.036	39.2
Area	a	0.409	0.005	89.1
	b	1.610	0.024	66.6

2.4 *Economic valuation model*

2.4.1 Costs due to foregone income when felling existing forest

The extraordinary and premature harvest in the eradication zone and the harvesting restriction in the observation zone represents a cost to the land owner. This cost has two elements: 1) the loss of future income from living trees in existing forest stands, and 2) the loss from postponing establishment of new forest. The first is calculated as the net present value (NPV) of future expected net income from existing forest, subtracting net income from harvesting now, while the latter is the interest on the value of bare land used for forestry for all future for the period until forest can be established again.

We refer to the value of the existing forest as stocking value (SV) and the value of bare land used for forestry as land expectation value (LEV). The sum of stocking value and land expectation value is referred to as forest value (FV), e.g. the value of forested land used for forestry for all future (see e.g., Buongiorno & Gilless, 2003). Eq. 8 and Eq. 9 shows Land Expectation Value and Forest Value, respectively.

Eq. 8 $$LEV = \left[H_n \cdot (1+p)^{-n} + \sum_{x=0}^{x=n}(D_x - c_x) \cdot (1+p)^{-x}\right] \cdot \left[\frac{(1+p)^n}{(1+p)^n - 1}\right]$$

Eq. 9 $$FV_q = \sum_{x=q}^{x=n}(D_x - c_x) \cdot (1+p)^{q-x} + (H_n + LEV) \cdot (1+p)^{q-n}$$

where H_n is income from harvest in year n, p is interest rate, D_x is income from forest management in year x, c_x is cost of forest management in year x and q is stand age.

The loss related to postponing the land expectation value, *LEVloss*, is calculated as

Eq. 10 $$LEVloss = \frac{\left[LEV \cdot (1+p)^t\right] - LEV}{(1+p)^t}$$

where LEV is the land expectation value, p is real rate of return and t is the length of the postponement.

In addition, the premature harvest leads to loss of the stocking value. The cost of this is calculated as FV less LEV as harvested timber may not be utilized.

There will be strong restrictions on harvest in the observation zone. Generally, harvest is prohibited. In case any wood is harvested, it must be either destroyed by burning or buried at site, or heat treated before transport. We estimate the cost of the harvest restrictions as the economic loss due to postponing harvest for a twenty year period. In the same manner as for the loss related to maintaining the eradication zone, the economic loss of postponing harvest in the observation zone can be calculated as

Eq. 11 $$FVloss = \frac{[FV \cdot (1+r)^t] - FV}{(1+r)^t}$$

where FV is the land expectation value, r is real rate of return and t is the length of the postponement.

Harvest restrictions in the observation zone will to some extent lead to over-maturing of stands that are already mature. Growth decreases and risk of damage increases with high age in stands, and the value is likely to decrease. We have not valued and included loss due to this in our estimates.

All valuations of forest land are done with Bestverd v2.0 (Gobakken & Svendsrud, 2004) which is based on Svendsrud (2001).

2.4.1.1 Assumptions at forest level for calculation of LEV for forest land

Public calculations are normally based on a risk free 3.5 % rate of return. Therefore, 4 % real rate of return is commonly used in long term public projects with low risk. However, the present harvesting level in Norwegian forestry is adjusted to a much lower rate of return than this. Eriksson *et al.* (2008) applied a 2.5 % rate of return in their analysis of economic consequences of the Swedish contingency plan for the PWN. We thus apply three different rate of returns, respectively 2, 3 and 4 % real rate of return.

The distribution of area on site index[1] is relatively even between counties (Figure 3). We thus assume that the same price level for roundwood and forest operations apply to all counties.

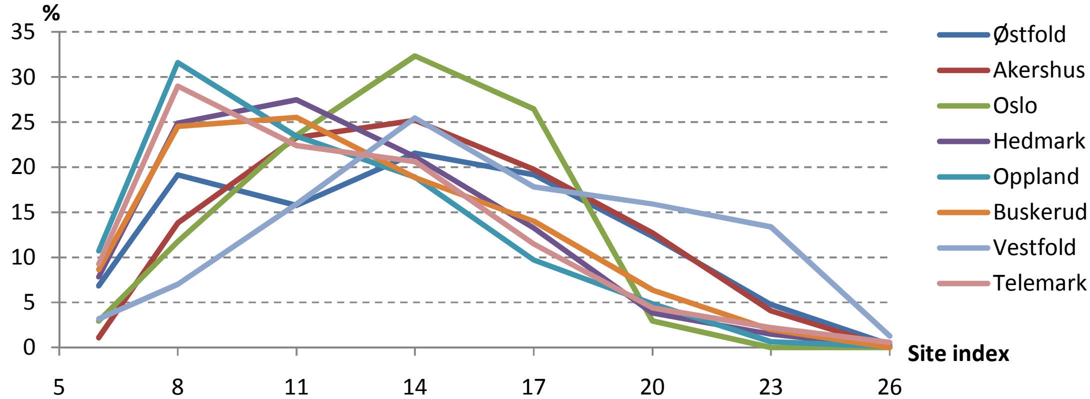

Figure 3 Site index distribution for relevant counties.

The LEV calculations gives an estimate of the loss of value due to the extra-ordinary harvesting and is based on future expected prices. We use statistics from Statistics Norway on roundwood prices for the period 1996 to 2008. Roundwood prices are shown in Table 3.

Table 3 Average prices (per m^3) for pulp and sawlogs weighted by sales volume for the period 1996-2008 for spruce, pine and hardwoods.

	Pulp			Sawlogs		
County	Pine	Spruce	Hardwood	Pine	Spruce	Hardwood
Østfold	202	241	217	370	400	435
Akershus	202	237	204	391	415	405
Oslo	184	238	244	387	385	-
Hedmark	199	232	224	407	422	396
Oppland	202	245	250	394	414	431
Buskerud	200	250	223	399	404	446
Vestfold	201	247	200	421	411	462
Telemark	198	255	210	389	397	429
Mean	200	242	214	397	412	436

Silvicultural costs of reforestation are based on statistics from Statistics Norway. Table 4 shows seedling costs and density for 2008. The average cost for seedlings was 4.6 NOK in 2008. This is somewhat greater than the average cost for the period 1996 to 2008. However, plant costs increased throughout the period, and we hence apply a plant cost of 5 NOK/plant.

[1] Site index expresses the inherent growing conditions through tree height at a certain age. Norway uses the H_{40}-system , i.e. tree height of dominant trees at age 40. See for instance (Tveite, 1977)

Planting density in 2008 was 1640 plants per hectare, which is slightly less than average for the period 1996-2008.

Table 4 Reforestation: Area, number of seedlings and costs for 2008. All costs in NOK.

	Area (ha)	Seedlings (in 1000)	Total cost (in 1000)	Density (N/ha)	Unit cost (NOK/pl)	Area cost (NOK/ha)
Østfold	456	882	4 221	1 940	4.8	9 260
Akershus/Oslo	563	1 064	5 080	1 890	4.8	9 030
Hedmark	2 935	5 245	21 700	1 790	4.1	7 390
Oppland	2 538	3 784	16 893	1 490	4.5	6 660
Buskerud	1 159	1 880	8 990	1 620	4.8	7 760
Vestfold	591	854	4 644	1 450	5.4	7 860
Telemark	918	1 276	7 233	1 390	5.7	7 880
Total	9 159	14 985	68761	1 640	4.6	7 510

Combining the above information with recommendations on planting densities in public regulations (*Forskrift for bærekraftig skogbruk, FOR-2006-06-07-593*), we arrive at reforestation costs as presented in Table 5. Reforestation costs for pine do not apply in our case, as only natural regeneration is assumed.

Table 5 Recommended and minimum reforestation density (plants/hectare) according to public regulation (FOR-2006-06-07-593), and estimated reforestation costs (NOK/hectare) for spruce and pine in different growing places.

	Spruce/hardwood dominated forest			Pine dominated forest		
	G26-G20	G17-G14	G11-G6	F20-F17	F14-F11	F8-F6
Recommended density	3000-1800	2300-1300	1400-600	3400-1900	2400-1200	1300-800
Minimum density	1500	1000	500	1500	1000	500
Average density	2400	1800	1000	2650	1800	1050
Cost	12000	9000	5000	13250	9000	5250

2.4.1.2 Assumptions at stand level for calculation of LEV for forest land

Operating costs are calculated according to Dale *et al.* (1993) and Dale & Stamm (1994). See Appendix 1. These functions are based on data for individual trees from spruce stands, but we apply them to the average tree and all tree species. The potential bias in estimated costs is most likely negligible at the aggregate level.

We use registered number of stems and stocking volume at sample plot level, rather than expected tree number and volume at optimal harvesting time. The basis is a machine cost of 700 NOK/hour and a load size of 15 m^3. Average estimated costs are shown in Table 6. Total average cost for felling and hauling is 104 NOK/m^3, with standard deviation 29.5 and a maximum and minimum of 36.5 NOK/m^3 and 308 NOK/m^3, respectively.

Table 6 Expected total operating costs (felling and hauling) for stands older than age class[2] 3 calculated with Dale *et al.* (1993) and Dale & Stamm (1994).

	Site index								
County	6	8	11	14	17	20	23	26	Total
Østfold	106	97	95	93	86	89	72	83	92
Akershus	107	105	110	93	86	80	75	.	94
Oslo	125	122	92	106	94	74	.	.	100
Hedmark	147	126	106	97	87	83	79	83	110
Oppland	133	121	103	94	86	81	71	79	109
Buskerud	124	112	100	90	86	82	80	.	101
Vestfold	103	88	102	103	91	93	84	75	95
Telemark	130	110	104	94	92	94	78	94	104
Total	134	118	104	95	88	85	78	86	104

The proportion of sawlogs at the individual sample plot is set to the average for the region for each species. The region average is based on statistics (Statistics Norway, http://www.ssb.no/english/subjects/10/04/20/) on traded volumes of different assortments in the period 1996 to 2008 (Table 7).

Table 7 Average proportions of sawlogs for pine, spruce and hardwoods for the period 1996 to 2008 based on total sales volume.

County	Pine	Spruce	Hardwood
Østfold	0.54	0.46	0.14
Akershus	0.60	0.50	0.11
Oslo	0.28	0.46	0.00
Hedmark	0.49	0.45	0.03
Oppland	0.47	0.42	0.10
Buskerud	0.45	0.36	0.11
Vestfold	0.63	0.36	0.09
Telemark	0.58	0.37	0.04

2.4.1.3 The value of a tree

For scenarios without any measures against the PWN, a share of the pine trees will get PWD and die. However, development of PWD is dependent on temperature increase and will only occur under climate change (scenario A2). Trees with PWD will be unevenly spread

[2] Age class is a relative measure of tree age where age is related to site index in order to compare stands of the same age but on different sites.

geographically, and the PWN model only provides us with an estimate of the number of trees that die from PWD. We use the calculated stocking values, the volume share of pine and the number of pine trees in each sample plot to estimate the value of a pine tree. The average value of a pine tree in the data set is 34.4 NOK with [32.7, 36.1] 95% confidence interval.

2.4.1.4 Alternative land use

During the time when there are restrictions on forest management, forest land could have been used to produce biomass for bioenergy from hardwoods. However, the value of wood for bioenergy is relatively low at present, and we do not include any specific value of this alternative land use in our calculations.

2.4.2 Assumption regarding the extra ordinary harvest

2.4.2.1 Costs of felling existing forest

A harvesting cost is already set for all areas classified as forest. We assume that this cost also applies in the case of the extra ordinary harvest that takes place in case of introduction of the PWN. It could be argued that the forwarding distance would change compared to the normal harvesting pattern, where we assume the same distribution of forwarding distances as in the normal case. Also, as harvested timber in this case will be destroyed rather than utilised for industry purposes, handling is easier, which will probably also decrease the cost. However, all parts of the tree must be collected for destruction and this will increase the hauling cost. We choose to apply the already calculated operating costs from the LEV calculations for all forest areas older than age class 2 (see previous section on stand level assumptions).

Large areas of young forest will need a combination of harvesting of larger remaining trees and complete cleaning of smaller trees. The cost of normal young growth tending is according to Statistics Norway (http://www.ssb.no/skogkultur/tab-2009-06-04-02.html) slightly less than 3000 NOK/ha (average for period 1999 to 2008). In addition to felling trees, they must be collected for destruction. Thus, the area cost for cleaning young stands is set to 6000 NOK/ha. We add this cost to the normal operating cost at stand level for the larger trees to find the overall area cost of the complete harvesting.

2.4.2.2 Costs of felling trees in other areas than forest

Table 8 shows average number of trees and volume per hectare for land use classes other than forest. Assumptions regarding the cost of removing trees in these areas will be based on this. Tree density is in most of these areas much lower than in a forest.

Table 8 Average (area weighted) volume and number of trees for different land use classes, and number and share of sample plots in each land use class.

	Volume m^3/ha	Number of stems	No of sample plots	Share of total
Other forest	28.4	253.3	697	9.2 %
Other	2.3	25.9	172	2.3 %
Settlements	1.5	9.3	464	6.1 %
Grazing land	6.4	19.9	33	0.4 %
Farm land	0	0	571	7.5 %
Forest	105.6	664.1	4771	62.7 %
Wetland/mire	0.8	15.1	903	11.9 %
Total	69.4	444.7	7611	

The most cost-efficient harvesting system for other areas than forest is probably manual harvesting rather than machine. Forwarding/hauling could be performed with forwarders or with farming tractors with suitable trailers. Tree dimensions will most likely differ from normal forest. Thus, we assume that felling itself will cost 100 NOK/m^3 and transport 50% more than normal prices in thinning. Assuming that thinning costs approximately 200 NOK/m^3, this yields a total cost of removing trees of 100 + 200*1.5 = 400 NOK/m^3.

The exception from these assumptions, is areas classified as ”Other forest”. These are unproductive areas, but both stocking volume and the number of stems are higher than other non-forest areas. In “Other forest”, we assume that harvesting costs lies between those in forest areas and other areas. Total harvesting costs in ”Other forest” is set according to normal thinning, approximately 200 NOK/m^3.

2.4.2.3 Cost of treating stumps with pesticide

All stumps must be treated with a suitable pesticide. The unit cost of pesticides is set to 50 NOK/liter. Approximately 0.1 liter is needed per stump, which gives a pesticide cost of 5 NOK/stump. The average number of conifer stumps is 445 per hectare, which leads to a pesticide cost of 2225 NOK/ha.

In commercial forestry, pesticides or even fertilizers are often used to prevent spreading of pathogens like e.g. *Heterobasidion annosum*. Treatment is often performed by harvesters at time of harvest. The cost of such treatment by machine is approximately 5-10 NOK/m^3 (http://www.skogkurs.no/Resyme/3/res3.html). With average stocking of 69.8 m3/ha, this suggests a labour cost of 700 NOK/ha when using the upper end of the interval. This should also then cover treatment of stumps from trees that are manually harvested. Total cost of stumps treatment ends up at 3000 NOK/ha.

2.4.2.4 Volume of wood for destruction

One eradication zone is approximately 2827 hectares and the average stocking in the full data set is 69.3 m^3/ha (Table 8). This sums up to 195 938 m^3 of roundwood, i.e. excluding branches and tree tops. The average tree is 130 liters for spruce and 310 liters for pine. Using data from Lehtonen et al. (2004), we find that the other tree parts (foliage and branches) constitutes approximately 40 and 17 % of the total above ground biomass (ex. stump), for stands of spruce and pine, respectively. For trees that do not grow in a stand, these percentages are probably higher. Therefore, we add 50 % to the roundwood volume and assume that the total volume of wood for destruction is ~300 000 m^3.

2.4.2.5 Machinery and capacity constraints

We have already set the costs for forest operations, but the judgement of machinery and capacity is relevant for planning and organisation of actions in the contingency plan.

In large forest operations with easy handling, a production of 150 m^3 per 7.5 hours shift is expected (personal communication Einar Østhassel/MEF - Norwegian Association of Heavy Equipment Contractors). In the extra-ordinary situation of a PWN detection, we assume it would be possible to run three shifts in a day. This yields a production of 450 m^3/day. However, with such running schedules over long periods of time, one could expect some unproductive time for maintenance. We thus assume an average running time of 20 hours/machine*day and a total production of 400 m^3/machine*day. Thus, 490 machine days are needed for one eradication zone. With 20 machines, the job could be done in a little less than four weeks.

2.4.2.6 Disposal of wood

All harvested biomass should be destroyed. This is most efficiently handled by burning the wood. There is very little experience with burning such amounts of fresh wood, and thus it is difficult to estimate the amount of time it will take to complete burning of all wood. Furthermore, fresh wood does not easily burn and a fair amount of ignition fuel is likely needed. The estimates of total costs related to disposal and burning of wood will hence be very coarse.

Burning could be done in different ways. We believe a practical system would be to work up roundwood into ranks or long piles, and burn these. A large, open field in the proximity of a larger water source would be a preferable place to establish burning sites, although this might not be possible in all places. Also, restrictions on transport within the eradication zone will necessitate a large amount of burning sites.

Assuming log length of 5 meters in average, a log pile of 4 meters height and 100 meters length, a volume share of solid wood of 65 % would give roughly 1 300 m^3 in each pile. The suggested pile size suggests a need for 230 piles, or on average one for every 12 hectares of land. We assume that a pile of this size can be completely burned in a week (7 days). This is a very uncertain estimate.

To ignite the wood piles efficiently, diesel is applied. Assuming a consumption of 0.5 liter/m^3 gives a total consumption of 150 000 liter. With a cost of 5 NOK/liter, the total cost is 750 000 NOK and the area cost 265 NOK/ha.

Burning sites must be surveyed by a trained and well-organised crew, and possibly also a helicopter with equipment for fire control and extinguishing. The necessary personnel could possibly be drawn from the Norwegian civil defence (www.sivilforsvaret.no) which have some training in and equipment for controlling fires. Man cost is set to 175 NOK/hour. Each pile is surveyed by two men at all times, implying 6 men per day and pile. This gives a cost of 58800 NOK/pile, a total cost of 13524 000 NOK and an area cost of 4783 NOK/ha.

The cost of helicopter readiness is approximately 22 000 NOK/day (incl. VAT) and approximately 7500 NOK/hour flying time when moving or fire-fighting. If for example 20 piles burns simultaneously, it takes 11.5 weeks to complete burning. The total cost of helicopter readiness is then 1 771 000 NOK, and the area cost is 626 NOK/ha.

Burning sites must afterwards be covered with soil both to cover ashes and for aesthetical reasons. This can be done with diggers or large shovels. One machine could cover something in the range of 500-1000 m^2 of land in a shift, based on easy terrain and soil being shipped in by truck. This means one burning site is covered in each shift. In addition to the digger, a truck is needed for hauling soil and another digger is needed to load the truck. Assuming soil is found nearby the burning site and the cost of machinery is 700 NOK/hour, the total cost of covering one burning site is 15 750 NOK. With the above-mentioned number of piles and land areas, the average cost is 1285 NOK/ha.

Burning all wood would imply several risk elements. There will most likely be a large ecological risk related to heat damage at burning sites. Also, even with a suitable fire control system in place there will be a risk of fire spreading from burning sites. It is, at this point, impossible to estimate the cost of such risks.

An alternative to burning is chipping. This would require chipping on site and transportation in closed containers to an industry site. Containers are at present the main means of chip transport and would thus need only minor adjustments to comply to the relevant regulations. At present in Norway, the cost of chipping is in the interval from 30 to 70 NOK/m^3 depending on equipment and chip quality. With an average cost of 50 NOK/m^3, the cost of chipping would be 5305 NOK/ha.

Transportation of chips is strongly dependent on transport distance, and can be calculated using Eq. 12.

Eq. 12 $TC = 12.299 + 0.2537 * km$

We assume an average transport length of 250 km, which gives an average transport cost of 76 NOK/m^3 of chips. If we assume that total volume for chipping is 300 000 m^3, the total volume of chips will be approximately 750 000 m^3. This gives a total cost of 57 000 000 NOK, and an area cost of 20 160 NOK/ha.

Productivity in chipping depends heavily on the size of equipment, and ranges from 5 m^3/hour for farm tractor carried chippers to 120 m^3/hour for large, specialized chippers (referring to equipment that exists in Norway today). In Norway, there exist maybe 10 chippers with an average capacity of approximately 100 m^3/hour. With all this equipment in place, it would thus take approximately 300 hours, or 20 days running two full 7.5 hour shifts per day, of chipping to process harvested wood in one eradication zone. Compared to burning of wood on site, there would be no ecological risks related to the chipping of wood.

Sales volume of forest wood chips was approximately 250 000 m^3 in Norway in 2009. However, there is also a large amount of green waste, scrap board and household waste used for power heat plants which could be substituted with chips. We do not give the chips any value, although the chips would necessarily represent a value if used in the heating season. This would also radically change the cost estimates.

The different factors and costs related to destruction of wood is summarized in Table 9. It is important to remember that assumptions concerning burning of wood are uncertain.

Table 9 Factors and cost in wood destruction.

Factor	Cost (NOK/ha)
Burning	
Fire ignition (mainly diesel)	265
Fire control, man power	4 783
Fire control, helicopter	626
Covering burning sites	1 285
Risk of fire spreading	?
Ecological damage and risk	?
Total area cost of burning wood	6 959
Chipping	
Chipping	5 305
Transport	20 160
Total area cost of wood chipping	25 465

2.4.3 Other assumptions

2.4.3.1 Surveillance and sampling

The cost of nematode sampling is assumed to be 1700 NOK per sample in the general survey and 1400 NOK per sample for the specific survey in the observation zone in the case of an attempt to eradicate the PWN (personal communication Christer Magnusson, Bioforsk). The general survey will include 400 samples per year. In addition to the sample cost, we assume an hour of work for collecting each sample. With labour cost of 175 NOK/hour, the total cost of the general survey is 750 000 NOK/year. The specific survey in the case PWN is detected will consist of 3000 samples in total for the eradication and observation zones. The 3000 samples are planned to be taken as quickly as possible, preferably within two years of detection. This gives an area cost of 34 NOK/ha.

2.4.3.2 Control and removal of host trees in eradication zone

Under the time when restrictions on forest management are in place, the eradication zone will be surveyed for presence of host trees for PWN. We assume a complete survey every 5 years, with removal of any host tree that has established since previous survey. We use the same cost as for tending of young stands, approximately 3000 NOK/ha. The NPV value of three surveys is 7407, 6746 and 6158 NOK/ha for interest rates 2, 3 and 4 % respectively.

2.5 Climate change scenarios

Table 10 shows historic (30 year) mean temperature for some geographic places within the region of our data set. This period, previous 30 years, is also used as the reference, i.e. current climate conditions. There is a decreasing temperature gradient from south-west to north-east.

Table 10 Mean temperatures for the period 1961 – 1990 for some geographic places in the modelling region.

County	(north-west) Oppland	(north-east) Hedmark	(central) Oslo/Akershus	(south-east) Østfold	(central) Buskerud	(south-west) Vestfold
Place	Fagernes	Trysil	Blindern	Sarpsborg	Lier	Sande
June	12.5	13.0	15.2	14.5	15.7	15.5
July	14.5	14.0	16.4	16.0	17.1	16.8
August	13.0	12.5	15.2	15.0	15.7	15.6
September	8.5	7.5	10.8	11.1	11.3	11.5

Downscaled and regional available climate change scenarios for Norway are IS92a for the years 1980-2049, or A2 and B2 for the period 2071-2100. We use climate change scenarios for Blindern/Oslo (59°56'N 10°43'E, 94 meter a.s.l.) for the period 2001-2049 according to emission scenario IS92a. Blindern is a fairly warm place, but not the warmest in the area of the data set. Temperature data series are downloadable at http://noserc.met.no/effect/dynamic/mapsearch/index.html, or see http://noserc.met.no/effect for a general description.

For the chosen climate change scenario, June to September mean temperature for the places in Table 10 varies between 13 and 16°C in the first part of the period and increases to between 14 and 17-18°C. Figure 4 shows the applied temperature scenario together with a smoothed curve for temperature, which are both applied in the result section. Smoothing was performed with function mkspline in Stata (www.stata.com) with knots every 5 years. The figure also shows tree mortality rate calculated as a function of temperature, according to Eq. 6.

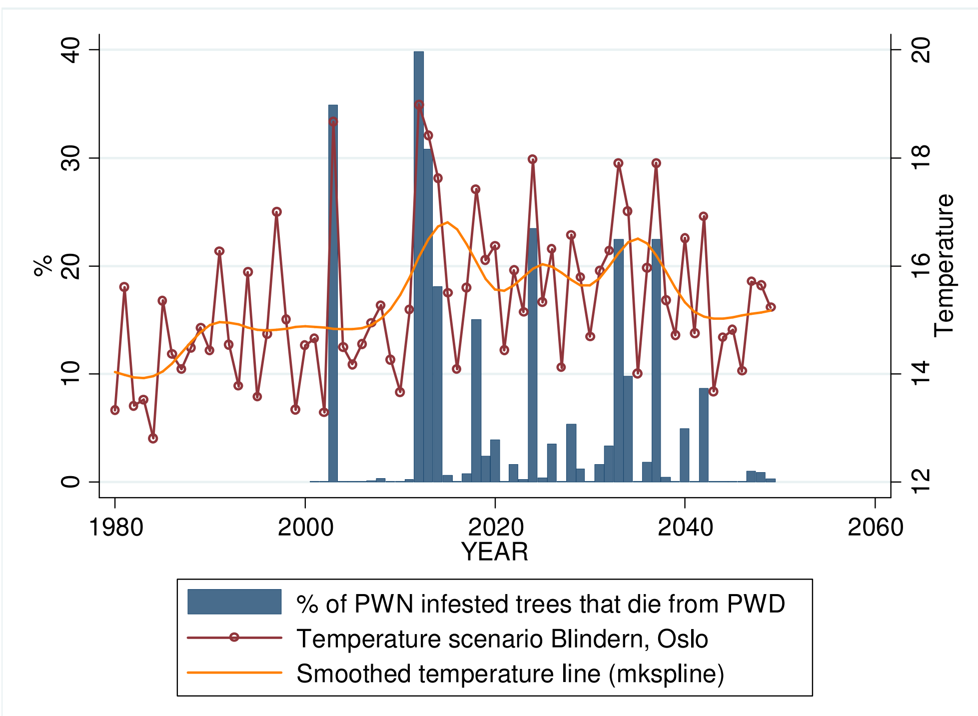

Figure 4 Temperature scenario (IS92a) for Blindern for years 1980-2049, a median smoothed spline for the temperature scenario and tree mortality rate due to PWD as a function of temperature.

3 Results

3.1 Biological modelling

Scenario A - no actions against PWN - leads to a situation as in Figure 5, where the number of trees infested with PWN increases over time. The PWN model is stochastic and the figure also shows 99% confidence intervals for the number of infested trees. In scenario A1 temperatures stay at the present level which hinders PWD from developing. In Scenario A2, future temperature increases and PWD develops in certain years. The accumulated number of trees that die from PWD, is relatively small and ends at 9568 trees. The trees that die are spread over an area of approximately 2900 km^2. This is 0.033 trees/ha, while the average stocking of conifer trees is 444 trees/ha.

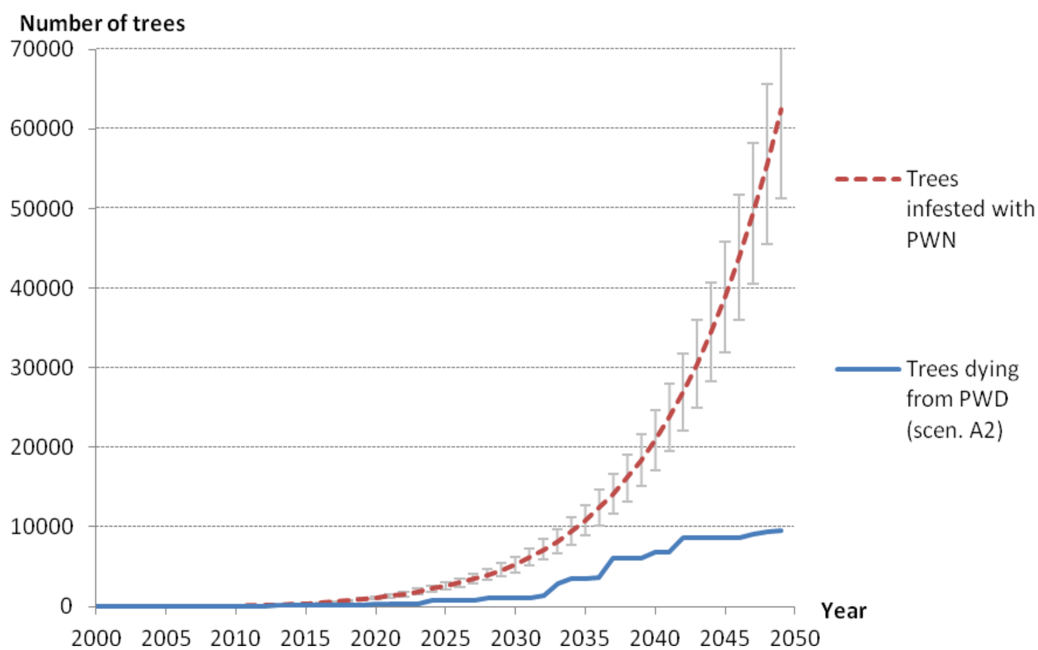

Figure 5 Accumulated number of infested trees (with 99% confidence intervals), and trees that develop and die from PWD. Temperature based on IS92a emissions scenario. 185 simulations.

The number of trees that die is determined by the actual temperature scenario that is used. Hence, a different realization of the temperature scenario would yield different results. A possible alternative would be to use a temperature trend based on the actual scenario, e.g. the smoothed series in Figure 4. Applying a temperature trend rather than the scenario temperature series will in most cases imply removing years with high temperatures where PWD and dying of trees is more likely to occur, and subsequently a much lower estimate of the number of trees that die from PWD. The smoothed trend depicted in Figure 4 leads to 3567 dead trees by 2050.

Under scenario B, Figure 6 shows accumulated area in the eradication and observation zone over a 50 year period under present climate. Thus, this is the estimated result of the Norwegian contingency plan assuming a sampling intensity of 400 samples per year. Clearly, the contingency plan is not able to stop the spreading of PWN.

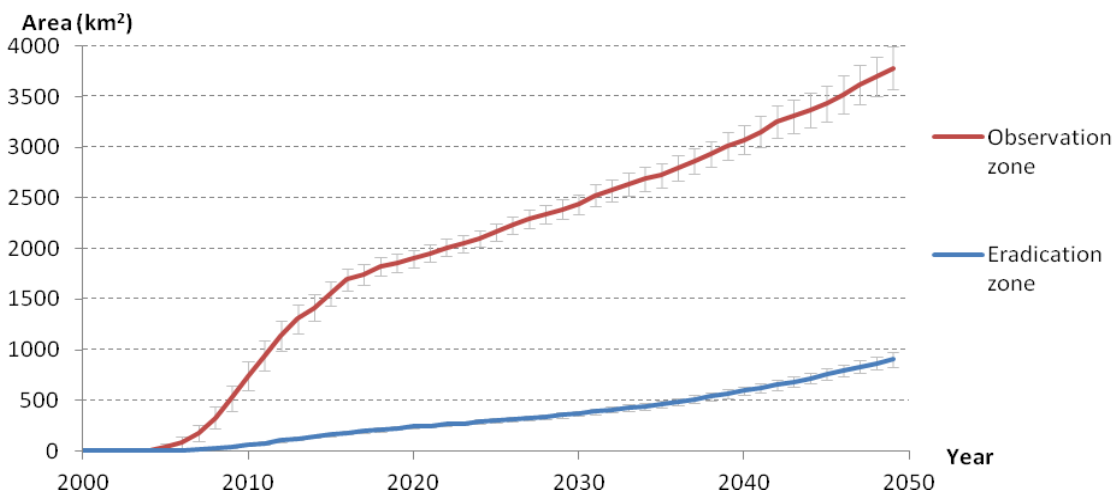

Figure 6 Accumulated area (with 99% confidence intervals) in the eradication and observation zone over a 50 year period as a result of the contingency plan. Present climate. Km^2. 205 simulations.

Due to the low sampling intensity, several years passes before detection of PWN. The initial area is seemingly small in the figure, but this is caused by the numbers in the figure being averages of all simulations. It is not until year 10 that the accumulated area in the eradication zone becomes larger than that of one full eradication zone (28.3 km^2). This happens in year 14 for the observation zone (1228.4 km^2).

3.2 Economic impacts

The direct cost of scenario A2 is low. The value of an average tree in the relevant region has been estimated to 34.40 NOK. Combined with the accumulated number of trees that die from PWD, total costs accumulates to 157 459, 110 287 and 77 907 NOK, respectively for 2, 3 and 4 % interest rate.

Different cost elements for the eradication and observation zones in scenario B are summarized together with total costs of one eradication measure in Table 11. The results are based on the average distribution of land use classes and, as such, cover the entire region.

Table 11 Summary table for cost assumptions according to measures in the PWN contingency plan. Net present value at time of contingency implementation and in NOK/ha.

Zone	Level	Cost factor	r = 4	r = 3	r = 2
Eradication zone	Stand level	Land expectation value loss	513	881	1 033
		Stocking value loss	8095	9 719	10 513
		Harvesting cost	7 980	7 980	7 980
	General	Treating stumps with pesticide	3 000	3 000	3 000
		Cleaning of host trees (NPV, 50 years)	6 158	6 746	7 407
		Disposal of wood	6 959	6 959	6 959
Sum for eradication zone			32 705	35 285	36 892
Observation zone		FV loss	4 913	5 219	4 470
		Survey	34	34	34
Sum for observation zone			4 947	5 253	4 504

The eradication zone has an area cost of approximately 33 705 NOK/ha to 36 892 NOK/ha, depending on the interest rate applied. The cost/loss related to stock value is largest for lower interest rates because lower interest rates implies longer rotations and the existing forest hence is further from its optimal rotation age. The loss of forest value in the observation zone has a different pattern. The loss increases with decreasing interest rate from 4 to 3 %. At 2 % interest rate however, the FV loss is less than for 3 and 4 %. At 3 and 4 % interest rate, a larger share of the forest is mature and ready for harvesting than at 2 % interest rate. Thus, the economic loss due to postponing harvest is greatest for the higher interest rate levels.

The total cost of one eradication measure (28.3 km^2 eradication zone and 1228.4 km^2 observation zone) is shown in Table 12. The NPC for all costs over 50 year horizon amounts to 700, 745 and 657 million NOK for 4, 3 and 2 % interest rate respectively.

Table 12 Total cost of the main measure according to the PWN contingency plan: a 3 km radius eradication zone and a 17 km radius observation zone. Net present value (NOK) at time of contingency implementation.

Zone	r = 4	r = 3	r = 2
Total cost eradication zone (radius 3 km = 2827.4 ha)	92 470 873	99 763 944	104 309 237
Total cost observation zone (radius 17 km = 122836.3 ha)	607 671 176	645 259 084	553 254 695
Total cost of one action (3+17 km)	700 142 049	745 023 028	657 563 932

The results from the simulations in the PWN model under scenario B (Figure 6) are combined with the area costs (Table 11) in Figure 7, which shows the progress in annual cost (NPV) of the proposed measures for eradication of PWN in the contingency plan.

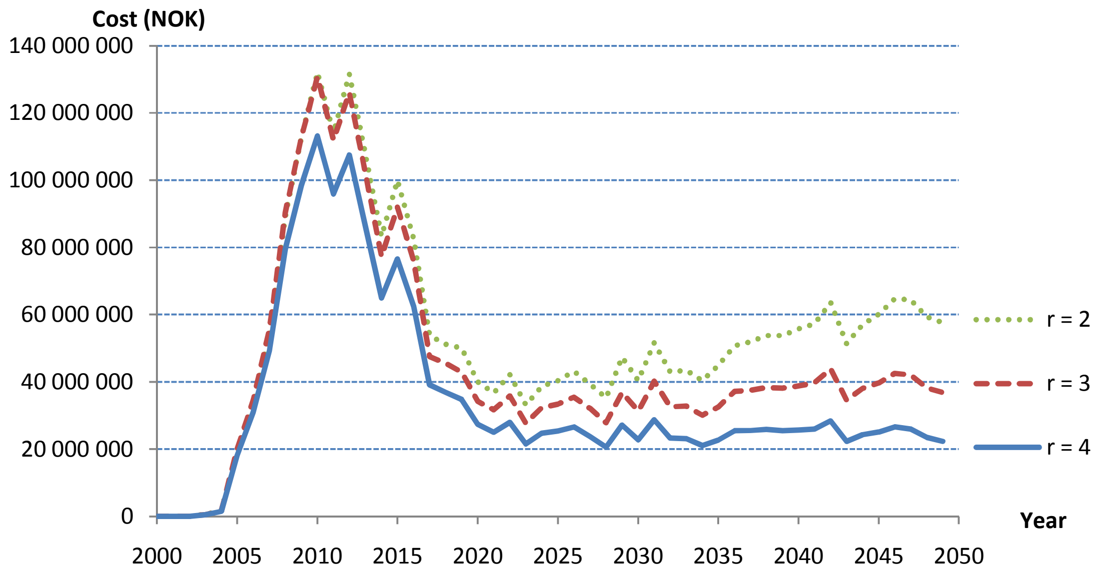

Figure 7 Annual cost (NPV) of measures for eradication of PWN over a 50 year period for different interest rate (2, 3 and 4 %).

The NPV of the accumulated costs of the contingency plan is 2.7, 2.2 and 1.7 billion NOK, for interest rates 2, 3 and 4 % respectively. The differences in total costs can mainly be explained by the discount rate effect, with less emphasis on future costs with increasing interest rate.

Largest costs are related to forest land. Regions with a large share of forest land, e.g., in Hedmark and Buskerud counties (see Table 1), will thus experience the largest costs if PWN is detected there.

4 Discussion

4.1 Importance of assumptions

The economic valuation of forest land is based on tested and well-behaving functions for forest growth and hence fairly reliable. The factor that is most difficult to assess is future roundwood prices, which are also important for the result. The valuation model also assumes optimal forest management for future forest rotations. It is uncertain how strongly deviations from this will affect the results. The largest cost related to forest land is in any case the loss of the standing stock in the eradication zone. The valuation of this forest is to a lesser degree dependent on the factors mentioned above.

Most likely, cost assumptions other than those related to the forest valuation are more uncertain. Burning of wood as part of the contingency measures is especially uncertain as there is a lack of experience regarding this.

4.2 Robustness of the results

The damage and cost under scenario A may seem small. A crucial factor for the damage is the number of trees that are infested by the nematode and hence may develop PWD under favourable climatic conditions. This is partly controlled by the infestation rate. In Økland et al. (2010), based on the existing literature this rate was set to 0.25 with sensitivity testing in the interval 0.1-0.4. However, *in a forest area in Japan a vector beetle (Monochamus alternatus) on average caused one to two trees to die by transferring the nematode when feeding* (Jordbruksverket, 2008a:30). This implies an infestation rate of 2, and is caused by *M. alternatus* being a more efficient vector than *M. sutor*. If we apply an infestation rate of 2, the accumulated number of dead trees becomes 76 545. The NPV of accumulated costs are in this case 1.26, 0.9 and 0.6 million NOK (2, 3 and 4 % interest rate). Even with a high infestation rate, total costs are relatively small, at least compared to the costs of the contingency plan.

Even if we combine a high infestation rate with a higher mortality rate than suggested by Eq. 6, costs are still modest. Assuming a mortality of 100 % and an infestation rate of 2, the number of trees that die is ~500 000 with an associated cost of 7.5, 5.0 and 3.4 million NOK (NPV, 2,3 and 4% interest rate).

Development of PWD is dependent on temperature and thus dependent on the climate change scenario that is chosen. An alternative to using the scenario directly would be to smooth the scenario to produce a temperature trend instead of the greatly fluctuating scenario. However, any such trend scenario would then avoid the temperature peaks in the scenario. Applying our function for the relation between temperature and PWD would produce very low mortality numbers and as such be of little interest in our setting.

A large part of the cost in the eradication zone is the loss of the standing timber (see Stocking value loss in Table 11). Salvaging some of the most valuable roundwood could significantly reduce costs. The average value of sawlogs in age classes IV and V if cut at premature (present) age using the average stocking and age structure, is approximately 4000 NOK/ha. The average volume of timber saved is 41 m^3/ha. This would hence save ~11-12 % of the costs in each eradication zone depending on the interest rate.

4.3 Effects not included

At this point, we do not account for loss in the economic value of *nonmarket ecosystem services, such as landscape aesthetics, outdoor recreation, and the knowledge that healthy forest ecosystems exist* (Holmes, Aukema, Von Holle, Liebhold, & Sills, 2009:18), which have been pointed out to be important. Neither do we value potential losses in biodiversity. The potential effects of the proposed measures on the mentioned elements are likely enormous.

In the case of detection of PWN in Norway there will be export restrictions on wood based products that are not heat-treated. Relevant products are fire wood, roundwood and chips. The export of these products is modest and in all cases less than import (see http://www.ssb.no/emner/09/05/uhaar/tab/t21.html). It should thus be possible to find markets for these products and volumes in national markets.

An attempt to restrict or stop dispersal of the PWN in Norway is strongly dependent a successful organisation of the necessary actions. A critical part of the contingency plan is the extra ordinary harvest. Clearly, the key issue is the mobilisation of the work force performing all necessary operations, especially machinery for forest operations.

4.4 The findings compared to previous studies

The calculations of potential costs of PWD in Sweden (Jordbruksverket, 2008a) did not include a spreading model and were focused on a comparison of eradication and containment of PWN. We are aware of few studies of forest damage caused by insects or plants in an economic context, and generally it seems that *most bioeconomic models in pest management consider only short-term revenues* (Sharov & Liebhold, 1998:833). Some exceptions are the bioeconomics of managing the spread of Gypsy moth in USA (Sharov & Liebhold, 1998), timber product market and trade implications of the Asian *Lymantria* in the United States (Prestemon, Turner, Buongiorno, Zhu, & Li, 2008), impacts of the *Sirex noctilio* in timber supply and harvesting in eastern Canada (Yemshanov et al., 2009), the effects of bark beetle disturbance on timber production and carbon sequestration under climatic change (R. Seidl, Rammer, Jager, & Lexer, 2008; Rupert Seidl, Schelhaas, Lindner, & Lexer, 2009), . However, some of these works are mainly concerned with the population spread model and others operate at a much aggregated level with *no fine-resolution spatial or temporal information about invasion dynamics and host resources* (Yemshanov et al., 2009:154).

In an analysis of managing the spread of exotic pest species with barrier zones, Sharov and Liebhold (1998:833) found that *the optimal strategy changes from eradication to slowing the spread to finally doing nothing, as the area occupied by the species increases, the negative impact of the pest per unit area decreases, or the discount rate increases*. In our case the area that is occupied is large, but the impact is fairly low. This suggests small efforts to eradicate PWN.

Bogich et al. (2008) presented a model to minimize the costs monitoring and managing an invasive species. They showed the importance of including both monitoring and management costs when making decisions regarding measures and programs. A combination of monitoring and management effort is also considered for PWN; however, for this species under Nordic conditions it seems difficult to find a sufficient combination that is not overriding the capacity of sampling and eradication resources (Økland et al., 2010).

Yemshanov et al. (2009) assessed the impact of *Sirex noctilio* on timber supply and harvesting in eastern Canada and concluded that adaptations in forest operations may mitigate some of the outbreak impacts and may reduce short-term costs, but are unlikely to prevent outbreaks overall.

5 Conclusions

This study illustrates that it is possible and useful to combine a biological model for the dispersal of PWN with economic modelling to estimate the costs of PWN direct damage and management as forgone income of industrial wood harvest. With regard to the objectives of the study we draw the following conclusions:

1. If no contingency measures are introduced under present climate conditions, the economic consequences of a future introduction and spread in Norway of PWN are zero, as no pine trees will develop PWD. Under a likely future climate as specified in chapter 2.5, our model estimates show that less than 300 trees will die per year over the first 50 years, i.e. the costs are also here negligible. The reduction of Norwegian export of wood based products is likely to be limited, and the cost is not calculated.

2. The model used in the study for analyzing the PWN dispersal shows that the present contingency plan (described in chapter 2.1) will not be able to stop PWN from spreading.

3. If the present contingency plan is introduced, the net present value of the accumulated costs (measured as reduced income from industrial timber production) of the contingency plan over a 50 year period is 2.7, 2.2 and 1.7 billion NOK, for interest rates 2, 3 and 4 % p.a. respectively. The differences in total costs can mainly be explained by the discount rate effect, with less emphasis on future costs with increasing interest rate. Largest costs are related to forest land. Regions with a large share of forest land, e.g., Hedmark and Buskerud (see Table 1), will thus experience the largest costs if PWN is detected there.

   These costs are losses caused only by reduced income from industrial timber production and the costs of the eradication measures. Other costs caused by e.g. reduced recreation or biodiversity, are not included in the above estimates, but would without doubt be very high.

4. Many of the factors used in the analysis are burdened with high uncertainty, but sensitivity analyses indicate that the main results are rather robust even for drastic changes in assumptions.

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