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ORIGINAL ARTICLE

Combining ecological and economic modelling in analysing a pest invasion contingency plan – The case of pine wood nematode in Norway

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Abstract

Introductions of the pine wood nematode (PWN), which causes Pine Wilt Disease (PWD), have devastating effects on pine forests in regions with susceptible host trees under suitable climate conditions. Norwegian authorities have proposed a contingency plan if PWN is detected in Norway. We compare the costs of implementing this plan with the costs of further spread and damage of PWN under two climate change scenarios: present and the most likely future climate. With the present climate, PWD will not occur in Norway. Under climatic change, the cost of PWD damage is approximately 0.078–0.157 million NOK (0.01–0.02 million Euros) estimated as net present value with 2 and 4% p.a. discount rate. In contrast, the corresponding costs of implementing the suggested contingency plan will be 1.7–2.2 billion NOK (0.2–0.25 billion Euros). These costs are caused by reduced income from industrial timber production and the costs of the eradication measures. Costs related to reduced recreation or biodiversity are expected to be very high, but are not included in the above estimates. 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. The results suggest that there is a need to revise the current PWN contingency plan in Norway.

Keywords: *Bioeconomics, boreal forest damage, Bursaphelenchus xylophilus, climate change, impact assessment, stochastic modelling.*

Introduction

The prospects of extensive damage by pest invasions are increasing and have been used as argument to prescribe strong eradication measures that can stop further spread from the beginning (Lockwood et al., 2007). 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 programmes may be very high (Haack et al., 2010; Hulme et al., 2009; Pimentel, 2002). It is thus of great interest to compare economic costs of alternative abatement strategies with the costs when no abatement strategies are applied.

Pine wood nematode (PWN), *Bursaphelenchus xylophilus* (Steiner & Buhrer, 1934), is a microscopic roundworm that inhabits the wood of pine trees. It is vectored to living trees and to cut wood by longhorn beetles in the genus *Monochamus* (Mamiya, 1984, Togashi & Shigesada, 2006). The nematode is carried in the tracheal system of the beetles and infects trees through feeding wounds made on shoots and branches. Cut wood and weakened trees are infected at oviposition of the beetles. In warm climates and in susceptible hosts the nematode infection of trees cause trees to die in what is known as Pine Wilt Disease (PWD). The nematode is native to North America where indigenous pine species normally tolerate the nematode infection.

For many years PWD has been an increasing problem in East Asian countries where PWN has been introduced (Japan, China, Taiwan and Korea) and is now the most important forest disease in Japan (Mamiya, 1984). The first European

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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 the nematode from spreading and to eradicate it from the EU territory (Rodrigues, 2008). Measures include felling and destruction of weakened pines within the infested area and the establishment of a surrounding host-free buffer zone. Despite these efforts, new infestations were detected outside the demarked area. The nematode has been detected also outside mainland Portugal, that is, in Spain in 2008 and 2010 (EPPO, 2010a, 2010b) and on the island of Madeira in 2009 (European Commission, 2010). The outbreak of PWN in Portugal triggered surveys for the nematode in several other European countries (European Commission, 2000; Magnusson et al., 2007; Swedish Board of Agriculture, 2008a), and outlines of contingency plans have been presented prescribing strong measures for eradication of PWN (EPPO, 2010b; e.g. Norwegian Food Safety Authority, 2007; Swedish Board of Agriculture, 2008a). The likelihood of PWN entering Norway by the pathway of coniferous wood packaging material is high (VKM, 2008). However, PWD is expected to occur only in areas with average summer temperatures exceeding 20°C, and to be rare or absent in cooler climates (Evans et al., 2008; Swedish Board of Agriculture, 2008a). Hence, the presence of the PWN would be difficult to detect in a Nordic climate due to the lack of symptoms of PWD.

In Norway, forest covers about 37%, or 119,000 km^2, of the land area, and pine *Pinus sylvestris* L. currently constitutes 32% of standing timber volume in the productive forest area (Statistics Norway, 2008). A PWN infestation and possible subsequent outbreaks of PWD may potentially cause large biological and economical damage. However, executing the proposed contingency plan may also be costly. When costly strategies are suggested as immediate abatement against PWN, it is important that cost calculations of the alternative of no abatements are based on long-term ecological models of the spread. Rather few studies of forest pests exist combining economy and ecology. Exceptions are studies of Asian Longhorned Beetle and Citrus Longhorned Beetle (Haack et al., 2010), the emerald ash borer (Kovacs et al., 2010), and the costs and ecosystem effects for invasive bark beetles (Økland et al., 2011) and insect herbivores (Gandhi & Herms, 2010). Except for Sharov and Liebhold (1998), it seems that most bioeconomic models in pest management consider only short-term revenues. Previous work has mainly been concerned with the population spread model (see e.g. Prestemon et al., 2008; Seidl et al., 2008, 2009; Yemshanov et al., 2009) or operate at an aggregated level with no fine-resolution spatial or temporal information about invasion dynamics and host resources (Yemshanov et al., 2009). Cost calculations for PWD exist in Sweden (Eriksson et al., 2008), but that study did not include an ecological spread model and focused on comparing eradication and containment of PWN. Kwon et al. (2011) evaluated different preventative silvicultural measures against PWD, but did not consider the costs of these measures.

Our comparative study of economical costs focuses on PWN and the Norwegian contingency plan for eradication of this species. We utilise a combination of ecological and economic modelling in a case study to analyse the cost of alternative pest management strategies for a hypothetical introduction of PWN in Norway. The ecological model simulates the spread of PWN and tree mortality following an infestation of PWN in Norway, both with and without the application of the measures stipulated in the draft contingency plan for Norway developed by the Norwegian Food Safety Authority (2007). The economical model utilises results from the ecological model to estimate the costs of the aforementioned management alternatives. Two main management alternatives (A and B) are analysed. Alternative **A** assumes that no measures are taken, neither to detect nor to eradicate PWN. It is divided in two scenarios, A1 and A2 according to climate assumptions. *Scenario A1* assumes that the current climate in Norway prevails, that is, no significant climate changes occur in the coming 50 years. *Scenario A2* equals A1 but with a climate change corresponding to a temperature increase of $\sim 2°C$ by the end of the coming 50-year period. Alternative **B** assumes immediate implementation of the proposed Norwegian contingency measures when PWN is detected (cf. paragraph 6.2 in Norwegian Food Safety Authority, 2007). This implies complete logging and destruction of all host trees (all conifer species except *Thuja plicata*) in a circle with 3 km radius around each detection point (hereafter referred to as the eradication zone) and an observation zone for intensive monitoring with a 17 km radius surrounding the eradication zone. The sampling intensity will be approximately 420 samples per year. All host trees in the eradication zone are immediately cut and destroyed by burning at site or, if economically feasible, utilised for chips or lumber production under conditions that prevent spread of PWN (sealed container transport or heating to 56°C for minimum 30 minutes, Swedish Board of Agriculture, 2008a). The eradication zone is kept clear of host trees for a 20-year period, and all forest management measures are banned in the observation zone for the same time period. In case of additional infestations, new zones of logging (3 km radius) and intensive monitoring (17 km radius) are established around the new points of detection.

Materials and methods

Forest data

The biological model for PWN dispersal and spread is based on harvesting data from 8 counties in south-eastern Norway (Økland et al., 2010). We apply the same data in this study, and use land and forest data from the permanent sample plots in the Norwegian National Forest Inventory (NFI; Anon., 2010a) for the period 2004–2009. Table I shows the relative distribution of NFI sample plots on land use classes and counties. Approximately 2/3 of the sample plots are classified as forest land.

The geographic extent of the counties in Table I is shown in the map in Figure 1. The NFI sample plots are distributed systematically according to a 3×3 km grid. Each circular plot has a size of 250 m^2. In total 20% of the plots are re-measured each year, and the plots are selected for re-measurement according to a Latin square design within a 45×45 km block of plots. Using sample plot information from the NFI implies that weighting is unnecessary when calculating average number.

A model for the spread of the pine wood nematode

For estimating forest damage, we use an extended version of the stochastic dispersal model in Økland et al. (2010). The model makes use of information available in the literature on known *Monochamus* vectors in combination with biological and climatic information from Scandinavian forest systems, including information from experimental studies (Schroeder & Magnusson, 1992) and PWN surveys in Scandinavia (Swedish Board of Agriculture, 2008b). There is abundant supply of host trees in Norway (Anon., 2010a), 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 *Monochamus sutor* (Linnaeus, 1758) can oviposit and develop in recently dead wood of both tree species, while *Monochamus galloprovincialis* (Olivier, 1795) is limited to recently dead pine trees (Ehnström & Axelsson, 2002; Ehnström & Holmer, 2007). 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 (Swedish Board of Agriculture, 2008a). Bergdahl and Halik (2004) documented that living pine trees can host PWN infestations for at least 14 years without showing symptoms of PWD. 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 during years with summer temperatures higher than normal (Swedish Board of Agriculture, 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 simulation model of PWN and PWD spread was developed in R (R Development Core Team, 2008). The model assumes that introduction of one PWN infested object in SE Norway leads to PWN-infection of dead wood objects utilised by the local *Monochamus* populations in the lowlands of SE Norway (*M. sutor* and *M. galloprovincialis*), which

Table I. 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
Counties	Agricultural land	Productive forest	Other forest land	Grazing land	Other	Settlements	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	2411
Oppland	8.3	62.0	8.5	0.6	2.2	5.3	13.2	19.2	1460
Buskerud	5.2	63.6	10.7	0.7	1.6	7.3	10.7	14.6	1108
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	1212
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

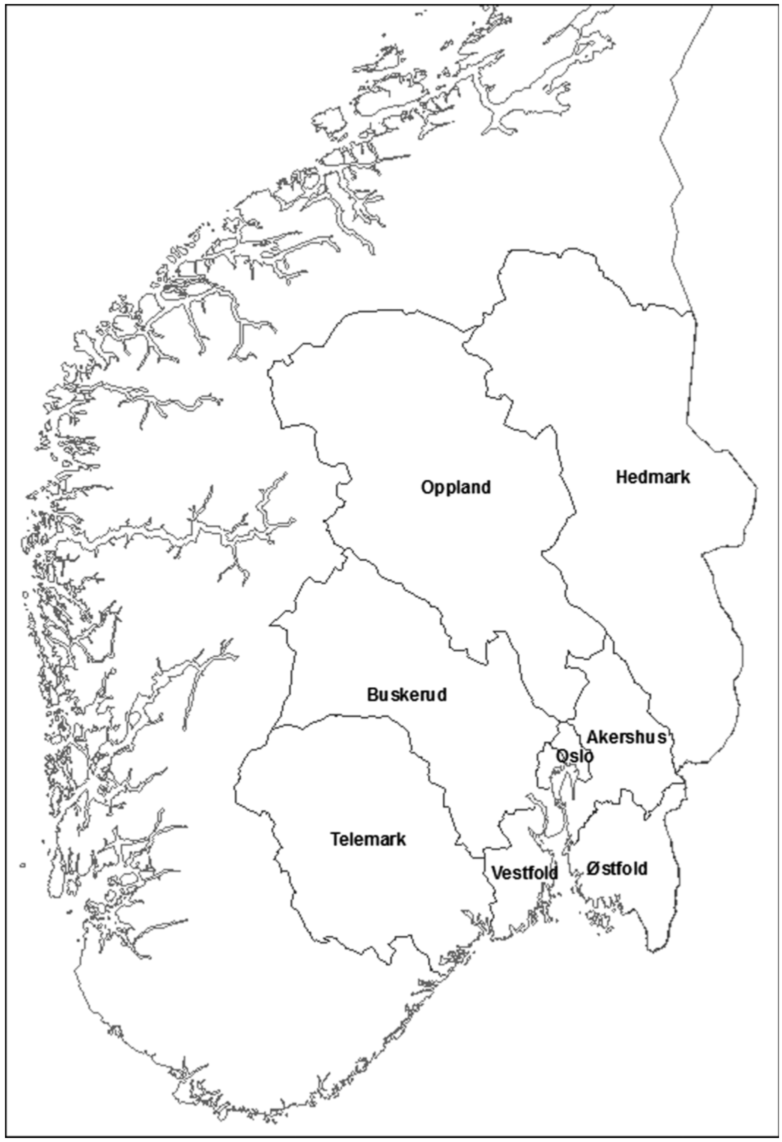

Figure 1. Map of southern Norway and the geographic extent of counties Østfold, Akershus, Oslo, Hedmark, Oppland, Buskerud, Telemark and Vestfold.

in turn starts a spread of PWN to an increasing proportion of the existing *Monochamus* population and its habitat objects. 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 (Schroeder et al., 1999; Schroeder & Lindelow, 2003; Trägårdh, 1929). Distances between such clear-cut areas and previous observations of *Monochamus* in Scandinavia (Forsslund, 1934; Trägårdh, 1929) indicate that many beetle individuals can undertake long-distance dispersal over several kilometres in Scandinavian forests (Økland et al., 2010).

From where individual beetles were reared and PWN-infested, we assume they spread with randomised direction and distance. Dispersal is based on a distribution function in agreement with distances within and between patches of its typical habitat in Scandinavia (1–2-year-old clear-cut areas with logging residues). Sixty-three thousand five hundred and twenty-five clear-cut areas in southern Scandinavia was used to estimate the typical distances within and between patches, and the distance distribution function was based on mark-recapture studies of *Monochamus alternatus* (Hope, 1842) (Takasu et al., 2000), which is divided into short and long dispersal corresponding to distances within and between patches respectively (Økland et al., 2010). The flight distances of this kernel (mean 14 metre 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 metre, and 95% of the distances were within the interval 58–437 metre. 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 *M. sutor* in SE Norway (Fritzøe and Løvenskiold) and mid Sweden (Dalarna and Värmland), the mean distance was 1170 metre, with 95% of the shortest distances being within the interval 66–5112 metre. This is about the same scale as the flight distances in the mark-recapture study of *M. alternatus* (mean 1820 metres), which was used in the long-distance part of the two-component dispersal kernel described by Takasu et al. (2000).

On their way to the final breeding habitat, vector beetles are assumed to infest living trees of both spruce and pine randomly during maturation feeding. At the final breeding habitat, beetles infest dead wood during oviposition and start a new generation of beetles that will be PWN-infested before they are reared and fly off from the dead wood. As the vector has a univoltine life cycle in the risk areas, the model uses annual time steps. The model keeps track of PWN-infested objects of Scots pine (*P. sylvestris*) and Norway spruce (*P. abies*).

Between objects, each individual of vector beetles were assumed to spread isotropically (uniform in all directions) with randomised direction θ of

$$\theta \sim \text{uniform}(0 - 2\Pi) \quad (1)$$

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 parameterisations described by Takasu et al. (2000), which includes a balance between short- and long-distance dispersal:

$$F(Z) = \sigma_L \cdot f_L + (1 - \sigma_L) \cdot f_s \quad (2)$$

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:

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

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

$$f_s(Z) = 0.\frac{0358}{\tau(0.3915)}.e^{-\left(\frac{z}{35}.69\right)^2.554} \quad (4)$$

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 (Swedish Board of Agriculture, 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).

Implementation of detection survey and contingency plan

The current PWN survey in Norway is based upon the EC Pine Wood Nematode Survey Protocol 2000 and the Draft Manual 2000-02-11 by Magnusson et al. (2000). Sampling is not dependent on PWD-symptoms, but focus on logging residues showing symptoms of *Monochamus* activity. Each sample requires extraction of nematodes and nematode identification by microscopy and often polymerase chain reaction (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 residues, 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). For detection of infestations in the simulation model (Økland et al., 2010), we used the same level of sampling intensity as in the Norwegian regular PWN survey, about 400 samples per year (Magnusson et al., 2007). When infested objects were found by the detection sampling in the simulation script, measures in the contingency plan were applied around each detection point.

As prescribed in the Norwegian contingency plan, the model used in this study removes all infections and suitable host tree objects in a radius of 3 km around the detection points before next time step of the 50-year-long simulation. In the 17 km wide observation zone around the zones of tree removal, an intensive sampling scheme with a total of 3000 samples is implemented. In the model, a new zone of tree removal was implemented for each new point of PWD detection before the next time step of the simulation.

Implementation of tree mortality and climate change

We used the PWD mortality percentages of pine trees estimated for various summer temperatures by the ForestETP (Swedish Board of Agriculture, 2008a) to estimate mortality rate (*Y*) as a function of mean temperature (*t*) for June to September, using the Generalised Logistic Function:

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

where A is lower asymptote, K is upper asymptote, B is growth rate, Q is a parameter depending on Y_0, v is the asymmetry coefficient which affects near which asymptote maximum growth occurs and 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 give a suitable shape, and estimation was done with the function for Nonlinear Least Squares (nl) in Stata 11/IC (Stata, 2010).

Figure 2 shows data points and fitted function for the relationship between temperature and the share of infested trees that develop PWD. There seems to be 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 of the 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, soil moisture and wind exposure to mention a few.

Current climatic conditions are based on a 30-year period from 1961 to 1990. Table II shows mean temperature for some geographic positions within the region of our data-set. Available climate change scenarios for Norway are IS92a for the years 1980–2049 based on the ECHAM4/OPYC3 model, or A2 and B2 for the period 2071-2100 based on the HADAm3 model (see NoSerC, 2010 for details). We use climate change scenarios for Blindern/Oslo (59°56′N 10°43′E, 94 m.a.s.l.) for the period 2001–2049 according to emission scenario IS92a.

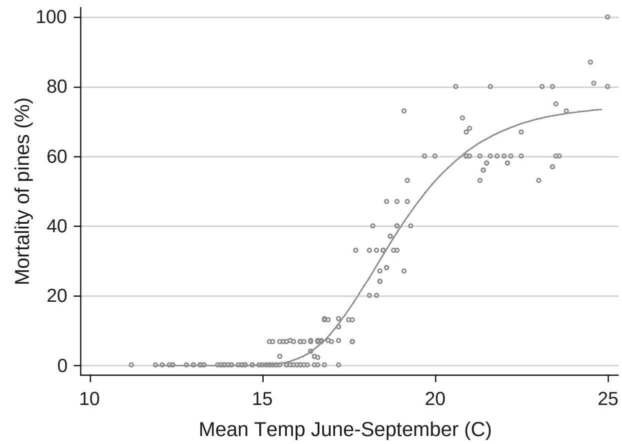

Figure 2. Data points and fitted function for the relative share of infested trees Pine Wilt Disease develops. Data source: Swedish Board of Agriculture (2008a).

Blindern is a fairly warm place, but not the warmest area in the data-set.

For the chosen climate change scenario, June to September mean temperature for the places in Table II varies between 13 and 16°C in the first part of the period and increases to between 14 and 17–18°C. Figure 3 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 (Stata, 2010) with knots every 5 years. The figure also shows tree mortality rate calculated as a function of temperature, according to Equation 1.

Simulations and statistical treatment

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 sampling intensity of the regular PWN survey (Magnusson et al., 2007) and the contingency plan (Swedish Board of Agriculture, 2008a). The stochastic 50-year simulations were repeated 1000 times, and average values for relevant variables were calculated. All results presented in later sections are based on averages from the simulations.

Economic valuations. The cost related to alternative A is based on the number of trees that die and thus not reaches harvesting age. Total costs are calculated as the number of dead trees multiplied by the value of those trees. We do not have specific information on the trees that actually die in the model. Instead we use average numbers based on valuation of all mature or near-mature trees.

When the contingency plan is executed in alternative B, there are additional costs to the landowner

Table II. Mean temperatures for the period–1990 for some geographic locations in the modelling region.

County Place	Oppland Fagernes	Hedmark Trysil	Oslo Blindern	Østfold Sarpsborg	Buskerud Lier	Vestfold 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

in the extraordinary and premature harvest in the eradication zone and the harvesting restriction in the observation zone. This cost has two elements: (1) the loss of future income from 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 existing forest as stocking value (SV) and the value of bare land used for forestry as land expectation value (LEV). The sum of these two is the forest value (FV, see e.g. Buongiorno & Gilless, 2003). Equations 3 and 4 shows Land Expectation Value and Forest Value, respectively.

$$\mathrm{LEV} = \left[H_n \cdot (1+p)^{-n} + \sum_{x=0}^{x=n} (D_x - c_x)(1+p)^{-x}\right] \cdot \left[\frac{(1+p)^n}{(1+p)^n - 1}\right] \quad (6)$$

$$\mathrm{FV}_q = \sum_{x=q}^{x=n} (D_x - c_x) \cdot (1+p)^{q-x} + (H_n + \mathrm{LEV}) \cdot (1+p)^{q-n} \quad (7)$$

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

$$\mathrm{LEVloss} = \frac{[\mathrm{LEV} \cdot (1+p)^t] - \mathrm{LEV}}{(1+p)^t} \quad (8)$$

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

In addition, the premature harvest leads to loss of the SV. As harvested timber may not be utilised, the cost of this is calculated as FV less LEV. Also, 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, as prescribed in the PWN contingency plan. The economic loss of postponing harvest in the observation zone can be calculated as in Equation 8, by substituting LEV with FV.

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 stand age, 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 based on Svendsrud (2001) and performed with Bestverd v2.0 (Gobakken & Svendsrud, 2004). In short, the valuations are based on a set of yield tables for different forest stands and a set of economic assumptions, such as roundwood price, reforestation costs and interest rate. We use statistics from Statistics Norway on roundwood prices for the period 1996 to 2008 and apply average prices. When relevant, corrections for low stocking are applied. See Raymer et al. (2009) for an example of a similar approach and further details on model functions.

Public project valuation in Norway is normally based on a risk free 3.5% p.a. rate of discount, and 4% p.a. real rate of discount is therefore common in long term public projects with low risk. The present harvesting level in Norway corresponds to a 2% p.a. rate of return. Eriksson et al. (2008) applied a 2.5% rate of discount in their analysis of economic consequences of the Swedish PWN contingency plan. To reflect various assumptions, we apply three different real rates of discount, respectively 2, 3 and 4% p.a.

In addition to loss of existing forest and related values, different costs arise due to actions under the contingency plan. Assumptions needed for estimation of costs of establishing the eradication and observations zones and corresponding parameters are left out. Different cost elements for the eradication and observation zones in alternative B are summarised together with total costs of one

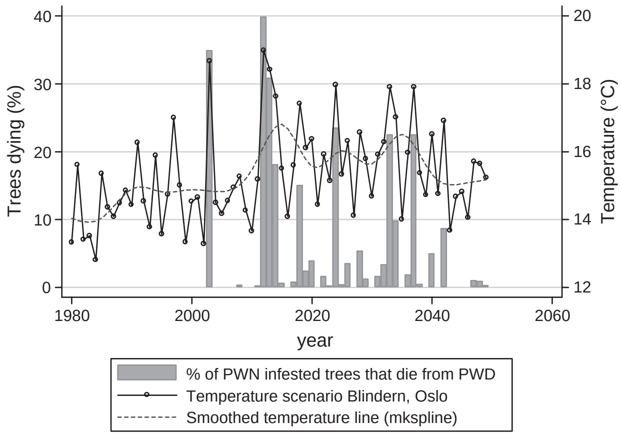

Figure 3. Temperature scenario (IS92a) for Blindern for years 1980–2049, a median smoothed spline for the temperature scenario and tree mortality rate due to PWD as a function of temperature.

eradication measure in Table III. The results are based on the average distribution of land use classes and, as such, cover the entire region.

The eradication zone has an area cost of approximately 34,000–37,000 NOK ha^{-1}, depending on the interest rate. The cost related to loss of SV is largest for lower interest rates because lower interest rates implies longer rotations and the contingency plan implementation necessitates harvest which is further away from its optimal rotation age compared to higher interest rates. The loss of FV 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, here, 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) then becomes as shown in Table IV.

Results

Figure 4 presents the situation without actions against PWN (alternative A), where the number of trees infested with PWN increases over time. The model of PWN spread is stochastic and the figure shows 99% confidence intervals for the number of infested trees. In scenario A1, our simulations resulted in no PWD-development and thus no trees killed, and scenario A1 may be referred to as the "business as usual"-scenario. In scenario A2, tree-killing occurs in years with temperatures above the threshold for PWD-development. The accumulated number of trees that die from PWD under A2 is however relatively small and ends at 9062 trees. The trees that die are spread over an area of approximately 2900 km^2. This is 0.033 trees ha^{-1}, while the average stocking of conifer trees is 444 trees ha^{-1}. Applying a temperature trend (which is unlikely in a dynamic climate) rather than the scenario temperature series, results in less years above the threshold for PWD-development, and subsequently a much lower estimate of the number of trees that die from PWD. The smoothed trend depicted in Figure 3 leads to 3613 dead trees by 2050 when climatic variability is ignored.

Figure 5 shows the accumulated area of eradication and observation when the contingency plan is applied (alternative B). In total, the contingency plan may require a large area of tree-removal. Due to the low sampling intensity, several years pass before PWN is detected. The initial area is seemingly small in the figure, but this is because the numbers are averages of stochastic simulations and PWN is detected at different time in different simulations.

Table III. Summary table for cost assumptions according to measures in the PWN contingency plan. Net present value at time of execution of the contingency plan. NOK ha^{-1}.

Zone	Level	Cost factor	Interest rate (%)		
			4	3	2
Eradication zone	Stand level	Land expectation value loss	513	881	1033
		Stocking value loss	8095	9719	10,513
		Harvesting cost	7980	7980	7980
	General	Treating stumps with pesticide	3000	3000	3000
		Cleaning of host trees (NPV, 50 years)	6158	6746	7407
		Disposal of wood	6959	6959	6959
Sum for eradication zone			32,705	35,285	36,892
Observation zone	FV loss		4 913	5219	4470
	Survey		34	34	34
Sum for observation zone			4947	5253	4504

Table IV. 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 execution of the contingency plan.

	Interest rate (%)		
Zone	4	3	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 = 122,836.3 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

First in year 10 does the area in the accumulated eradication zone become 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).

The costs of scenario A2 are low. Based on the inventory data and economic assumptions, the net value of an average tree is 34.4 NOK. Combined with the accumulated number of trees that die from PWD, total costs accumulate to approximately 154,000, 109,000 and 78,000 NOK, respectively for 2, 3 and 4% p.a. interest rates.

The results from the simulations in the PWN model under alternative B (Figure 5) are combined with the area costs (Table IV) in Figure 6, which shows the development of annual costs of the proposed measures for eradication of PWN in the contingency plan. The NPV of the accumulated costs of the contingency plan is 2.6, 2.2 and 1.6 billion NOK, for interest rates 2, 3 and 4% respectively. On average for the 50 years period covered by the analysis, this corresponds to an annual cost of 84, 84 and 75 million 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.

Discussion

Uncertainties

The economic valuation of forest land (Svendsrud, 2001) is based on tested and well-behaving functions for forest growth and hence fairly reliable. It is extensively used throughout Norway for forest valuations purposes. The factor most difficult to assess is future prices of roundwood, which are important for the estimated values. The valuation model also assumes optimal forest management for future forest rotations. It is uncertain how strongly deviations from this will affect the results, but is likely of minor importance as the economic loss due to non-optimal forest management in Norway seems relatively small (Solberg & Haight, 1991). 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 earlier. Cost assumptions other than those related to the forest valuation are more uncertain. The burning cost of wood as part of the contingency measures is especially uncertain as there is a lack of experience regarding this.

Damages and costs under scenario A2 may seem smaller than could be expected when PWN is allowed to spread in a warmer climate. 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

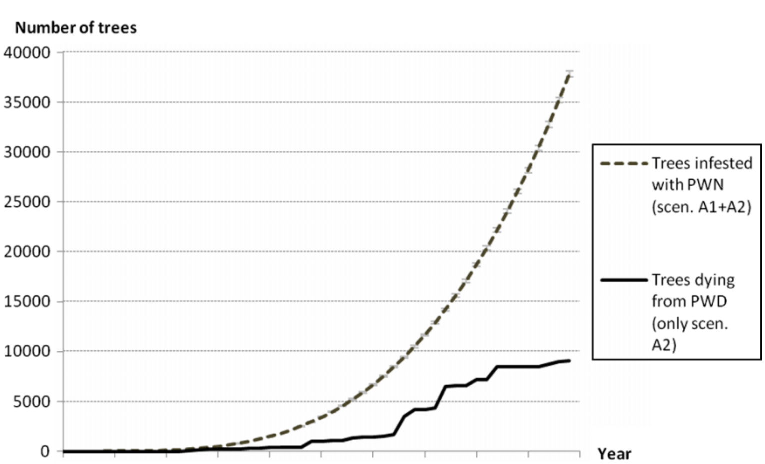

Figure 4. Accumulated number of infested trees (with 99% confidence intervals), and trees where PWD develop causing them to die. Temperature based on IS92a emissions scenario.

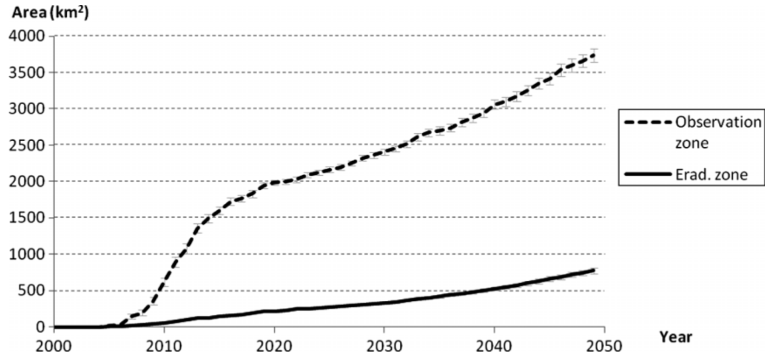

Figure 5. Accumulated area (with 99% confidence intervals) in the eradication and observation zone over a 50-year period as a result of the contingency plan. Present climate. Km^2.

0.1–0.4. However, in a forest area in Japan a vector beetle (*M. alternatus*) on average caused 1–2 trees to die by transferring the nematode when feeding (Swedish Board of Agriculture, 2008a). 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 1.3, 0.9 and 0.6 million NOK (2, 3 and 4% interest rate). Even with a high infestation rate, total costs are relatively small compared to the costs of the contingency plan. Even if we combine a high infestation rate with a higher mortality rate than suggested by Equation 1, costs are still modest. Assuming a mortality of 100% and an infestation rate of 2, the number of trees that die over the 50-years period is about 500,000 with an associated cost of 7.5, 5.0 and 3.4 million NOK measured as NPV and at respectively 2, 3 and 4% p.a. discount 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, such a trend scenario would be unrealistic by avoiding the temperature peaks in the scenario that occur naturally in a variable and dynamic climate. 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. This point could even be relevant for the annual time steps in our model, as this can be seen as a smoothing of climatic events over the year. What could for instance be the effect on the vector of drastic climatic events, like a cold spell in spring in a specific year?

A large part of the cost in the eradication zone is the loss of the standing timber. Salvaging some of the most valuable roundwood could significantly reduce costs. The average value of sawlogs in mature forest if cut at premature (present) age using the average stocking and age structure, is today approximately 4000 NOK ha^{-1}, and the average volume of timber saved is 41 m^3 ha^{-1}. This could hence save 11–12% of the costs, depending on the interest rate.

At this point, we do not account for loss in the economic value of non-market ecosystem services, such as landscape aesthetics, outdoor recreation and the knowledge that healthy forest ecosystems exist (Holmes et al., 2009), which have been pointed out to be important. Neither do we value potential losses

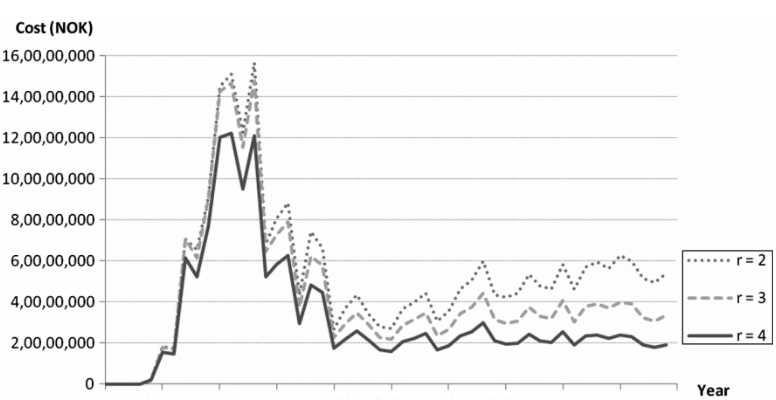

Figure 6. Annual cost (NPV) of measures for eradication of PWN (scenario B) over a 50-year period for different interest rate (2, 3 and 4%).

in biodiversity. The potential negative effects of the proposed measures in alternative B on the mentioned ecosystem services are most likely very high.

If PWN is detected in Norway, export restrictions will be enforced on wood based products that are not heat-treated, for example, fuelwood and roundwood. The Norwegian export of these products is at present both modest and less than imports (Anon., 2010b). It should thus be possible to find national markets for these products and volumes.

An attempt to restrict or stop dispersal of invasive forest pests is strongly dependent on a successful organisation of the necessary interventions and good balance between detection survey and eradication strategies (Bogich et al., 2008). A critical part of the contingency plan is the extraordinary harvest, where the key issue is mobilisation of the workforce performing all necessary operations, especially machinery for forest operations. It could be suggested to calculate the cost of increased sampling effort that could lead to earlier detection of PWN. However, the number of samples needed for successful eradication appears to be unrealistically high when symptoms of wilting (PWD) does not occur, and even very high sampling intensities are unlikely to prevent further spread (Økland et al., 2010). Thus, cost calculations for various levels of sampling intensities were not included in this study.

Lessons to learn

In an analysis of managing the spread of exotic pest species with barrier zones, Sharov and Liebhold (1998) found that the optimal strategy changed from eradication to slowing the spread to finally doing nothing, because, as the area occupied by the species increased, the negative impact of the pest per unit area decreased. 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 minimise the costs of monitoring and managing an invasive species. They showed the importance of including both monitoring and management costs when making decisions regarding measures and programmes. A combination of monitoring and management effort is also considered for PWN, but 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). However, a balance of monitoring and managing may be of interest in case of PWN if the purpose should be to slow the spread of PWD. 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.

Soliman et al. (2010) state that the wider scope an impact assessment has and the more complex it is, the closer it will come to an estimate of the total cost of a disease invasion or introduction. In the case of PWN in Norway, the effects on the whole economy and even the effects on the forest sector are likely to be small, implying that it is sufficient to include the costs as we have done.

The costs of disease control are dependent on both structural costs arising from preventive measures and incidental costs arising from reactive measures (Breukers et al., 2008). Our analysis does not include structural costs, as we focus on the costs of the contingency plan rather than the total costs of control. Also, such structural costs could be very complex and should in the case of PWN include, for example, such elements as a valuation of the necessary actions that must be taken in countries that export to Norway to meet Norwegian import regulations. We have not included this, as our results demonstrate rather clearly that the costs of the contingency plan are very high even excluding the structural costs. Furthermore, our study has not considered costs which may occur in warmer countries by importing wood from undetected PWN-infestations in Norway. In practice however, it seems that introduction of PWN must be considered as an irreversible process and very difficult to detect in countries where symptoms are not visible. Thus, introduction of PWN in symptom-free areas may have impacts beyond national-economical interests and represents a significant challenge for future research on pest management of this species (Robinet et al., 2011). If the spread of PWN in northern Europe in a changing climate should be avoidable, the question will also arise how future forest management can plan for a tree species composition that optimises resistance against forest pests, future market options, aesthetic values, recreational land use and so on. This will probably be very difficult to estimate.

Concluding remarks

The costs related to controlling the spread of PWN and PWD in Norway according to the existing contingency plan are very high compared to the likely direct costs of the disease itself. Estimated costs are losses caused only by reduced income from industrial timber production and the costs of the eradication measures. Other costs caused by, for example, reduced recreation or biodiversity are not included, but would without doubt be very high. 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 assumptions of future climate change, we estimate that the cost due to tree mortality will be relatively low. The reduction of Norwegian export of wood based products is likely to be limited, and these costs are not included in the present calculations. 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. Our results suggest a need for revising the existing contingency plan for PWN/PWD in Norway.

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References

Anon. (2010a). National Forest Inventory. Retrieved June 30, 2010, from http://www.skogoglandskap.no/en/national_forest_inventory

Anon. (2010b). External trade in commodities, yearly series. Imports and exports by three-digit SITC, 2006–2008. Retrieved June 30th, 2010, from http://www.ssb.no/english/subjects/09/05/uhaar_en/tab-21-en.html

Bergdahl, D. R. & Halik, S. (2004). Persistence of the Pine wood nematode in asymptomatic Scots pines. In M. Mota & P. Vieira (Eds.), *The Pinewood nematode, Bursaphelenchus xylophilus: Proceedings of an International Workshop*, August 20–22. University of Évora, Portugal. Nematology Monographs and Perspectives 1, pp. 177–183.

Bogich, T. L., Liebhold, A. M. & Shea, K. (2008). To sample or eradicate? A cost minimization model for monitoring and managing an invasive species. *Journal of Applied Ecology*, *45*, 1134–1142.

Breukers, A., Mourits, M., Werf, W. v. d. & Lansink, A. O. (2008). Costs and benefits of controlling quarantine diseases: A bio-economic modeling approach. *Agricultural Economics*, *38(2)*, 137–149.

Buongiorno, J. & Gilless, J. K. (2003). *Decision methods for forest resource managers*. Amsterdam and Boston: Academic Press.

European Commission (2000). *Pinewood nematode survey*. Brussels: European Commission.

European Commission (2010). *Summary report of the meeting of the standing committee on plant health held on 29–30 March 2010*. D(2010) 410595, 4. Brussel: European Commission. Retrieved from http://ec.europa.eu/food/fs/rc/scph/sum_2930032010_en.pdf.

Ehnström, B. & Axelsson, R. (2002). *Insektsgnag i bark och ved* [Insect gnaw in bark and wood]. Uppsala: Artdatabanken, Sveriges lantbruksuniversitet. (In Swedish)

Ehnström, B. & Holmer, M. (2007). *Skalbaggar: långhorningar: Coleoptera: Cerambycidae* [Bark beetles: long horns: Coleoptera: Cerambycidae]. Uppsala: ArtDatabanken, Sveriges lantbruksuniversitet. (In Swedish)

EPPO (2010a). Isolated finding of *Bursaphelenchus xylophilus* in Spain. *EPPO Reporting Service, 3, 2010/051*, from http://archives.eppo.org/EPPOReporting/2010/Rse-1003.pdf [Retrieved date]

EPPO (2010b). Addendum (This article corrects: PM 9/1(2): Bursaphelenchus xylophilus and its vectors: procedures for official control, EPPO Bulletin 39 (3), 454–45.). *EPPO Bulletin*, *40*(3), 389.

Eriksson, L.-O., Nordfjell, T. & Gref, R. (2008). Tallvedsnematod–analys av kostnader och resursåtgång vid bekämpning av ett utbrott i Sverige [Pine Wood Nematide–analysis of costs and resource use in figthing an outbreak in Sweden]. *Rapport fra Sveriges Lantbruksuniversitet, 213*, 44. (In Swedish)

Evans, S., Evans, H. F. & Ikegami, M. (2008). Modeling PWN-Induced Wilt Expression: A Mechanistic Approach. In: M. Mota & P. Vieira (Eds.), *Pine wilt disease: A worldwide threat to forest ecosystems*, pp. 259–278. Dordrecht: Springer.

Forsslund, K.-H. (1934). Tallbockens (*Monochamus sutor* L.) uppträdande på brandfält i Norra Sverige sommaren 1933 [Pine Sawyer (*Monochamus sutor* L.) behaviour on firest fire fields in Northern Sweden during summer 1933]. *Svenska skogvårdsföreningens tidskrift, 1934(I–II)*, 30–37. (In Swedish)

Gandhi, K. & Herms, D. (2010). Direct and indirect effects of alien insect herbivores on ecological processes and interactions in forests of eastern North America. *Biologival Invasions*, *12*, 389–405.

Genovesi, P. (2005). Eradications of invasive alien species in Europe: A review. *Biological Invasions*, *7(1)*, 127–133.

Gobakken, T. & Svendsrud, A. (2004). 05.10.2009. BestVerd–Verdiberegning av skogbestand [BestVerd–Valuation of forest stands]. Retrieved March 24, 2010, from http://www.umb.no/ina/artikkel/bestverd-verdiberegning-av-skogbestand. (In Norwegian)

Haack, R. A., Herard, F., Sun, J. H. & Turgeon, J. J. (2010). Managing invasive populations of Asian longhorned beetle and citrus longhorned beetle: A worldwide perspective. *Annual Review of Entomology*, *55*, 521–546.

Holmes, T. P., Aukema, J. E., Von Holle, B., Liebhold, A. & Sills, E. (2009). Economic impacts of invasive species in forests: Past, present, and future. *Annals of the New York Academy of Sciences*, *1162*, 18–38.

Hulme, P. E., Pysek, P., Nentwig, W. & Vila, M. (2009). Will threat of biological invasions unite the European Union? *Science*, *324(5923)*, 40–41.

Kovacs, K. F., Haight, R. G., McCullough, D. G., Mercader, R. J., Siegert, N. W. & Liebhold, A. M. (2010). Cost of potential emerald ash borer damage in U.S. communities, 2009–2019. *Ecological Economics*, *69(3)*, 569–578.

Kwon, T.-S., Shin, J. H., Lim, J.-H., Kim, Y.-K. & Lee, E. J. (2011). Management of pine wilt disease in Korea through preventative silvicultural control. *Forest Ecology and Management*, *261(3)*, 562–569.

Lockwood, J. L., Hoopes, M. F. & Marchetti, M. P. (2007). *Invasion ecology*. Malden, MA: Blackwell Publishing.

Magnusson, C., Schroeder, M. & Tomminen, J. (2000). Nordic pine wood nematode survey–Draft Manual 2000–02–11. The first version was presented at the working group on PWN in Brussels 2000-01-26.

Magnusson, C., Thunes, K. H., Nyeggen, H., Overgaard, H., Rafoss, T., Haukeland, S. et al. (2007). Surveillance of Pine wood nematode (PWN) *Bursaphelenchus xylophilus*–Norwegian Surveys 2000–2006. *Bioforsk Report*, *2(104)*, 22.

Mamiya, Y. (1984). The pine wood nematode. In: W. R. Nickle (Ed.), *Plant and insect nematodes*, pp. 589–626. New York: Marcel Dekker.

Mota, M. M., Braasch, H., Bravo, M. A., Penas, A. C., Burgermeister, W., Metge, K. et al. (1999). First report of *Bursaphelenchus xylophilus* in Portugal and in Europe. *Nematology*, *1*, 727–734.

Norwegian Food Safety Authority (2007). Faglig beredskapsplan for furuvednematode. Forslag 16. oktober 2007 [Contingency plan for Pine Wood Nematode. Draft 16th October 2007]. Retrieved December 6, 2009, from http://mattilsynet.no/aktuelt/nyhetsarkiv/planter/plantehelse/forslag_til_faglig_beredskapsplan_for_furuvednematode_52153. (In Norwegian)

NoSerC (2010). Norwegian service centre for climate modelling, project description 2003–2004. Retrieved June 30th, 2010, from http://noserc.met.no/PD/index.html

Økland, B., Erbilgin, N., Skarpaas, O., Christiansen, E. & Långström, B. (2011). Inter-species interactions and ecosystem effects of non-indigenous invasive and native tree-killing bark beetles. *Biological Invasions*, *13(5)*, 1151–1164.

Økland, B., Skarpaas, O., Schroeder, M., Magnusson, C., Lindelöw, Å. & Thunes, K. (2010). Is eradication of the pinewood nematode (*Bursaphelenchus xylophilus*) likely? An evaluation of current contingency plans. *Risk Analysis*, *30(9)*, 1424–1439.

PHRAME (2007). *Development of improved pest risk analysis techniques for quarantine pests, using pinewood nematode, Bursaphelenchus xylophilus, in Portugal as a model system*. Final Report from the EU project PHRAME (Plant Health Risk and Monitoring Evaluation), July 2007. London: Forestry Commission Great Britain. Retrieved from http://www.forestry.gov.uk/pdf/PHRAMEJuly07.pdf/$FILE/PHRAME July07.pdf

Pimentel, D. (2002). *Biological Invasions: Economic and environmental cost of alien plant, animal and microbe species*. Boca Raton, FL: CRC Press.

Prestemon, J. P., Turner, J. A., Buongiorno, J., Zhu, S. S. & Li, R. H. (2008). Some timber product market and trade implications of an invasive defoliator: The case of Asian Lymantria in the United States. *Journal of Forestry*, *106(8)*, 409–415.

R Development Core Team (2008). R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing.

Raymer, A. K. P., Gobakken, T., Solberg, B., Hoen, H. F. & Bergseng, E. (2009). A forest optimisation model including carbon flows: Application to a forest in Norway. *Forest Ecology and Management*, *258(5)*, 579–589.

Robinet, C., Van Opstal, N., Baker, R. & Roques, A. (2011). Applying a spread model to identify the entry points from which the pine wood nematode, the vector of pine wilt disease, would spread most rapidly across Europe. *Biological Invasions*, *13*(*12*), 2981–2995.

Rodrigues, J. M. (2008). National eradication programme for the pinewood nematode. In: M. M. Mota & P. Vieira (Eds.), *Pine wilt disease: A worldwide threat to forest ecosystems*, pp. 5–14. London: Springer Netherlands.

Schroeder, L. M. & Lindelow, A. (2003). Response of *Ips typographus* (Scolytidae: Coleoptera) and other bark- and wood-boring beetles to a flash-flood event. *Scandinavian Journal of Forest research*, *18(3)*, 218–224.

Schroeder, L. M. & Magnusson, C. (1992). Transmission of *Bursaphelenchus mucronatus* (Nematoda) to branches and bolts of Pinus sylvestris and Picea abies by the cerambycid beetle *Monochamus sutor*. *Scandinavian Journal of Forest Research*, *7*, 107–112.

Schroeder, L. M., Weslien, J., Lindelow, A. & Lindhe, A. (1999). Attacks by bark- and wood-boring Coleoptera on mechanically created high stumps of Norway spruce in the two years following cutting. *Forest Ecology and Management*, *123(1)*, 21–30.

Seidl, R., Rammer, W., Jager, D. & Lexer, M. J. (2008). Impact of bark beetle (*Ips typographus* L.) disturbance on timber production and carbon sequestration in different management strategies under climate change. *Forest Ecology and Management.*, *256(3)*, 209–220.

Seidl, R., Schelhaas, M.-J., Lindner, M. & Lexer, M. J. (2009). Modelling bark beetle disturbances in a large scale forest scenario model to assess climate change impacts and evaluate adaptive management strategies. *Regional Environmental Change*, *9(2)*, 101–119.

Sharov, A. A. & Liebhold, A. M. (1998). Bioeconomics of managing the spread of exotic pest species with barrier zones. *Ecological Applications*, *8(3)*, 833–845.

Solberg, B. & Haight, R. G. (1991). Analysis of optimal economic management regimes for *Picea abies* stands using a stage-structured optimal-control model. *Scandinavian Journal of Forest Research*, *6(1)*, 559–572.

Soliman, T., Mourits, M. C. M., Oude Lansink, A. G. J. M. & van der Werf, W. (2010). Economic impact assessment in pest risk analysis. *Crop Protection*, *29(6)*, 517–524.

Stata (2010). Stata: Data analysis and statistical software. Retrieved June 1, 2010, from www.stata.com

Statistics Norway (2008). Forestry Statistics 2008. Official Statistics of Norway. NOS D 431. Record No. 1894. Retrieved November 18, 2011, from http://www.ssb.no/english/subjects/10/04/20/nos_skogstat_en/

Svendsrud, A. (2001). Tabeller for beregning av verdien av skogbestand [Tables for valuation of forest stands]. *Rapport fra skogforskningen, Supplement(17)*, 16 [30]. (In Norwegian)

Swedish Board of Agriculture (2008a). Konsekvensanalys av angrepp av tallvedsnematod i svensk skog [Consequences of an outbreak of pine wood nematode in Swedish forests]. *Report 2008*(19), Jönköping, Sweden. (In Swedish)

Swedish Board of Agriculture (2008b). *Report on the pine wood nematode survey in Sweden 1 November 2006–31 October 2007. Dnr 20 2220/08*. Jönköping, Sweden: Swedish Board of Agriculture.

Takasu, F., Yamamoto, N., Kawasaki, K., Togashi, K., Kishi, Y. & Shigesada, N. (2000). Modeling the expansion of an introduced tree disease. *Biological Invasions*, *2*, 141–150.

Togashi, K. & Shigesada, N. (2006). Spread of the pinewood nematode vectored by the Japanese pine sawyer: modeling and analytical approaches. *Population Ecology*, *48*, 271–283.

Trägårdh, I. (1929). On the injury of the pine-sawyer (*Monochamus sutor* L.) and its prevention. *Meddelanden från Statens Skogsförsöksanstalt*, *25*, 171–228.

VKM (2008). *Pest risk assessment of the pine wood nematode (PWN)* Bursaphelenchus xylophilus *in Norway–Part 1*: Norwegian Scientific Committee for Food Safety 08/906-4.

Yemshanov, D., McKenney, D. W., de Groot, P., Haugen, D., Sidders, D. & Joss, B. (2009). A bioeconomic approach to assess the impact of an alien invasive insect on timber supply and harvesting: A case study with Sirex noctilio in eastern Canada. *Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere*, *39(1)*, 154–168.