Potential impacts of climate change on Dutch forests

Mapping the risks

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ABSTRACT

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The aim of this study was to assess, spatially explicit, the potential impact of climate change on Dutch forests. To deal with the uncertainty of climate change, the effects of four climate scenarios were studied. The following aspects of climate change were taken into account: decreased water availability in case of summer droughts, increased soil water levels in case of increasing precipitation, forest fire, salinization and insect pests. Information on the sensitivity of tree species to these aspects was combined with information on the composition of forests and with information on the exposure to these aspects. If drought occurs more often, this might reduce tree growth in a large proportion of the forests. The potential impact of the other aspects was much smaller. A general adaptive strategy should focus on increasing tree species diversity. Most pressing is to increase our knowledge of the drought resistance and vulnerability of tree species.

Keywords: climate change, impacts, adaptation, forests, insect pests, The Netherlands

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Preface

In dit rapport worden de belangrijkste resultaten gepresenteerd van het project "rol van bossen in geïntegreerde oplossingsrichtingen en adaptatiestrategieën voor ruimtelijke knelpunten bij klimaatverandering" (BO-01-004-409). Dit project werd uitgevoerd in 2008, in opdracht van het ministerie van LNV, en was onderdeel van het beleidsondersteunend onderzoek met als thema Klimaat binnen het cluster Vitaal Landelijk Gebied. De resultaten uit dit project zijn aangeleverd aan het project "geïntegreerde oplossingsrichtingen en adaptatiestrategieën voor ruimtelijke knelpunten bij klimaatverandering" (BO-01-004-407). In ons project zijn gegevens gebruikt van het project "gevolgen klimaatverandering op de hydrologische randvoorwaarden voor landbouw en natuur in Nederland" (BO-01-004-408).

De kaartjes zoals die hier worden gepresenteerd zijn bedoeld om aan te geven in welke regio's binnen Nederland het bos mogelijk in de knel komt bij klimaatverandering. Mogelijk positieve effecten van klimaatverandering op bosgroei, zoals een langer groeiseizoen, zijn hierbij nog niet meegenomen. De onderliggende klimaat- en bosgegevens hebben een relatief lage resolutie en de kaartjes zijn dan ook niet bedoeld om informatie te geven over mogelijke veranderingen in individuele bossen.

Wij willen Lodewijk Stuyt (Alterra) bedanken voor informatie over verzilting in Nederland en Jaco van der Gaast en Harry Massop (beiden Alterra) voor hun constructieve opstelling bij het aanleveren van de gegevens over grondwaterstanden en waterbeschikbaarheid.

Summary

Climate change can potentially influence forests in many ways. To quantify the potential risks, and to formulate adaptive measures, information is needed on which forest areas are likely affected. In this study, we aimed to assess, spatially explicit, the potential impact of climate change on Dutch forests. To deal with the uncertainty of our future climate, the effects of four climate scenarios were studied. Aspects of climate change which were taken into account were: decreased water availability during the growing season in case of increased drought, increased soil water levels in case of increased summer precipitation, the incidence of forest fires, salinization and insect infestations.

First, a literature review was conducted to evaluate the sensitivity of Dutch tree species to these aspects of climate change. The information from literature was then combined with information on the composition of the Dutch forests and with information on the exposure of these forests to the different aspects of climate change. Finally, maps were constructed showing the potential impacts of the different aspects of climate change. Only for the aspect 'insect pests', not a map but a table was constructed presenting the future risks.

The results indicate that if drought events occur more regularly in future, they will have a negative impact on the growth of a large proportion of our forests. The potential impact of the aspects forest fire, rise of the groundwater level and salinization were all much smaller. Insect pests are currently a very important damaging agent to forests in Europe and they are expected to become more abundant under climate change. The potential impact of climate change appears to be largest on elevated sandy soils, since drought, forest fire and a rise of the water table all might have an impact on forests in these areas. On the clay and peat soils in the western and north-western parts of the Netherlands, increased salinization during droughts will have a negative impact on trees and locally this impact might be severe. The potential impact of the different aspects is especially large under the climate scenario W+ and to a lesser extent under the scenario G+.

This study is an initial exploration of potential impacts of climate change and focussed on the risks. In a future study, potential positive effects of climate change should be considered too. Due to the variation in forest types and site conditions and the uncertainty of the future climate, a general adaptive strategy is hard to formulate. What seems relevant for all aspects of climate change, for all climate scenarios, and for most forest types, is to stimulate tree species diversity. Since drought appears to have the largest potential impact, it is further most pressing to increase our knowledge of the drought resistance and vulnerability of tree species.

1 Introduction

Like in the rest of the world, the climate in the Netherlands is changing. Temperatures are currently increasing and also for the future, temperatures are expected to rise. Studies suggest that mild winters and hot summers will become more common in the Netherlands, and winters are expected to become wetter. What our summers will look like, wetter or drier, is more uncertain (KNMI 2006, 2008; Van den Hurk et al. 2006). Climate change can have many effects on our society (MNP 2005; Van Dorland et al. 2008) and it will also influence our forests. To quantify the vulnerability of our forests and to formulate adaptive measures, information is needed on which forest areas are likely affected (Van Ierland et al. 2001; Nabuurs & Hommel 2007). Presently, no studies are available which map the potential effects of climate change on Dutch forests.

The aim of this study was to assess, spatially explicit, the potential impact of climate change on Dutch forests

Climate change can have many different effects on forests. Generally, a distinction can be made between effects which directly affect trees and forests and effects which do so indirectly. An example of a direct effect is the impact of enhanced CO_2 concentrations and a higher temperature on the growth of tree species (Saxe et al. 2001), another example is the impact on the phenology of plants (www.natuurkalender.nl. Menzel et al. 2006). Climate change can also indirectly affect forests, for instance through the impact of climate change on forest fires (Schelhaas et al. 2003), on salinization in coastal areas (MNP 2005; Jacobs 2007; Paulissen & Schouwenberg 2007) or on the distribution of pathogens and diseases (Moraal et al. 2004; Moraal 2007).

In our study, we took a limited number of aspects of climate change into account. We focussed on the risks, and did not consider potential positive effects, like the fertilizing effect of higher CO_2 concentrations on tree growth. The first aspect we studied was the effect of decreased water availability for plant growth, in the case of decreased summer precipitation. We further studied the potential damage of higher soil water levels, in case of increased summer precipitation. Other aspects which we studied were: the incidence of forest fires, salinization and insect infestations. The potential impact of storms on forests was not taken into account since the expected change in wind speed will be small compared to natural fluctuations (KNMI 2006). We further limited the study to the effects of climate change on trees and did not consider for instance the soil or the herb layer of the forests. Much research to climate change is presently undertaken, but climate change predictions are still hard to make. To deal with this uncertainty, the effects of four climate scenarios on the forests were studied.

Outline

In chapter two, we give an overview of the data and the method which were used. In chapter three, the results of a literature review are presented and we present the assumptions which were used to construct the maps showing the potential impacts. For the aspect ‘insects pests’, not a map but a table was constructed. In chapter four, the maps and this table are presented and discussed. Chapter five contains a synthesis of the results and some suggestions for adaptive measures.

2 Method

2.1 Outline

To evaluate the sensitivity of Dutch tree species to changes in water availability and changes in the level of salinity of soil water, and to evaluate the sensitivity of tree species to forest fires and insect pests, we first conducted a literature review. The Wageningen Library Catalogue was searched, using the words 'verdroging', 'droogte', 'vernatting', 'zoutschade', 'verzilting', 'bosbrand' combined with the keywords forestry or forest. Further, general literature on the autecology of the Dutch tree species was consulted and literature on the effects of climate change on forests in possession with the authors was used. The information from this literature review was then combined with information on the composition of the Dutch forests and with information on the exposure of the forests to the different aspects of climate change. Finally, using ArcMap, a number of maps was constructed showing the potential impacts of different aspects of climate change. Only for the aspect 'insect pests', not a map but a table was constructed, presenting the future risks.

The terms we used to describe the impacts of climate change on Dutch forests were based on the definitions used by the IPCC and the ATEAM-project (Metzger et al. 2004) (Table 1). We regarded the potential impact of climate change a function of the *exposure* and the *sensitivity*, while the *vulnerability* of the system was regarded a function of the *potential impact* and the *ability to adapt* to the changes (Figure 1).

Table 1. Definitions used to describe the impact of climate change on a system, based on the definitions by (Metzger et al. 2004).

Term	Definitions, based on the ATEAM-project
Exposure	The nature and degree to which ecosystems are exposed to environmental change
Sensitivity	The degree to which a human-environment system is affected, either adversely or beneficially, by environmental change
Potential impact	All impacts that may occur given projected environmental change, without considering planned adaptation
Adaptive capacity	The potential to implement planned adaptation measures
Vulnerability	The degree to which an ecosystem service is sensitive to global change plus the degree to which the sector that relies on this service is unable to adapt to changes

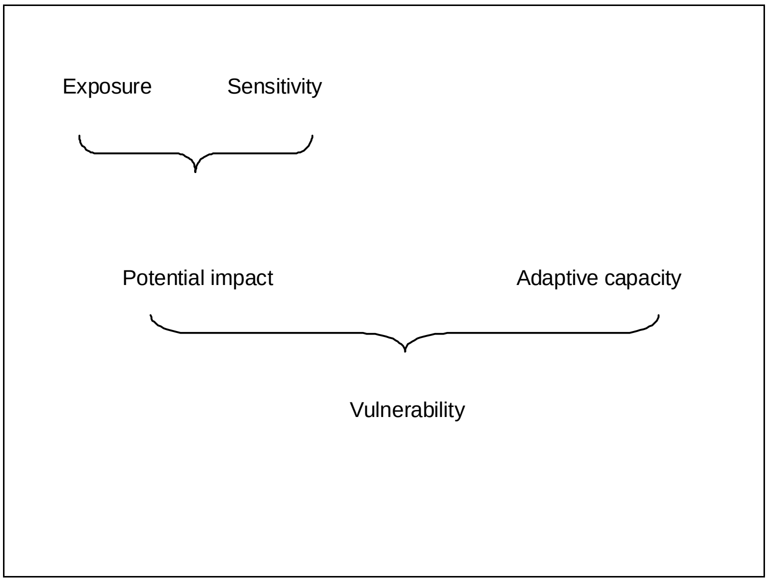

Figure 1. The terms used to describe the vulnerability of an ecosystem service to climate change, after (Metzger et al. 2004).

2.2 Climate scenarios

For the Netherlands, climate change scenario's have been constructed by the Royal Netherlands Meterological Institute (KNMI). In our study we used the so called KNMI'06 climate scenarios (KNMI 2006; Van den Hurk et al. 2006). To construct these scenarios, results of GCM simulations, Regional Climate Model simulations and statistical downscaling on observed time series were used by the KNMI. The GCM projections showed a range in mean global temperature rise of approximately +1°C to +2°C, for the period 1990-2050 (KNMI 2006). The simulations further revealed that for the Netherlands changes in the atmospheric circulation pattern over Europe can be important. To represent the variability of the model simulations, four scenarios were chosen by the KNMI, which combine two different levels of mean global temperature rise (+1°C or +2°C, abbreviated with G and W) with two anticipated atmospheric circulation regime changes; a strong and a weak change of circulation. The two scenarios in which a change in the circulation pattern is assumed are coded with a plus (the G+ and W+ scenario) (KNMI 2006; Van den Hurk et al. 2006). The produced scenarios mainly focus on changes for the year 2050.

2.3 Tree species

In this study, we estimated the impact of climate change on the present day forest composition and did not consider possible changes of this forest composition in future. To assess the present day tree species composition, we used data from the latest Dutch forest inventory (Dirkse et al. 2007). This inventory was conducted in the period 2001-2005. A first result of this inventory was the construction of a map showing the forested areas in the Netherlands (Dirkse et al. 2001). During the forest inventory, this map was used to select sampling plots. In total 3622 plots were selected and sampled during the inventory and in each plot information on tree species composition and stand age was collected (Daamen & Dirkse 2005; Dirkse et al. 2007). Each plot was assigned one dominant tree species. In this assignation no difference was made between the two native oak species *Quercus robur* and *Q. petraea*, between the birch species *Betula pendula* and *B. pubescens* and between the different species of the genus *Populus* (Dirkse et al. 2007). In the Netherlands especially poplar trees of the hybrid *Populus x euramericana* (synonym for *P. x canadensis*) are common (Maes 2006; Schotveld in Wiersma & Westra 1981; Schmidt 1987; Weeda et al. 2003b). During our literature review we focused especially on the species which were the dominant species in most of the forested area: *Pinus sylvestris*, native oak (*Quercus robur, Q. petraea*), birch (*Betula pendula, B. pubescens*), *Fagus sylvatica*, *Populus*, *Alnus glutinosa*, *Fraxinus excelsior*, *Pseudotsuga menziesii*, *Picea abies*, *Larix kaempferi*, *Pinus nigra var. maritima* and *Quercus rubra*.

3 Results of the literature review and the assumptions which were used to construct the maps

3.1 Decreased water availability during the growing season

Drought and climate change

The effects of climate change on water availability during the growing seasons in future, differs considerably between the four KNMI scenarios. All four scenarios show an increase in average summer temperature. In the two scenarios without a changing atmospheric circulation pattern (G and W scenarios), the potential evaporation in summer is expected to increase with a few percent, and so is the amount of precipitation (Van den Hurk et al. 2006). For these two scenarios, soil moisture deficits are expected to be similar to present values (RWS 2007). In the two scenarios with a change in the atmospheric circulation pattern, the potential evaporation is expected to increase with 8 to 15% in summer while the amount of precipitation is expected to decrease with 10% (G+) or even 19% (W+). As a consequence, under these two scenarios, soil moisture deficits during summer are larger than deficits presently. Especially under the W+ scenario summer droughts can be severe (RWS 2007).

The effect of climate change on groundwater levels was modelled by Van der Gaast & Massop (2009). They calculated the average lowest (GLG) groundwater level and the average water level in spring (GVG) in 2050, for each of the four KNMI scenarios. This modelling exercise showed that for the two plus scenarios, in which a change of the circulation patterns was assumed, the average water level in spring (GVG) might slightly increase, while the average lowest groundwater levels (GLG) will decrease in future. Especially the 'stuwwallen', higher sandy areas like the Veluwe or the Utrechtse Heuvelrug, will be drier under these scenarios (Van der Gaast & Massop 2009). For the two scenarios without a change in the circulation pattern (W and G scenario), only in some areas the average lowest groundwater level will slightly decrease.

Tree species need water for their growth. In the seventies and eighties of the previous century, research to the relation between soil water supply and the growth of tree species intensified in the Netherlands. The results of these studies and the results of a literature review were summarized by Van den Burg (1987, 1990). Especially the growth of the species *Fraxinus excelsior* and *Alnus glutinosa* declines with decreasing water availability, as mentioned in other literature as well (Arnoldussen in: Schmidt 1987; Wiegers in: Schmidt 1987; Weeda et al. 2003a). Of the coniferous species, *Picea abies* does not grow well on dryer sites (Schmidt-Vogt in: Schmidt 1987).

Assumptions

To obtain estimates of the growth reduction by drought, information on the amount of water which can be supplied by the soil to trees (Van der Gaast & Massop 2009), was combined with information on the growth of tree species at different levels of soil water supply (Van den Burg 1990). We estimated the potential tree growth for the current situation and for the W + scenario.

Information on the relation between tree growth and soil water supply was obtained from the studies by Van den Burg (1987, 1990) (see Appendix 1). For the two species of birch no data were presented in table 11 of Van den Burg (1990). Most of the plots which are dominated by birch however can be found on nutrient poor sandy soils (database of the Dutch forest inventory 2001-2005). On these sites, *Betula pendula* is the common species of birch (Weeda et al. 2003a). This species is known to stand dry conditions well (Schoenmakers en de Graaf in: Schmidt 1987; Wiersma & Westra 1981) and for 'birch' we therefore assumed a relatively high tree growth on soils with low soil moisture availability (see Appendix).

Based on the data by Van den Burg, we constructed a table with the relation between tree growth and soil water supply (see Appendix 1). The tree species were divided into three groups. The first group are species which are resistant to drought and contains species like pine and native oak. These species keep a relatively high growth even when the soil can not supply much water. The third group of species are the species which are very sensitive to drought and which hardly grow when the soil water supply is low. Common ash and alder are in this group. Then there is a large group of species, containing beech, spruce and larch, which are intermediate between these two groups in their reaction to a low soil water supply.

In the original table presented in Van den Burg (1990), the soil water supply was divided into five groups, from a very low level of water supply (<50 mm) to the upper level of >200mm (see Appendix 1). The upper level is given to soils which can supply trees in a '10% dry year', during a growing season of 150 days (1 April – 1 September), with enough water to sustain normal growth (Van Soesbergen in: Van den Burg 1990; Van der Gaast & Massop 2009). A 10% dry year, means a dry but not extremely dry year, which occurs statistically once every ten years. In such a 10% dry year, during the growing season, the potential evapotranspiration would be 200 mm larger than the precipitation. Under the W+ scenario, temperatures are higher and precipitation is lower than presently and during the period 1 April – 1 September this 'precipitation deficit' will increase to 290 mm, in a 10% dry year (data provided by Van der Gaast en Massop). Van der Gaast and Massop also provided data on the soil water supply for the current situation. In their scenario of the current situation, the precipitation deficit, in a 10% dry year and during a growing season of 150 days (1 April – 1 September), was not 200 mm but 220 mm. Based on these data, we adapted the relations between soil water supply and tree growth. For the W+ scenario, we assumed tree growth to be 100% if the soil was able to supply more than 290 mm of water (see Appendix 1). The other classes were adapted correspondently. For the scenario of the current situation, tree growth was assumed to be optimal if the soil was able to supply more than 220 mm of water (see Appendix 1) and the other classes were adapted correspondently.

Information on the supply of soil water was provided by Van der Gaast & Massop (2009). They calculated the supply of water from the soil to trees under the current climate and under the W+ scenario. The supply of soil water to trees was calculated as the maximum of the potential groundwater supply by capillary rise and the available water in the root zone of the trees at the start of the growing season. The potential ground water supply was based on the average lowest water level (GLG) (see Van der Gaast & Massop 2009).

The information on the soil water supply was provided by Van der Gaast as two maps, showing the soil water supply for a 10% dry year for the current situation and for the W+ scenario. Using the program ArcMap, for each forest inventory plot tree growth under the current situation and under the W+ scenario was calculated using the relations presented in Appendix 1. Further, for each inventory plot tree growth under the W+ scenario was expressed as tree growth in the current situation.

3.2 Increased soil water levels during the growing season

Increased soil water levels and climate change

For the temperate regions, an increase in total annual precipitation is expected under climate change. According to the G and W scenarios, both summer and winter precipitation will increase with 3-7% percent. Under the G+ and W+ scenarios, winter precipitation is expected to increase as well, with even 7-14%, but summer precipitations will decrease with 10-19%. Not only is the amount of precipitation expected to change, but also the intensity of showers. In all four scenarios, the amount of precipitation which falls during intense showers in summer is expected to increase. The amount of rain which falls during prolonged periods with heavy rain in winter is expected to increase for all scenarios as well (KNMI 2006; Van den Hurk et al. 2006).

The effect of climate change on groundwater levels was modelled by Van der Gaast & Massop (2009). They calculated the average lowest (GLG) groundwater level and the average water level in spring (GVG) in 2050, for each of the four KNMI scenarios. This modelling exercise showed that for the two plus scenarios the average lowest groundwater levels (GLG) will not increase in future (but will decrease), while the average water level in spring (GVG) increases with at most 10cm. Under both the W and G scenario, both the average lowest groundwater level and the average water level in spring are higher than the actual values for a number of areas in the Netherlands. Especially areas situated on elevated sandy soils, like the Veluwe or the Utrechtse Heuvelrug, will be wetter under these scenarios (Van der Gaast & Massop 2009).

Tree roots need oxygen for their functioning and a lack of oxygen caused by a high groundwater level can harm trees. Such damage to the roots of trees can be recognized by the drying out and dying off of twigs and buds in the upper parts of the crowns of trees during dry periods (Olsthoorn et al. 2003; Stuijfzand et al. 2007, 2008). A waterlogged soil might even lead to a dieback of total tree crowns. The way in which the extra water enters the soil, appears to be of importance for the kind of damage water might cause to trees (Stuijfzand et al. 2008). When due to an excess of water, the level of the groundwater starts to rise, it drives out oxygen from the soil. Inundation of land by water however, has a different impact upon the oxygen availability in the soil. When land is inundated, for instance during a flood, the oxygen can be captured in the soil by the water flowing over it.

Last decades in the Netherlands, many forests and nature reserves suffered from increased desiccation due to the lowering of groundwater levels (Nabuurs 1992; Hendriks 1994; De Vries & Hendriks 1996), but see also Van der Gaast et al. (2008). To reduce the effects of desiccation in forests, forest owners often tried to retain water, for instance by filling up ditches or by increasing the water level using dams. In some areas, these measures resulted in damage and even death of trees due to excess soil moisture in spring and summer (Olsthoorn et al. 2003; Moraal et al. 2004). To get a better understanding of the effects of raising groundwater levels on tree species, field surveys and field experiments were undertaken in response. The findings of these studies were summarized in Olsthoorn et al. (2003). Common species like *Quercus robur* and *Fagus sylvatica* appear sensitive to a sudden rise of the water table during the growing season.

Assumptions

We used information on the effects of climate change on groundwater levels (Van der Gaast & Massop 2009) and information on the sensitivity of tree species to a rise in groundwater level (Olsthoorn et al. 2003), to estimate the impacts of increased water levels on tree species. Both the effects of an increased average lowest water level (GLG) and the effects of an increased average water level in spring (GVG) were assessed.

First, for each forest inventory plot, we determined the changes in average lowest groundwater level (GLG) under climate change. This change was calculated in ArcMap, using maps of the actual GLG and of the GLG under different scenarios of climate change, provided by Van der Gaast & Massop (2009). Then, for each forest inventory plot the impact of these changes in GLG on the tree species were assessed. To estimate the impact, for each forest inventory plot, information on the actual groundwater level ('grondwatertrap', the Gt, also provided by Van der Gaast & Massop (2009)) was combined with information on the sensitivity of tree species to rises of groundwater level (Olsthoorn et al. 2003) (see Appendix 2). In Olsthoorn et al. (2003) no information on the common species *Picea abies*, *Pinus sylvestris* and *Pinus nigra var. maritima* was presented. *Picea abies* and *Pinus sylvestris* appear to have a high tolerance for high groundwater levels (Wiersma & Westra 1981; Van den Burg 1990; Van Baren en Schoenmakers in: Schmidt 1987; Weeda et al. 2003b). Information on the tolerance of *Pinus nigra var. maritima* to high groundwater levels was not found and it was assumed that this species was sensitive to a change in groundwater level.

Following the same procedure, also the effects of a rising average water level in spring were assessed. Again, the changes in water level under climate change were determined, using data provided by Van der Gaast & Massop (2009). Then the impacts of these changes in GVG were assessed, using the same sensitivity of tree species as for the GLG (Appendix 2).

3.3 Forest fire

Due to the higher temperatures and increased evapotranspiration in summer, climate change is likely to increase the exposure of forests to fire (Schelhaas & Moriondo 2007). Another process however, the change of tree species composition due to forest succession is likely to reduce this exposure. In general, coniferous forests, and especially young stands of pine trees, are more susceptible to the initial stages of a forest fire than stands of broadleaved trees (Wijdeven et al. 2006). In the Netherlands, the area of coniferous forest is decreasing while the area of mixed forests is increasing (Dirkse et al. 2007). This change in forest composition will probably continue in future, resulting in a reduced chance of a forest fire to occur (Wijdeven et al. 2006; Schelhaas & Moriondo 2007).

Assumptions

To assess impact of forest fire under climate change, we divided the forest inventory plots in three categories (Wijdeven et al. 2006). Plots consisting of broadleaved trees and plots with both broadleaved and coniferous trees were assumed not to be susceptible to the initial stages of a forest fire. Plots with mainly coniferous trees were assumed to be moderate susceptible to the initial stages of a forest fire and plots with pine trees established after 1975 were assumed to be highly susceptible to the initial stages of a forest fire. Basal area was used to distinguish between coniferous plots, mixed plots and plots dominated by pines. Coniferous plots were those plots where the basal area of all coniferous trees was more than 70% of the total basal area in the plot. Plots were dominated by pine when the basal area of the pine trees in the plots was more than 70% of the total basal area.

3.4 Salinization

Salinization and climate change

Salinization in the Netherlands is affected in different ways by climate change. A distinction can be made between 'external' and 'internal' salinization. External salinization is the entering of saline surface water into an area, through canals, streams and ditches while internal salinization in an area is caused by saline groundwater rising to the soil surface (Jacobs 2007). Saline sea water can enter the Netherlands through open connections to the sea, like the Nieuwe Waterweg, causing external salinization. The distance saline sea water travels upstream depends on the sea level and the discharge of rivers, and is therefore affected by climate change (Jacobs 2007; RWS 2007). Internal salinization is affected by climate change too. The amount of internal salinization in the western and northern parts of the Netherlands is increasing due to a lowering of the water and soil levels in these regions (Oude Essink 2007a, 2007b). In the western and northern parts of the Netherlands, the land is subsiding as a result of the construction of 'polders' and the draining of arable land. The lowering of the soil and water levels in these areas results in an increased seepage of groundwater to these regions.

Climate change will affect internal salinization in several ways. A rising sea level will increase the amount of saline seepage water entering the coastal areas (Oude Essink 2007b). Water in oceans reacts only slowly to global change and therefore there is not a large difference in sea level rise for the period 2000 – 2050, between the four KNMI'06 scenarios (KNMI 2006). Also the amount of saline seepage water entering our coastal areas is predicted to be fairly constant under different climate change scenarios(RIZA 2005). It is expected that the amount of saline seepage water will increase in 2050, to a level that is 15-20% higher than today (RWS 2007). Besides sea level rise, internal salinization is also affected by changes in the amount of precipitation and temperature. Chloride concentrations in surface water and top soil are influenced by the amount of incoming saline water but also by the amount of available fresh water. The regional Dutch water management, the Waterschappen, try to prevent adverse effects of salinization by washing out saline seepage water with fresh water. If the quantity of available fresh water is low, due to a lack of precipitation, high evapotranspiration, or external salinization, flushing polders with fresh water becomes difficult and chloride concentrations will rise (RIZA 2005). Salinization will therefore especially be a problem in dry and warm years, when the amount of precipitation is low, when river discharges are low and when the evapotranspiration is high. This is shown by observations from the extremely dry and warm year 1976 (Van den Burg & Schoenfeld 1977; RIZA 2005) and by the calculations of chloride concentrations in surface water under different scenarios of climate change (RIZA 2005; RWS 2007).

Water containing salt (NaCl) damages trees mainly by the effect of the chloride ions. When chloride ions are taken up by the roots of trees, this can lead to a growth reduction or to visual damage like the necrosis of the edges of leaves. When salt concentrations are high enough, it might even lead to the dying off of the tree, (Van den Burg & Schoenfeld 1977; Van den Burg 1983). Tree species differ in their sensitivity to saline soil water. Following the drought of 1976, a number of field surveys to the damage of tree species by saline soil water were conducted in the Netherlands and the results of these surveys and the results of a literature review were summarized in Van den Burg (1983).

Assumptions

To estimate the impact of salinization on Dutch forests, information on the exposure of the forests to salinization was combined with information on the sensitivity of three species to saline water. To assess the effects of salinization on trees, ideally information on chloride concentrations in the top soil (0 to -1 m) under different scenarios of climate change is needed. However, such information is still lacking (pers. comm. G. Oude Essink, Deltares). We therefore assumed forests to be exposed to saline water in those areas where the amount of entering saline seepage water (zoutbezwaar-zoutbelasting) is expected to be high in future. We distinguished three categories of exposure to salinization (see Appendix 3):

- Areas where the exposure to saline water is low, consisting of the geographical regions (Bal et al. 2001) sandy soils ('hogere zandgronden' and 'duingronden'), river clay soils ('rivierklei'), the hilly part of Limburg ('heuvelland') and low lying peat ('laagveen') in Friesland and Overijssel, where almost no entering of saline sea water is expected (RIZA 2005; RWS 2007).

- Land where the exposure to saline water is moderate. Included in this category were the geographical regions ('zeeklei') and peat ('laagveen') (geographical regions according to Bal et al. (2001)), since in these regions saline seepage water is expected to enter (Figures 11, 12 in RWS 2007). Parts of Overijssel and Friesland which are situated on peat, where excluded from this category, since in this region no saline seepage water is expected (RIZA 2005; RWS 2007).
- Land where the exposure to saline water is high. This category consists of those areas where under the G scenario of the KNMI and during a very dry year, the concentration of salt in surface water is expected to be higher than 1 g/l (Figure 12 in RWS (2007)). Land included in this category were The polder Wieringen, the Lauwersmeer, the islands of Terschelling, Ameland en Schiermonnikoog and land situated on sea clay (Bal et al. 2001) in Zeeland and on Texel.

The tree species were divided in two groups (see Appendix 4), based on their sensitivity to saline soil water. This division was mainly based on the NaCl concentration at which species show visual damage from saline soil water. The species in the first group, which are more sensitive to saline water, show visual damage when the soil moisture concentrations of NaCl are lower than 4 g/l (Van den Burg 1983). The species in the second group are somewhat less sensitive to saline water, showing visual damage at concentrations higher than 4 g/l NaCl (Van den Burg 1983).

To assess the effects of salinization on the trees in the forest inventory plots, the information on the exposure to saline water was combined with information on the sensitivity of tree species. This resulted in four impact categories from low (0) to high (3) (Table 2).

Table 2 Potential impact of saline water to the forest inventory plots.

Sensitivity of tree species to saline water (see appendix)	Exposure to saline water (see appendix)	Potential impact
Main tree species somewhat less sensitive for salinization	Low exposure (no entering of saline seepage water (fig 11 (RWS 2007))	0
	Moderate exposure (entering of saline seepage water (fig 11 (RWS 2007))	1
	High exposure (entering of saline water and high concentrations in surface water (fig 11-12 (RWS 2007))	2
Main tree species sensitive for salinization	Low exposure (no entering of saline seepage water according to fig 11 (RWS 2007))	0
	Moderate exposure (entering of saline seepage water according to fig 11 (RWS 2007))	2
	High exposure (entering of saline water and high concentrations in surface water, fig 11-12 (RWS 2007))	3

3.5 Insect pests

3.5.1 Current situation

Massive attacks of insects and diseases (bacteria, viruses, fungi) may constitute major risk factors for the health and vitality of forest ecosystems. Large scale outbreaks can cause considerable economic loss to forest owners. These biotic damages may result in the deterioration of tree condition, not only in the year of occurrence, but also in later years. Insects and fungi often appear on trees weakened after drought, frost, hail, storm or forest fires and thus are part of the natural dynamics of forests, which in some cases may contribute to a serious destabilization of the stands. Insect populations are likely to react to long-term environmental change processes such as those caused by climate change. Extreme weather conditions such as heavy storms and drought can elevate the risk of a mass propagation of e.g. bark beetles. To obtain relevant data on the current situation of forest damage in the European Union, a questionnaire was developed with among other themes - the current situation on forest damage in the EU (Schuck & Requardt 2007) (Table 3). From Table 3, it can be concluded that the main threats to the forests in the EU are insects, followed by storms/windfall and wildlife grazing. However, in different regions, also fire, drought (Southern Europe) and diseases (Northern Europe) have a high regional significance (Schuck & Requardt 2008). So, damage by insect pests and diseases has a high ranking for countries in Western Europe, such as The Netherlands.

Table 3. Average ratings of the main threats to forests in Europe according to questionnaire responses (Schuck & Requardt 2008). Scale from 1-5: 1= negligible; 2= occasionally a problem at local scale; 3= regularly problem at local scale; 4= regularly a problem at local scale, but with a tendency of large scale distribution; 5= serious problem at large scale.

Damaging agent	Northern	Central	Western	Eastern	Southern	Total
Insects	3.4	3.8	3.1	3.0	3.0	3.3
Wildlife grazing	3.4	2.5	3.0	2.7	1.8	2.7
Storm/windfall	2.8	3.0	3.6	2.7	1.6	2.8
Drought	1.4	2.5	2.9	3.3	3.0	2.6
Diseases	3.2	2.5	2.4	2.7	2.2	2.6
Fire	1.8	3.0	2.0	2.3	3.4	2.5
Pollution	1.2	2.0	2.4	2.3	1.8	2.0
Invasive species	1.2	1.8	2.6	2.0	1.4	1.8
Domestic animals	1.0	2.3	1.3	1.7	2.4	1.7
Poor management	1.2	2.0	2.0	1.3	3.0	1.7
Snow/ avalanches	1.6	1.8	1.4	1.7	1.6	1.6
Illegal logging	1.4	1.8	1.1	2.7	1.2	1.5

3.5.2 Direct and indirect effects of climate change on insect pests

Climate change is expected to have an important impact on the manifestation of insect pests and diseases on forest trees. Two kinds of effects may be expected on the occurrence of insects, a direct and indirect effect. Direct effects are the result of changes in the insects' physiology such as larval performance, overwintering and distribution. In particular, increased temperatures will allow many species to expand their distributional ranges northwards or to higher altitudes. They will also cause more frequent outbreaks because the higher winter temperatures allow a higher survival and more rapid development. Furthermore, certain insects can produce more generations during a growing season. Indirect effects are related with changes in the quality or vitality of the host trees. Most studies have concluded that insect pests will generally become more abundant (Battisti, 2006; Cannon, 1998; several references in Vanhanen, 2008). It is hard to find indications that some pests are expected to decrease in the future.

Direct effects
The geographic distribution of many forest insects is more limited than their host distribution. Therefore, insect distribution could change very rapidly in response to climatic variations. European and Dutch butterfly populations extended northwards, and southern ranges reduced (Evans et al. 2002; Ellis et al. 1997). The same is likely to be the case for forest insect pests. Species distributions are often limited in their northern range by winter temperatures and increase in mean annual temperature means may favour populations to extend their geographic distribution. An example is the oak processionary moth, *Thaumetopoea processionea*. This South-European species is occurring in The Netherlands since 1991, and causes with its irritating hairs many problems to people. The related pine processionary moth, *Thaumetopoea pityocampa*, previously limited at about the Loire valley in France, moved 90 km north in the last 30 years. In 2003, this insect was negatively impacted by high summer temperatures in the continental areas, but an increase of the winter temperature may have allowed the survival of remaining larvae and the progress of the migration front. Another example of a direct effect is the warmth-loving oak buprestid beetle, *Agrilus biguttatus*. This rare species became a pest in The Netherlands and other European countries, presumably because of the elevated temperatures (Moraal & Hilszczanski 2000). Elevated temperatures and high moisture also favour sap-sucking aphids such as the poplar woolly aphid, *Phloeomyzus passerinii* and the beech woolly aphid, *Phyllaphis fagi* (Roualt et al. 2006).

Indirect effects
Indirect effects of climate change have been noted to alter the behaviour of insects and their hosts such as altering of synchrony between host and insect pest development in spring. Oak bud burst has already advanced up to 20 days during the late 20th century. The time of egg hatching of spring feeders such as the winter moth, *Operophtera brumata*, should be synchronized with the time of bud burst (Evans et al. 2002). The change may also affect the quality of the host on which the herbivore feeds. Egg hatching during a drought period is negatively affected by leaf texture changes (several references in Vanhanen 2008).

Rising atmospheric CO_2 concentrations may lead to a decline in food quality for certain plant-feeding insects, as a result of reduced foliar nitrogen levels (Evans et al. 2002). Some insects respond by increasing leaf consumption and consequently the damage to the tree, whereas others show higher mortality and lower performance. The level of plant chemical defences may also be affected by a change of CO_2 (many references in Battisti 2008).

Future climate change models for Western Europe predict an increase in temperature, drought periods, and heat waves during the growing season. Although drought directly affects tree physiology and growth, the impact of secondary factors (insect pests, pathogens and fire) is often greater than the impact of the original stress and can lead to important tree mortality. In 2003, Western and Central Europe experienced a drought and heat waves that led to extensive forest damage. The French Forest Health Department (DSF) made pest observations from 2003–2004, during and after the drought, to study changes of population levels of the main forest insect pests. Forest pest insects were separated in 4 feeding guilds: wood-borers, leaf-consumers, leaf-miners and sap-feeders. The impact of water stress varied according to feeding guilds. These observations give us indications of the impacts of extreme climatic events for the future.

Wood-borers, such as the bark beetles *Ips typographus* and *Pityogenes chalcographus* feeding on Norway spruce were positively influenced by prolonged water stress and the decline of host resistance. The first mechanical defence of conifers against wood-borer attacks, the resin flow, is reduced under severe water stress but is increased under a moderate drought. In contrast with *Ips typographus* and *Pityogenes chalcographus* on Norway spruce, whose populations increased in 2004, populations of *Ips acuminatus* on Scots pine have decreased (Roualt et al. 2006). However, for Scots pine in Switzerland, the drought of 2003 led to more tree mortality as a result of infestations by the buprestid beetle, *Phaenops cyanea* (Wermerlinger et al. 2008). Conifers react differently to water stress. For example, Norway spruce is the conifer least resistant to water stress, particularly on unfavourable sites. Scots pine was one of the conifers species least weakened by drought at the end of August 2003. May be, they were not stressed enough to attract *Ips acuminatus.* Following the 2003 drought, also wood-boring insects on oak, fir and beech have increased.

In contrast, defoliators (such as *Lymantria dispar* and *Thaumetopoea pityocampa*) profited better from the increased nitrogen in plant tissues linked to moderate or intermittent water stress (Roualt et al. 2006). The field observations showed the importance of the soil water status in tree resistance against pest attacks. Thus, the 2003 drought confirmed observations from earlier droughts that, in case of bad choice of tree species in some plantations, site matching becomes a prominent and primary cause of the development of pest outbreaks (Roualt et al. 2006). Broadleaf defoliators (such as the winter moth *Operophtera brumata* and oak leaf roller moth *Tortrix viridana* may be negatively affected by continuous high water stress but the populations increased in 2003 and 2004 – they may have benefitted from the warm spring, without suffering from the dry and hot summer.

It was concluded that the insects responded differently after the dry summer in 2003. The secondary wood-boring insects showed a significant increase in 2003, while the primary defoliating insects reacted with an increase in 2003 and 2004 (Roualt et al. 2006). An increased incidence of summer drought would make trees more vulnerable to attack by weak pathogens (secondary insects). On the other hand, increased winter rainfall may raise water tables enough to kill roots, thereby reducing effective rooting depth and making trees more vulnerable to summer droughts (Redfern & Hendry

2002). Consequently, drought followed by a warm wet winter will likely promote outbreaks. The impacts of the 2003 drought illustrate the sensitivity of most of the major Western European forest insect species to extreme drought and heat waves.

In some scenarios, climate change may lead to an increase of storms. The occurrence of many storm-felled trees will form optimal breeding substrates for secondary bark beetles. They may reach very high population densities and become a threat for healthy trees. Bark beetle species such as *Ips typographus, Tomicus piniperda, Dendroctonus micans* and *Phaenops cyanea* are capable of becoming primary pest insects (Moraal et al. 2004; Moraal 2008; Wermerlinger et al. 2008). The resistance of trees has been acknowledged for a long time to be a crucial factor for the success or failure of bark beetle attack. But the assessment of the impact of climate change on bark beetles has hardly started (Wermerlinger et al. 2008).

3.5.3 Invasive species – new threats

Exotic phytophagous insects are invading forest ecosystems worldwide. So far, 109 invasive insects on woody plants, 57 from North America and 52 from Asia have established populations in European forests (Mattson et al. 2007). Climate change will almost undoubtedly affect the ability of non-native insect and pathogen species to establish and spread. Rising temperatures in particular will likely benefit invading insects and pathogens and expand their potential range (Hunt et al. 2006).

The combined effects of increased global trade of timber and wood products and climate change are likely to result in exotic pests such as the Asian longhorn beetles *Anoplophora chinensis* and *A. glabripennis* becoming more prevalent. These species are already established in some European countries. When accidently introduced into Europe, the Asian emerald ash borer, *Agrilus planipennis* and the American southern pine beetle, *Dendroctonus frontalis,* may become a serious threat, because these wood-boring beetles are able to kill millions of trees. Climatic comparisons and simulations of climatically or biogeographically suitable areas for targeted high risk species have become increasingly important in targeting preventive or eradicative efforts to prevent establishment in Europe are provided by the EPPO (European Plant Protection Organisation). The EPPO produces lists of pests recommended for regulation as quarantine pests (Vanhanen 2008; www.eppo.org).

3.5.4 Assumptions

The data from the literature review were used to construct a table with estimates on the future risks of insect pests. The pest insects were separated in 4 feeding guilds: wood-borers, leaf-consumers, leaf-miners and sap-feeders. In this table, the scores on the 'risk of manifestation' and the 'potential damage on trees' are an assumption based on our own expert judgement.

4 Potential impacts, results and discussion

4.1 Drought

Results

Because of the higher temperatures and the smaller amount of precipitation under the W+ scenario, the precipitation deficit would increase to about 290 mm, in a 10% dry year, compared to 220mm under the current climate (paragraph 3.1). For trees to grow optimally, this amount of water needs to be supplied by the soil. The data provided by Van der Gaast and Massop show that the soil water supply in a 10% dry year hardly changes from the current situation to the W+ scenario. In the current situation, the average soil water supply to the trees in the forest inventory would be about 193 mm. Under the W+ scenario this would be slightly higher, 203 mm. A main reason for this small change of the soil water supply, is that the average water level in spring (GVG) is similar under the current situation and in the W+ scenario (Van der Gaast & Massop 2009).

In the current situation, a low supply of soil water already seems to limit tree growth (Table 4, Figure 2). Especially on the elevated sandy soils, like the Veluwe and the Utrechtse Heuvelrug the supply of water appears to limit tree growth. Under the W+ scenario however, with the higher evapotranspiration and lower precipitation, the growth of trees is limited in many more plots by a low soil water supply. Most of these extra plots are situated on sandy soils and are distributed all over the Netherlands. As a result, the growth of trees in many of the forest inventory plots is lower under the W+ scenario than in the current situation (Figure 3). The overall result shows that because of a low water supply, growth under the W+ scenario might be about 19% lower than growth in the current situation (Table 4).

Table 4. The average growth in the forest inventory plots, both for the scenario of the current situation and for the W+ scenario. The inventory plots were grouped in three groups, based on the sensitivity to a low water supply of the dominant tree species (see Appendix 1).

Sensitivity of species to low water supply ↓	Average growth in current situation	Average growth under W+ scenario	Growth in W+ scenario (as proportion of current situation)
	As proportion of maximum growth		
Resistant	77 %	63 %	81 %
Intermediate	78 %	63 %	79 %
Sensitive	99 %	90 %	90 %
Total	78 %	64 %	81 %

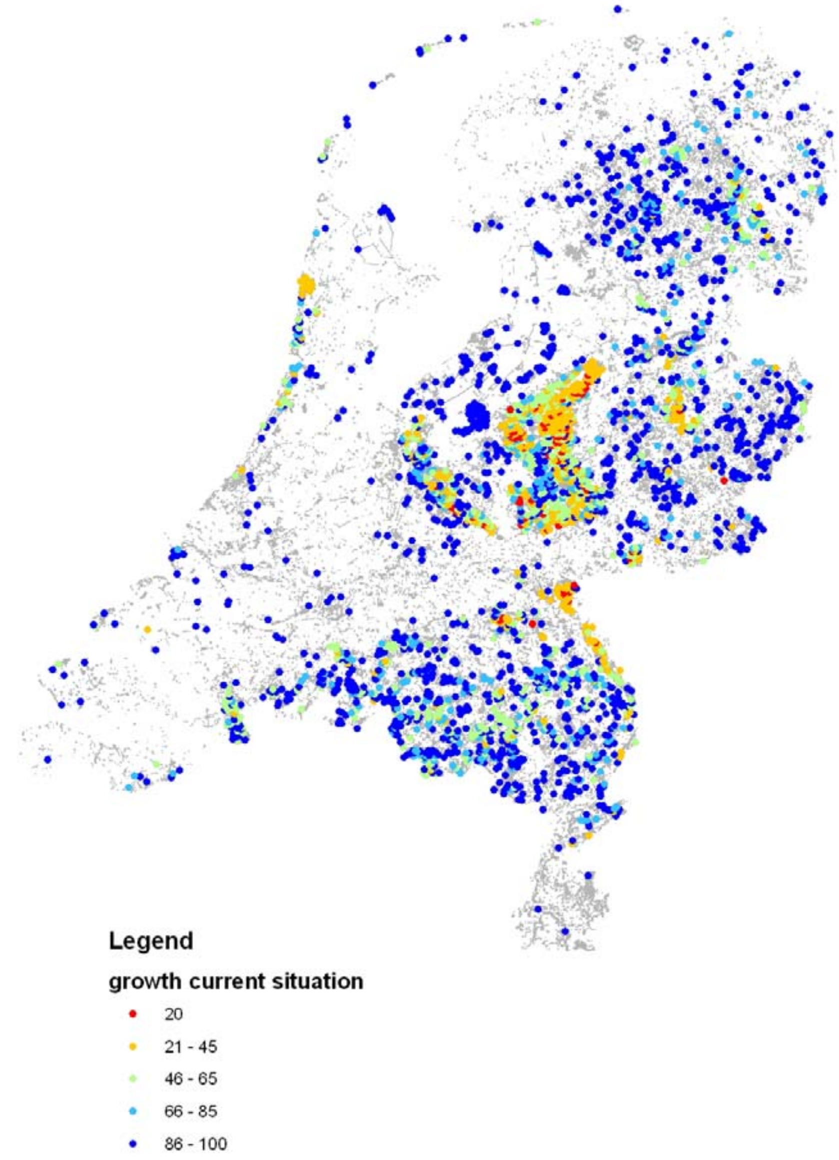

Figure 2. Limitation of tree growth by the soil water supply for the scenario of the current situation. Tree growth is expressed in percentages, as proportion of the maximum value of the mean increment at that site.

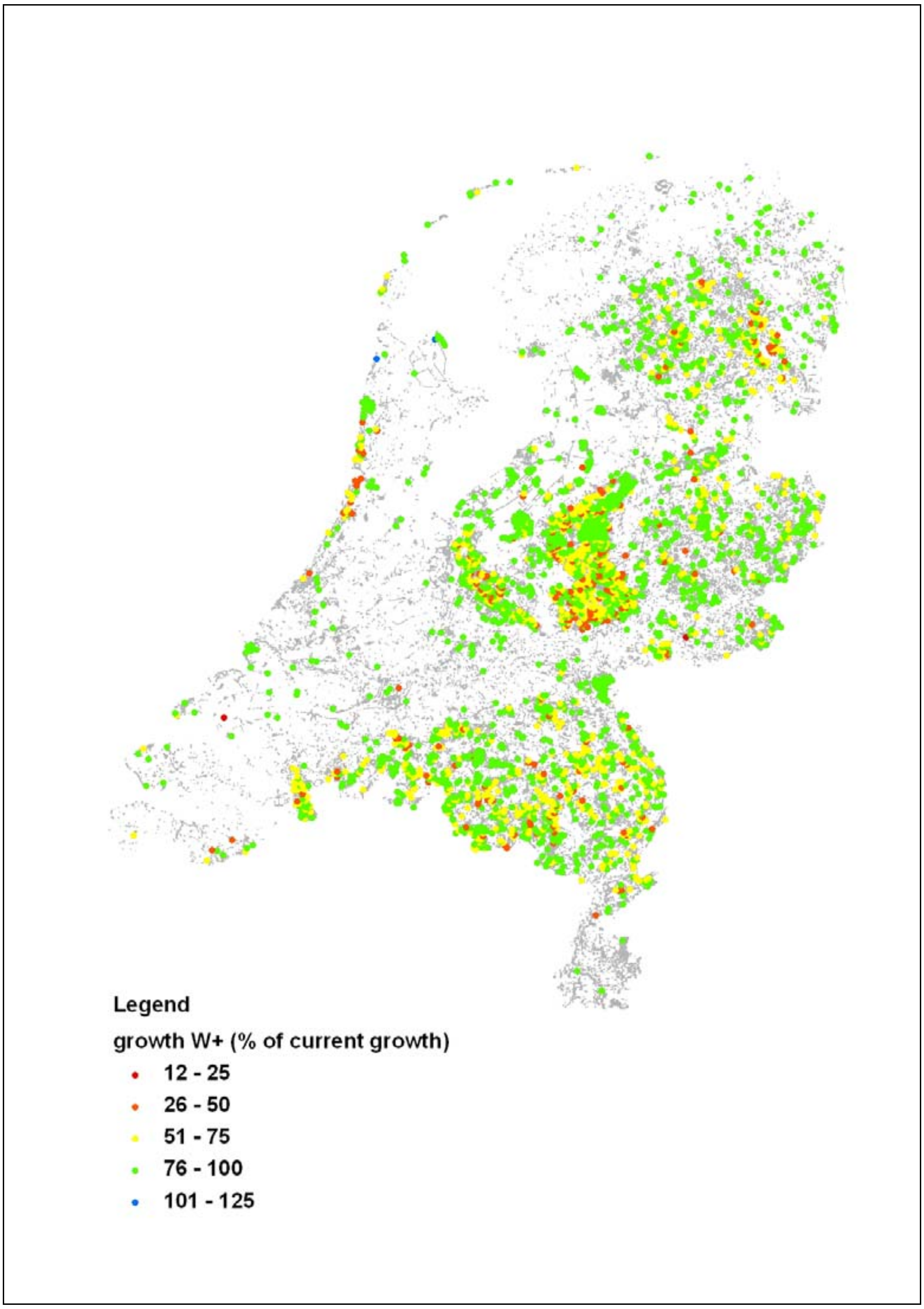

Figure 3. Limitation of tree growth by a low soil water supply, under the W+ scenario. Tree growth is expressed in percentages, as proportion of the growth in the current situation.

Table 5. Proportion of plots within a certain growth class, for three groups of tree species (based on their sensitivity to a low water supply, see Appendix 1).

Sensitivity of species to low water supply ↓	Growth class (growth in W+ scenario, as proportion of growth in current situation) **0-25%**	**26-50%**	**51-75%**	**76-100%**	**101-125%**
Resistant	0	5.1	36.4	58.1	0.1
Intermediate	0	16.1	14.1	69.8	0
Sensitive	1.7	0	5.1	93.2	0
Total	0.1	7.9	29.2	62.8	0.1

In about 63% of the plots, growth will stay more or less at its current level (Table 5). Based on their sensitivity to a low soil water supply, we divided the tree species into three groups (paragraph 3.1, Appendix 1). A large group of forest inventory plots which showed a strong reduction in growth was dominated by the 'resistant species' (Table 5, Figure 4). In 36.4% of the plots dominated by these species, tree growth will be only 51-75% of the growth in the current situation (Table 5). In many of these plots, the soil water supply, both in the current situation and under the W+ scenario, is calculated to be in the range of 80-180 mm. These plots are situated on soils with a low ground water level in summer (GLG) and can be found on the Veluwe, Utrechtste Heuvelrug, Drenthe, Brabant, Limburg and the dune areas. Many of these plots are dominated by the species *Pinus sylvestris* and also native oak is a common species in these plots.

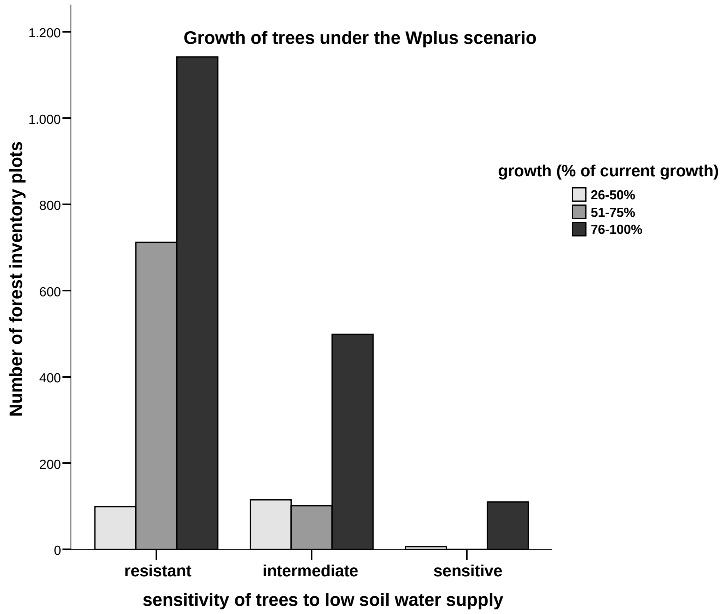

Figure 4. Number of plots within a certain growth class, for three groups of tree species (based on their sensitivity to a low water supply). Growth under the W+ scenario is expressed as proportion of growth in current situation.

Within the 58.1% of plots of the resistant species which do not show a large growth reduction (Table 5), there are hundreds of plots situated on similar soil conditions with a low groundwater level in summer. However, these plots already had a low maximum growth under the current climate. Under climate change, their growth stayed at this low level and therefore hardly changed. But within this group of 58.1%, there were also several hundreds of plots which did have a relatively high growth and which were able to keep up this growth under climate change. These plots were situated on soils with a somewhat higher ground water level in summer. Obviously this higher ground water level might enable these trees to keep growing, even during dry summers.

Within the group of species which are intermediate sensitive to a low water supply, also a large growth reduction was observed (Table 5, Figure 4). In about 200 plots growth is expected to be much lower under the W+ scenario than in the current situation. Also many of these plots are situated on the elevated and sandy soils. Many of these plots are dominated by species like beech, spruce, larch and *Quercus rubra*.

Discussion

The results indicate that under the W+ scenario, in a large proportion of the inventory plots the growth of trees will be limited by summer droughts. An important cause for the increased summer droughts is the high precipitation deficit which was used for this scenario. Based on data provided by Van der Gaast and Massop, we assumed a precipitation deficit of 290mm in a 10% dry year. Other studies confirm the strong increase of the precipitation deficit under the W+ scenario (KNMI 2006; Van den Hurk et al. 2006; RWS 2007). The precipitation deficit is likely to increase under the G+ scenario as well and it is therefore likely that drought will also limit growth of trees in many inventory plots under the G+ scenario. Although not as strongly as under the W+ scenario. Under the G and W scenario, precipitation and evapotranspiration during summer more or less balance each other (Van den Hurk et al. 2006; RWS 2007; Van der Gaast & Massop 2009), so for these two scenarios the precipitation deficits in summer are not expected to increase. Therefore, under the G and W scenarios, drought will probably not cause an extra growth limitation compared to the current situation.

We estimated the potential impact of drought by combining information on the soil water supply with information on the relation between tree growth and soil water supply. The data which were used to construct relations between water supply and tree growth are based on experiments and measurements conducted sometime in the past (Van den Burg 1987, 1990). Under climate change however, many aspects of the growth of trees will change. For instance, the growing season will be longer, since the growth of trees will start earlier in the year (Saxe et al. 2001; Menzel et al. 2006). Further, at a certain level of water supply, higher temperatures and higher CO_2 levels may allow for a higher growth (Saxe et al. 2001; Loustau et al. 2007; Eggers et al. 2008). Overall, the maximum growth of trees with a sufficient water supply might be higher than the maximum levels in the past. Therefore, the potential impacts as were estimated by us (Figure 3) are probably overestimations of the real impacts. To assess the combined effects of a longer growing season, elevated CO_2 and drought, simulation models might be applied.

Information on the soil water supply was obtained from the study by Van der Gaast (Van der Gaast & Massop 2009). The model which they used might slightly overestimate the effect of climate change on the average lowest groundwater level

(GLG). Especially in very dry areas, like the Veluwe, and in very wet areas (Van der Gaast & Massop 2009).

4.2 Rise of groundwater level

Results

For the two plus scenarios, in which a change of the circulation patterns is assumed, the average lowest groundwater levels (GLG) will not increase in future but decrease (Van der Gaast & Massop 2009). We therefore do not expect that under these two scenarios, a rising average lowest groundwater level will cause damage in forests. Under the W and G scenarios, the lowest average groundwater levels will be higher than the actual values for a number of areas in the Netherlands. Especially areas situated on the elevated sandy soils like the Veluwe or the Utrechtse Heuvelrug, will be wetter under these scenarios (data by Van der Gaast). In these areas, infrastructure which might drain the extra precipitation is missing, leading to these increased water levels. In other areas in the Netherlands, much of the extra precipitation will be discharged through for instance ditches, and no strong rise of the water table is foreseen (Van der Gaast & Massop 2009). On the elevated sandy soils where water tables might rise, groundwater levels are often situated several meters below the soil surface. Therefore in only 0.6% (G scenario) and 1.5% (W scenario) of the plots, a rising lowest groundwater level might cause damage. In these plots, the lowest groundwater levels are often situated more than one meter below the surface, but the increase of the lowest groundwater level in these plots might be high (more than 40 cm). Most of these plots concern forests with *Pinus sylvestris* or oak on elevated sandy soils (Figure 5).

Besides the effects of a rise of the average lowest groundwater level (GLG), also the effects of a rise of the average water level in spring (GVG) were assessed. The results for the rise of the GVG were very similar to the results for the rise of the GLG. Like for the GLG, also for the GVG hardly any increase in water level is expected under the W+ and G+ scenarios. Under the G and W scenarios, especially areas situated on elevated sandy soils will be wetter. In 1% of the plots under the G scenario and 2% of the plots under the W scenario a rise of the average water level in spring might cause problems to trees. Like for the GLG most of these plots are situated on the Veluwe or the Utrechtse Heuvelrug, and most of these plots concern forests with the species *Pinus sylvestris* or oak.

Figure 5. Potential impact of a rise of the average lowest water level (GLG) on the trees in the forest inventory plots, under the W scenario.

Discussion
In some areas, a rising groundwater level will probably stimulate tree growth. In the present study however, we tried to assess potential risks and therefore this potential positive effect was not taken into account.

If the expected rise of the groundwater level will really harm trees will depend on the time period in which the rise of the water level takes place. The increase of groundwater level which we calculated, is the differences between the present average groundwater level and the average groundwater level in the year 2050 (Van der Gaast & Massop 2009). It is however unclear how fast the change in groundwater level will be. Will the groundwater levels rise gradually during this period of more than 40 years, or will there be wet and drier periods? We used information on the sensitivity of tree species from the study of Olsthoorn et al. (2003) (see Appendix 2) to assess the effect of a rise of the groundwater level on trees. The changes in groundwater level presented in Olsthoorn et al. are assumed to take place within 10 years. If the change of the groundwater level is very gradual and takes place during a period longer than 10 years trees might even be able to cope with larger rises of groundwater level than the threshold values which we used (Appendix 2).

4.3 Forest fire

Results
For 2907 forest inventory plots, their susceptibility to forest fires could be estimated and in only 3% of these plots the susceptibility to forest fire was found to be high. 42% of the plots had a medium susceptibility and in 55% of the plots the susceptibility was low. In the southern part of Limburg, in the eastern part of Gelderland, in the coastal areas and in the province Flevoland most plots were not susceptible to forest fire. Plots which were moderately tot highly susceptible to fire were mostly situated on the sandy soils of the north-eastern, southern and central parts of the Netherlands (Figure 6). In these areas, plots which were not susceptible to fire were common as well. Since dry weather and high temperatures stimulate the change of a forest fire to occur, the potential impact of forest fires will be largest under the W+ scenario.

Discussion
To assess the potential impact of forest fires, we applied a static method. Both tree species distribution and the susceptibility of tree species to forest fire were kept constant. As described in paragraph 3.3, both factors are likely to change in future. The area with coniferous forest is currently decreasing, making the forests less susceptible to fire. Rising temperatures on the other hand will make forests more susceptible to fire. For a better, less static assessment of the forest fire risk under climate change, an approach using a simulation model seems needed.

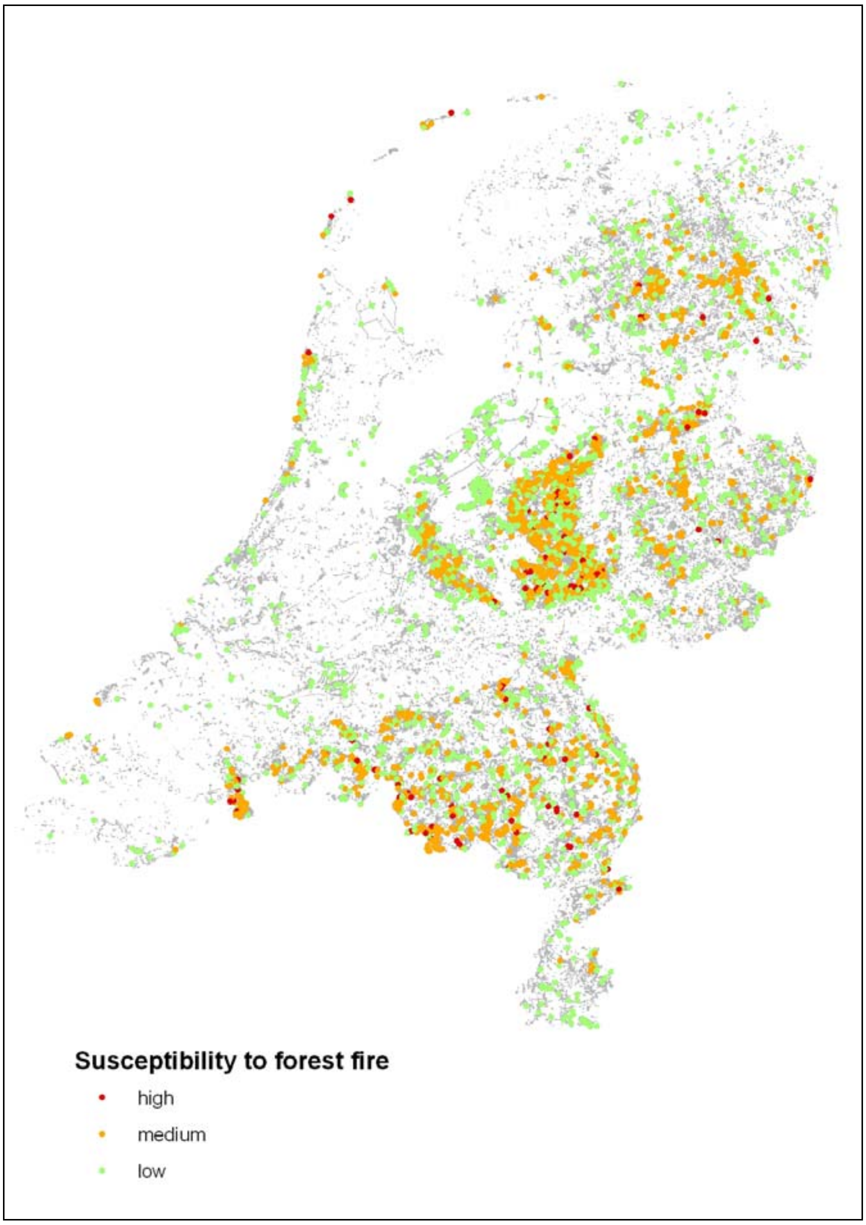

Figure 6.Susceptibility of the forest inventory plots to forest fire

4.4 Salinization

Results

The potential impact of salinization could be estimated for 3514 inventory plots. In 92% of these plots the potential impact was found to be low (Figure 7), what can be explained by the distribution of our forests. Most of our forests are situated on higher grounds in the central, eastern and southern parts of the Netherlands where saline seepage water is not present (RIZA 2005). In 4.5% of the plots to potential impact by salinization was moderate. This category consists mainly of plots with species which are somewhat less sensitive to salinization, situated on areas with a moderate exposure to saline water. Common tree species in these plots were *Fraxinus* *excelsior*, *Quercus robur* and Salix spp. Areas where this category was common were the Biesbosch, Flevoland and the province Groningen (Figure). In the Biesbosch Salix spp was a common tree species, in Flevoland especially *Fraxinus excelsior* and *Quercus robur* were common and in Groningen *Fraxinus excelsior* was a common species. In 3.2% of the plots the potential impact of salinization was found to be moderate to high (category 2). This category consists mainly of plots with Populus spp which are situated on areas with a moderate exposure to saline water. Many of these plots were situated in Flevoland. In only 12 plots (0.4%) the potential impact of salinization was found to be high (category 3). Except for one plot, all these plots were dominated by Populus spp. These plots were mainly situated in the province Zeeland.

Discussion

As described in paragraph 3.4, salinization will especially be a problem in dry and warm years. The W+ climate scenario of the KNMI is the scenario with the driest summers (RWS 2007) and therefore salinization is a larger risk under this scenario than under the other three KNMI'06 scenarios. Under the G and W scenario, the increase of the evapotranspiration in summer will probably be balanced by an increased precipitation (Van den Hurk et al. 2006; RWS 2007; Van der Gaast & Massop 2009). But also under these scenarios, the salinization risk will probably increase, due to the lowering of the soil and water levels in the western and northern parts of the Netherlands and the increased seepage of groundwater to these regions (see paragraph 3.4).

The results show that in the areas where during dry years high concentrations of salt in the surface water are expected (Appendix 3), like Zeeland or the Waddden islands often only small patches of forest are present. The potential impact of salinization on our forests seems therefore small. Locally however, salinization might have a high impact, since in the areas where forests are exposed to salinization, these forests are often the only patches of trees available. These small patches of trees might be very valuable to the people living in their vicinity.

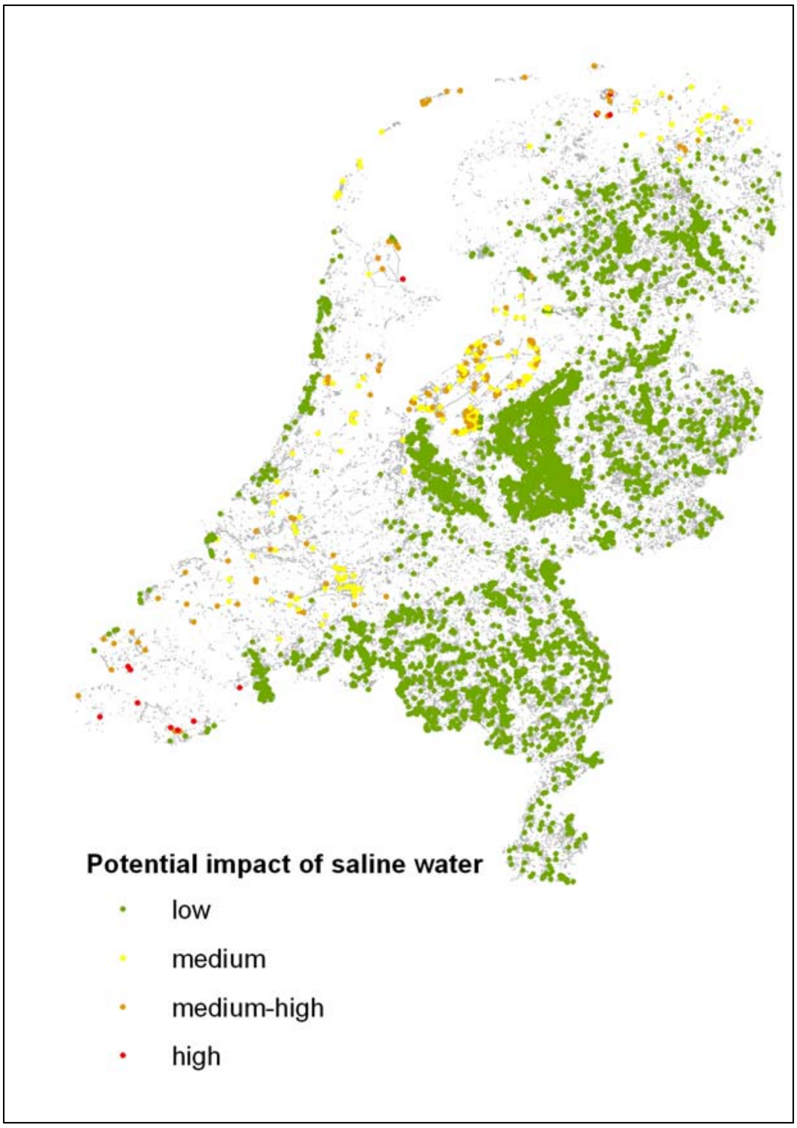

Figure 7. The potential impact of saline seepage water to trees in the forest inventory plots.

4.5 Insect pests, a table showing the future risks

Results

The data from the literature review (paragraph 3.5) were used to construct Table 6. Background information on the biology and potential damage of the individual pest species is given in Appendix 5. Most of the pests mentioned in the table are already present in The Netherlands. Others are present in mid- and southern Europe and are shifting northwards onto our region. Some primary pest insects - most leaf-consumers - are presumed to increase due to elevated temperatures. They may weaken the trees so that secondary pests may increase. Secondary pest insects are dependant on weakened trees e.g. by defoliation or drought. Many of them are capable to cause mortality of weakened trees before they could recover (Roualt et al.

2006). The predictions are that several secondary pest insects - most wood-boring species - will become very important in the future, because they cause tree mortality.

In Table 6 also some important potential invasive species are mentioned which are not present yet in Europe but which are expected to establish here in the future. New invasive insect species may present a threat to our forests because they lack their natural enemies and therefore may cause tree mortality on a large scale. In Table 6, most of these species have been given a high score from ++ to +++ for their potential damage.

Discussion

The long-term impacts of climate change on insect pests are difficult to predict. Here, some generalized predictions were made, based on current pest distributions and the severity of insect outbreaks in individual regions after the summer drought of 2003. For several reasons it is hard to predict the potential impacts. Firstly, there are so many interactions, which make it is extremely difficult to predict the impact of climate change. Secondly, drought can have a significant effect on plant and insect populations but a few years of lower temperatures and higher rainfall may reverse the changes induced by the drought. Further there may be delayed effects on the insects themselves, on their host plants and on the responses of the natural enemies (Battisti 2006; Roualt et al. 2006).

The analysis of invasive species is mostly based on expert judgment, and is very much a 'vision of the future' and not 'hard science'. It should be placed in the context of indicating those insect pests for which there is an ongoing and future need for monitoring (Forestry Commission 2008).

Table 6. Present and future risks of insect pests on trees in The Netherlands

Taxonomic group - Homoptera (aphids, cicada), Coleoptera (beetles), Lepidoptera (moths), Nematoda (micro roundworms).
Feeding Guild - Sap-feeders such as aphids suck on the phloem vessels in leaf or stem. Leaf-miners produce galleries inside a leaf. Wood-borers excavate tunnels in the bark or the wood.
Leaf-consumers may cause defoliation of broadleaved or coniferous trees.
Primary / Secondary pest - Primary pest organisms are able to infest vital trees. Secondary pest organisms only infest trees weakened by primary pests or trees weakened by abiotic factors such as drought.
Impact on trees and other effects - Less wood increment may have effects on CO_2 storage. Less seed production may have effects on natural tree regeneration and on food supply for wild animals.
Weakening of trees may be followed by secondary pests which may cause mortality. Some insect larvae cause annoyance to people with their irritating hairs.
Risk on manifestation: scale -, +, ++, +++ (no, low, moderate, large risk on manifestation at present time or in the future due to climate change).
Potential damage on trees and forests: scale +, ++, +++ (low damage with few dead trees, moderate damage with weakened trees and low mortality rate, heavy damage with high mortality rate).

Tree genus	**Insect species Common name**	**Insect species Latin name**	**Feeding Guild**	**Secondary / Primary pest Requirement**	**Habitat 1 = Forests 2=Roadside plantings 3 = Urban trees**	**Distribution** **- NL** **- EU not NL** **- Invasive Species**	**Impact on trees and other effects**	**Climate factors as important triggers**	**Risk on manifestation P = Present F = Future -,+, ++,+++**	**Potential damage on trees and forests +, ++,+++**
Aesculus	Horse chestnut leaf miner	*Cameraria ohridella*	Leaf-miner	Primary	1,2,3	Invasive species,in NL	Less wood increment	Elevated temperatures	P +++ F +++	++
Fagus	Beech woolly aphid	*Phyllaphis fagi*	Sap-feeder	Primary	1,2,3	NL	Less wood increment	Elevated temperatures	P ++ F +++	++
Fagus	Beech splendour beetl	*Agrilus viridis*	Wood-borer	Secondary	1	NL	Weakening and mortality	Elevated temperatures and drought	P + F +++	+++
Fagus	Beech bark beetle	*Taphrorychus bicolor*	Wood-borer	Secondary	1	NL	Weakening	Drought and storm	P + F ++	++
Fagus	Beech leaf-miner	*Rhynchaenus fagi*	Leaf-miner	Primary	1	NL	Less wood increment and less seed production	Elevated temperatures	P + F ++	++
Fraxinus	Emerald ash borer	*Agrilus planipennis*	Wood-borer	Primary	1,2,3	Invasive species Originating from Asia – established in N-America, not yet in EU	Mortality	Unknown	P - F +	+++
Larix	Large larch beetle	*Ips cembrae*	Wood-borer	Secondary	1	NL	Mortality	Drought and storm	P + F ++	++

Picea	European spruce bark beetle	*Ips typographus*	Wood-borer	Secondary and primary	1	NL	Mortality	Drought and storm	P ++ F +++	+++
Picea	Green spruce aphid	*Elatobium abietinum*	Sap-feeder	Primary	1	NL	Weakening	Elevated temperatures and drought	P + F ++	++
Picea	Great spruce bark beetle	*Dendroctonus micans*	Wood-borer	Secondary	1	NL	Weakening	Elevated temperatures and drought	P + F ++	+
Picea	Spruce budworm	*Choristoneura fumiferana*	Leaf-consumer	Primary	1	Invasive species Not yet in EU	Mortality	Elevated temperatures	P - F +	+++
Picea	Small spruce bark beetle	*Pityogenes chalcographus*	Wood-borer	Secondary	1	NL	Mortality	Drought and storm	P + F ++	++
Pinus	Pine processionary moth	*Thaumetopoea pityocampa*	Leaf-consumer	Primary	1	EU	Annoying urticating hairs	Elevated temperatures	P - F +	++
Pinus	Engraver beetle	*Ips acuminatus*	Wood-borer	Secondary	1	NL	Dying of branches and weakening	Elevated temperatures and drought	P + F ++	+
Pinus	Pine shoot moth	*Rhyacionia buoliana*	Wood-borer	Secondary	1	NL	Decreasing timber quality	Elevated temperatures and drought	P + F ++	+
Pinus	Pine stenographer beetle	*Ips sexdentatus*	Wood-borer	Secondary	1	NL	Decreasing timber quality	Drought and storm	P + F +	+
Pinus	Pine buprestid beetle	*Phaenops cyanea*	Wood-borer	Secondary	1	NL	Mortality	Drought and storm	P+ F ++	++
Pinus	Pinewood nematode	*Bursaphelenchus xylophilus*	Wood-borer	Primary	1	Invasive species from N-America established in Portugal	Mortality	Elevated temperatures	P - F +	+++
Pinus	Common pine shoot beetle	*Tomicus piniperda*	Wood-borer	Secondary	1	NL	Less wood increment	Drought and storm	P + F ++	+
Pinus	Southern pine beetle	*Dendroctonus frontalis*	Wood-borer	Primary	1	Invasive species Not yet in EU	Mortality	Elevated temperatures	P - F +	++
Populus	Hornet moth	*Sesia apiformis*	Wood-borer	Primary	1,2,3	NL	Mortality	Drought	P+ F ++	+
Pseudotsuga	Douglas fir beetle	*Dendroctonus pseudotsugae*	Wood-borer	Primary	1	Invasive species Not yet in EU	Mortality	Elevated temperatures	P - F +	+++

Pseudotsuga	Douglas fir Tussock moth	*Orgyia pseudotsugata*	Leaf-consumer	Primary	1	Invasive species Not yet in EU	Mortality	Elevated temperatures	P - F +	+++
Quercus	Oak pinhole borer	*Platypus cylindrus*	Wood-borer	Secondary	1	NL	Decrease of timber quality	Drought	P + F ++	+
Quercus	Green oak leaf-roller moth	*Tortrix viridana*	Leaf-consumer	Primary	1,2,3	NL	Weakening, Less seeds	Warm spring	P +++ F +++	++
Quercus and other broadleaved trees	Small winter moth	*Operophtera brumata*	Leaf-consumer	Primary	1,2,3	NL	Weakening, Less seeds	Warm spring	P +++ F +++	++
Quercus and other broadleaved trees	Large winter moth	*Erannis defoliaria*	Leaf-consumer	Primary	1,2,3	NL	Weakening, Less seeds	Warm spring	P +++ F +++	++
Quercus and other broadleaved trees	Gypsy moth	*Lymantria dispar*	Leaf-consumer	Primary	1,2	NL	Weakening	Elevated temperatures	P ++ F +++	++
Quercus	Oak processionary moth	*Thaumetopoea processionea*	Leaf-consumer	Primary	1,2,3	NL	Annoying irritating hairs	Elevated temperatures	P ++ F +++	++
Quercus	Oak buprestid beetle	*Agrilus biguttatus*	Wood-borer	Secondary	1,2,3	NL	Mortality	Elevated temperatures	P ++ F +++	++
Several species of broadleaved trees	Asian longhorn beetle	*Anoplophora glabripennis*	Wood-borer	Primary	1,2,3	Invasive species from Asia, established in NL since 2008	Mortality	Elevated temperatures	P + F ++	++
Several species of broadleaved trees	Asian longhorn beetle	*Anoplophora chinensis*	Wood-borer	Primary	1,2,3	Invasive species from Asia, established in NL since 2007	Mortality	Elevated temperatures	P + F ++	++

5 Synthesis

5.1 Main results

The main results of our analyses are summarised in Table 7. As described in the introduction, in this study we focussed on the potential risks of climate change on forests and did not consider potential positive effects. Our study indicates that drought is probably the most important aspect of climate change, which can potentially harm a large proportion of our forests. The potential impact of the aspects 'forest fire', 'rise of the groundwater level' and 'salinization' were all much smaller than the potential impact of drought. Measurements conducted before and after the drought of 2003 show the potentially large impact of drought on forest growth within Europe (Ciais et al. 2005).

In this study, we did not create a risk map for the aspect 'insect pests', but constructed a table presenting the potential impacts (Table 6). This table indicates that insect pests are expected to become more abundant in future. The results of the literature review further showed that insect pests are currently a very important damaging agent to forests (Table 3). Therefore, the potential impact of insect pests is large as well.

Table 7. This table presents the potential impacts of the different aspects, the areas where the impacts are expected and the climate scenarios under which the impacts are most likely.

	Potential impact	Area	Climate scenario
Drought	Strong reduction of growth in about one third of the inventory plots	Sandy soil distributed all over the Netherlands	W+ scenario and smaller impact under G+
Rise of groundwater level	Damage to trees in 1.5% of inventory plots	Sandy soils, especially Veluwe and Utrechtse Heuvelrug	W scenario and smaller impact under G scenario
Forest fire	3% of inventory plots are susceptible to forest fire	Sandy soil distributed all over the Netherlands	W+ scenario and smaller impact under G+
Salinization	Potential impact high in 0.4% of the inventory plots, moderate to high in 3.2%, and moderate in 4.5% of the plots	Areas in the west and north-western part of the Netherlands. Especially Zeeland and the Wadden islands.	Extremely dry years, especially W+ scenario, impact smaller under other scenarios (W+>G+>W>G)
Insect pests	Insect pests are currently the main damaging agent to forests, and pests are expected to become more abundant	No area indicated	Main circumstances: elevated temperatures might stimulate many species, drought can make trees more susceptible, storm can create breeding sites

The potential impact of climate change appears to be highest on the higher sandy soils (Table 7). Droughts, forest fire and a rise of the water table all might have an impact on forests in these areas. On the clay and peat soils in the western and north-western parts of the Netherlands, the aspect salinization might harm tree growth (Figure 7). Locally this impact might be large.

The potential impact of the different aspects is especially high under the W+ scenario, and to a lesser extent under the G+ scenario (Table 7). Under the W+ scenario, the number and extent of dry periods will probably increase. This will not only directly affect the growth of trees, but dry periods will also increase the potential impacts of the aspects salinization, insect pests and forest fire. Under the W and G scenario, not dry periods, but periods with an increased amount of soil water during the growing season might have an impact in some forests.

5.2 Adaptive measures

It is not clear what our future climate will look like. Will our climate develop like the W+ scenario, with increased summer droughts, or will it develop more like the G scenario, in which summers appear to be wetter? In addition, forests differ considerably in site conditions. The uncertainty of the future climate and the large variation in site conditions make it hard to formulate a general adaptive strategy. One advice, however, which seems relevant for all aspects of climate change, for all climate scenarios, and for most forests, is to stimulate tree species diversity.

Currently, the number of tree species in many forests is already increasing. This increase is caused by natural succession and is also stimulated by forest management (Van den Bos 2002; Van der Jagt et al. 2002; Verkaik 2008). Despite this increase, many forests are still dominated by only a limited number of species. Especially *Pinus syvlestris* and *Quercus robur* dominate many forests (Dirkse et al. 2007). A larger diversity of tree species seems desirable to decrease the potential impact of the different aspects of climate change on forests. Nabuurs and Hommel (2007) discuss a number of tree species which appear to have potential in our future forests. Some of these species are currently missing in many forests or are only present at low numbers. In some forests, it might therefore be necessary to introduce new species, by planting or sowing them. Climate change makes it increasingly important that these species match well with site conditions. To lessen the risk of forest fires, especially the use of broadleaved species should be stimulated. Care should be taken with the use of exotic tree species. Particularly exotic species of genera which are not indigenous to the Netherlands form a risk. Natural enemies of insect pests on these species are often lacking and insect pests probably benefit from climate change.

The potential impact of drought and salinization are especially high under the W+ scenario, due to the expected dry summers. To prevent damage by these two aspects, the water management in a number of forest areas might be adapted. In areas where ample fresh water is available even in dry summers, fresh water might be used to prevent damage by salinization (RWS 2005). For forests with a shallow water table it is perhaps possible to prevent damage from summer droughts by retaining extra water in winter (Stuijfzand et al. 2007, 2008).

Since drought appears to have the largest potential impact on our forests it is most pressing to have good knowledge of the drought resistance of tree species. A study, as currently undertaken, to the relation between the diameter growth of trees in Dutch forest reserves and weather conditions (Nabuurs et al. 2007), might provide such essential information. Also studies to the growth of different provenances of common tree species in the Netherlands are important, and especially the performance of southern provenances is of interest. When some provenances perform better than others under climate change, the use of these provenances, as seed source or seedling, should be promoted.

Our study focussed on potential risks of climate change and did not consider positive effects. In some forests, a rising groundwater level in summer would probably stimulate tree growth. An increased growing season and a higher concentration of CO_2, will probably stimulate tree growth as well (Saxe et al. 2001; Menzel et al. 2006). For a good understanding of the impact of climate change, in a future study potential positive effects of climate change should be considered too. The assessment of the combination of a longer growing season, elevated CO_2, higher temperatures and changes in soil water availability would probably require the application of a simulation model of forest or tree growth. Such a study would also enable the comparison of the performance of different tree species.

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Appendix 1 Sensitivity of tree species to drought

The relation between soil water supply and tree growth is shown, for the present situation and for the W+ scenario. Tree growth is presented as the proportion (in percentages) of the maximum value of the mean increment at the site. Tree species were divided in three groups, based on data by Van den Burg (see table below).

	Soil water supply				
Scenario of current situation	>220mm	220-170mm	170-120mm	120-70mm	<=70mm
W+ scenario	>290mm	290-240mm	240-190mm	190-140mm	<=140mm
Group 1, resistant *Pinus sylvestris* *Quercus robur* *Quercus petraea* *Pinus nigra* *Pseudotsuga menziesii* *Betula* spp.	100	95	85	60	35
Group 2, intermediate *Quercus rubra* *Larix kaempferi* *Fagus sylvatica* *Picea abies* *Populus* spp. Other species	100	80	65	45	20
Group 3, sensitive *Fraxinus excelsior* *Alnus glutinosa*	100	85	40	10	5

For a number of common Dutch tree species, the relation between soil water supply and tree growth is presented. These data are after table 11 from the study by Van den Burg (1990). Tree growth is shown as the proportion (in percentages) of the maximum value of the mean increment at the site.

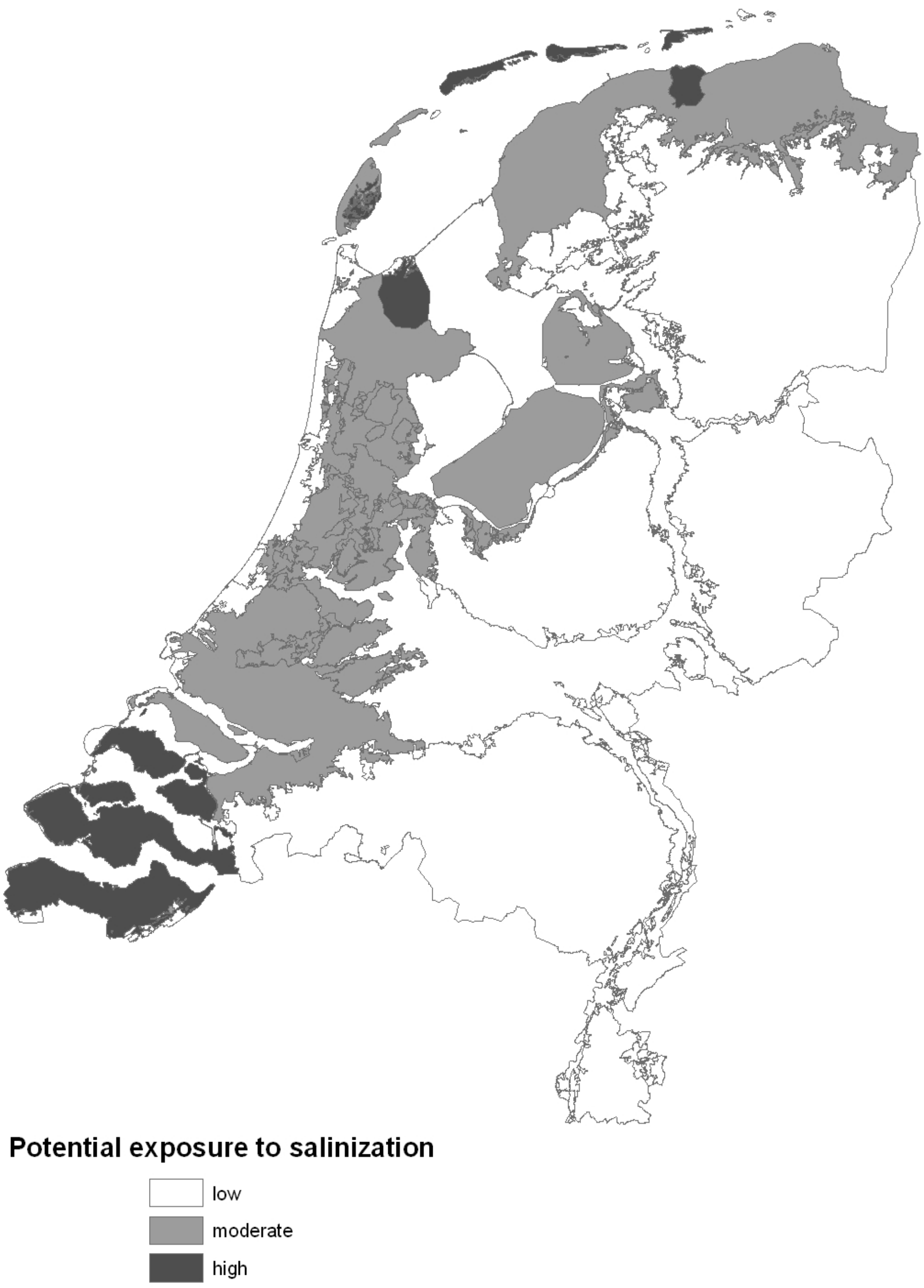
	Soil water supply				
	>200mm	200-150 mm	150-100mm	100-50mm	<50mm
Pinus sylvestris	100	93	85	66	37 (estimated)
Pinus nigra var. maritima	100	98	84	60	No data
Pseudotsuga menziesii	100	98	84	54	No data
Larix kaempferi	100	96	77	49	No data
Picea abies	100	83	59	39	No data
Quercus robur	100	94	88	67	No data
Quercus petraea	100	83	66	50	No data
Quercus rubra	100	80	62	49	No data
Fagus sylvatica	100	79	59	38	No data
Populus hybrid 'Robusta'	100	90	74	21	No data
Populus 'hybrid 'Dorskamp'	100	95	80 (estimated)	55 (estimated)	No data
Fraxinus excelsior	100	87	54	14	No data
Alnus glutinosa	100	85	35	<10	No data

Appendix 2 Sensitivity of tree species to an increased ground water level

Threshold values for damage to tree species by a rise of the GLG (average lowest groundwater level) or GVG (average water level in spring), for different groundwater levels and for a number of tree species. Values larger than these threshold values are assumed to cause damage. Data based on Olsthoorn et al. (2003), except for the species Picea abies, Pinus sylvestris and Pinus nigra var. maritime (see text).

groundwater level Gt ‘grondwatertrap’	Threshold values for change in GLG or GVG (cm)			
I, GHG <25 GLG <50	20	10	10	0
I, GHG >25 GLG <50	20	20	10	10
II, GHG <25 GLG 50-80	20	20	10	10
II, GHG 25-40 GLG 50-80	30	20	20	10
II, GHG >40 GLG 50-80	30	20	20	10
III, GHG <25 GLG 80-120	30	30	20	20
III, GHG 25-40 GLG 80-120	30	30	30	20
IV, GHG 40-80 GLG 80-120	40	30	30	30
IV, GHG >80 GLG 80-120	40	40	30	30
V, GHG <25 GLG 120-180	40	30	30	30
V, GHG <25 GLG >180	40	40	30	30
V, GHG 25-40 GLG 120-180	40	30	30	30
V, GHG 25-40 GLG > 180	50	40	30	30
VI, GHG 40-80 GLG 120-180	50	40	40	40
VI, GHG 40-80 GLG >180	50	50	40	40
VII, GHG 80-140, GLG 120-180	50	50	50	40
VII, GHG 80-140, GLG >180	No limit	No limit	50	40
VIII, GHG >140 GLG 120-180	50	50	50	40
VIII, GHG >140 GLG >180	No limit	No limit	No limit	No limit
	Alnus glutinosa, *Populus* spp, *Salix* spp	*Fraxinus excelsior*	*Betula* spp, *Picea abies*, *Pinus sylvestris*, *Ulmus* spp, *Tilia* spp.	Other species

Appendix 3 Salinization regions



Appendix 4 Sensitivity of tree species to saline water

Threshold values for damage to tree species by soil moisture concentrations of NaCl (g/ l soil moisture) (after Van den Burg (1983), with approximate or tentative values between brackets) and the sensitivity score used in this study (1 = sensitive, 2= somewhat less sensitive).

Species	No visual damage observed	Limit or range for incipient visual damage	Visual damage	Incipient dying-off or serious damage	Sensitivity used in this study
Alnus glutinosa	0 - 2 to5	2 - 5	1-6	>(3 to 5)	2
Betula pendula	0 - 7	7	>7	4 (after flooding)	2
Betula pubescens	0 -4 to 6	4 - 6	> 4 to 6	4 (after flooding)	2
Fagus sylvatica	0 - 2 to 4	2 - 4	2 to 4 - 10	> 7 to 10	2
Fraxinus excelsior	0 - 3 (to 6)	3 - 4	(0.5 to 4) - 11	7 - 11	2
Larix spp	0 - 2	2	>2		1
Larix kaempferi					1
Picea spp.	0 - 1	(1)	> (1)	(1) (1after flooding)	1
Picea abies					1
Pinus sylvestris	0 - 2 to 4	2 - 4	> 2 to 4 - 4	> 4	1
Pinus nigra	0 - 4 to 8	4 - 8	> 4 to 8		2
Pinus nigra var. maritime					2
Populus x euramericana	0 -(1 to 4)	2 (1 to 4)	> 1 to 4	> 6	1
Populus spp.					1
Pseudotsuga menziesii	0 - 2 to 3	2 - 3	2 to 3- 4	4 - 10	1
Quercus robur	0 - (5 to 10)	8 (5 to 10)	> 8 (5 to 10)	6 (after flooding)	2
Quercus petraea					2
Quercus rubra	0 - 2 to 10	2 - 10	> 2 to 8 -10		2
Other species					2

Appendix 5 Description of the insect species

The order of species in this appendix is the same as in Table 6.

Horse chestnut leaf miner - *Cameraria ohridella*

This leaf miner was first observed in Macedonia in northern Greece and was described as a new species in 1986.

Since 1998, the horse chestnut leaf miner has been established in The Netherlands (photo: Leen Moraal)

Its larvae are leaf miners on the chestnut *Aesculus hippocastanum*, causing significant damage to the appearance of the trees. Eventually the leaves die and drop off; when new ones grow they are again infected. This cycle can repeat itself several times in one season. Despite the poor appearance of infested trees, there is no evidence that damage by the moth leads to a decline in tree health, the development of dieback, or tree death. Trees survive repeated infestations and re-flush normally in the following year. It appears that most of the damage caused by the moth occurs too late in the growing season to greatly affect tree performance. Consequently, there is no reason to fell and remove trees just because they are attacked by *C. ohridella.* Hotter summers will increase the number of generations per year and hence the amount of damage. A warmer climate will extend geographic range northward (Broadmeadow & Ray 2005; Forestry Commission 2008).

Status: Invasive species, occurring in Europe and since 1998 in The Netherlands.

Relation with climate change: under elevated temperatures more generation are produced.

Potential damage: primary pest.

Beech woolly aphid - *Phyllaphis fagi*

Pale yellow, sap-feeding aphids, which are covered by white woolly fibres, form dense colonies on young shoots and the undersides of leaves. Winged aphids fly from infested plants in midsummer in search of other beech trees. The foliage becomes sticky with the honeydew that is excreted by the aphids and can develop

sooty moulds. In heavy attacks the foliage at shoot tips is distorted and leaves may dry up. The attack from beech woolly aphids varies from one year to another depending of the actual climate the specific year. Heavy infestations can result in brown and shrivelled leaves and dead shoots. Growth may considerably retard. In forests with natural regeneration the young plants may die (Browne 1968; Schwenke 1972). Elevated temperatures and high moisture favour sap-sucking aphids such as the beech woolly aphid, *Phyllaphis fagi* (Roualt et al. 2006).
Status: European species, occurring in The Netherlands.
Relation with climate change: increasing populations by elevated temperatures.
Potential damage: primary pest, healthy trees are susceptible, loss of increment.

Beech splendour beetle - *Agrilus viridis*
The larvae make zigzagging galleries under the bark of branches and trunks, which become (partly) girdled. The beetle is a secondary pest which attacks weakened trees. In the past, mass attacks on mature beeches have been observed. Outbreaks of this beetle occur especially after hot dry years. The result is many dying branches in the canopy (Moraal 2002; Schwenke 1974). After the drought of 2003, many attacks were observed in Germany. The trees showed black slime flux on the spots where the beetles bored into the living weakened trees (Delb 2005)
Status: European species - occurring in The Netherlands.
Relation with climate change: warmth-loving insect, drought makes trees susceptible, storm-felled trees form optimal breeding substrates.
Potential damage: secondary pest, mortality.

Beech bark beetle - *Taphrorychus bicolor*
This bark beetle produces 2 generations per year. It mainly breeds in dying branches and felled trees, where the larvae make their galleries under the bark. Only when the beetle reaches high population densities, healthy beeches are being attacked (Moraal 2002).

Beech bark beetle (photo: www.waldwissen.net)

In Germany, many beeches were attacked by this bark beetle after the drought of 2003. The trees showed black slime flux on the spots where the beetles bored into the living weakened trees (Delb 2005).
Status: European species - occurring in The Netherlands.
Relation with climate change: warmth-loving insect, drought makes trees susceptible, storm-felled trees form optimal breeding substrates.

Potential damage: secondary pest, weakening of trees.

Beech leaf-miner - *Rhynchaenus fagi*
The small adult beetles overwinter in the soil and the eggs are laid in spring on the young leaves. Each larva mines in the tissue forming a blotch. Leaves on which the adults have fed appear shot-holed. Growth may considerably retard. By feeding on the immature seeds they fall prematurely. Rich seed years may be reduced up to 50% which may affect natural regeneration and reducing food for wild animals (Schwenke 1974). Elevated temperatures have a positive impact on the beetle's development (Roualt et al. 2006)
Status: European species, occurring in The Netherlands.
Relation with climate change: increasing populations by elevated temperatures.
Potential damage: primary pest, healthy trees are susceptible, loss of increment and less seed production.

Emerald ash borer - *Agrilus planipennis*
This is an exotic pest from Asia (China, Japan, Korea) and forms the most serious threat to all ash trees of the 6 native ash species in North America. The larvae produce long zigzagging beetle tunnels under the bark and kill the tree (Poland & McCullough 2006). To date, nearly 30 million ash trees have been killed in Indiana, Ohio, Illinois, Michigan, and adjacent Canada (www.emeraldashborer.info).

Since 2002, nearly 30 million ash trees have been killed by the asian emerald ash borer (photo: James W. Smith; forestryimages.org).

When accidently introduced into Europe, this insect may become a serious threat to millions of ash trees (Eppo). The species is not a considered to be major pest of ash in its native regions. The insect can fly relatively long distances (>1km) and has a high reproductive potential. Despite the low density of ash trees in Canadian forests, the beetle's directed host-searching ability is high (Haack et al. 2002). This species is

still absent in Europe, but the insect can be transported to other continents with plants and wood products (including wood, wood packaging, wood chips, firewood) containing bark, moving in international trade. Between 1985 and 2000, 38 confirmed detections of *Agrilus* spp. were made at points of entry in USA (Haack et al. 2002). Since its establishment in North America, major efforts have been underway to increase understanding of the ash borer's biology and climatic requirements. Investigations into the insect's thermal requirements are ongoing. It seems highly probable that *A. planipennis* would be able to establish in most of Europe, where *Fraxinus* spp. are common. In China, one generation per year is produced; two years are required for development in colder climates. So, climate change with higher temperatures, may allow more generations, and by that, heavier infestations. (Eppo; Haack et al 2002).
Status: Asian species, already in North-America, not yet in Europe.
Relation with climate change: combined effects of climate change and increased global trade of timber and wood products are likely to result in invasive pests.
Potential damage: primary pest, extreme high mortality. Hotter summers will increase the number of generations per year and hence the amount of damage. A warmer climate will extend geographic range northward. Currently absent from Europe but recent exotic pest in USA and Canada (from China) (Broadmeadow & Ray 2005).

Larch beetle - *Ips cembrae*
Adults emerge from hibernation sites in May. There may be one or two annual generations depending on the length of the summer season. The second generation may fly in August/September. There may also be a sister brood of the first generation, flying in June. The larvae produce galleries under the bark. The new generation adults have a maturation feed in late summer, either in branches of younger trees or near to the brood gallery, if there is still fresh bark present. This species is a secondary pest in native European larch plantations, breeding in logs, wind-blown stems and dying trees. In Germany, timber from the April felling of larch is rapidly attacked and severely invaded. Drought conditions on drier sites may promote attack on green trees (Roualt et al. 2006). The introduced population in the UK is able to attack live trees suffering from drought stress (Evans et al. 2002; Forestry Commission 2008). The introduced population in the Netherlands has developed on storm-damaged trees. As in the case of other conifer bark beetles, *Ips cembrae* is a vector for a blue stain fungus, *Ceratocystis laricicola*, which decreases the quality of the timber (Forestry Compendium)
Status: European species, occurring in The Netherlands.
Relation with climate change: drought makes trees susceptible, storm-felled trees form optimal breeding substrates.
Potential damage: secondary pest, mortality.

European spruce bark beetle - *Ips typographus*
In the spring, the adults that have overwintered undergo a temperature-dependent maturation process before migrating to breeding sites. Host trees have defence mechanisms against attacking beetles (e.g. resin exudates and changes in the chemical composition of the phloem). Drought makes trees susceptible and storm-felled trees

form optimal breeding substrates (Roualt et al. 2006). The males bore into the bark and prepare the nuptial chambers (5-7 mm in diameter). They then attract one to three (or four) females using sexual pheromones. After mating, the females start to prepare the maternal galleries, parallel to the cambium fibres, inside the phloem and bark. Each female lays 30-80 eggs. Oviposition and fecundity are dependent on the population/infestation density and temperature, where lower temperatures inhibit fecundity. In favourable climatic conditions, the full development of one generation takes from 2 to 2.5 months. Thus, the number of generations per year depends on the climatic conditions. In the lowlands of Europe, the insect usually has two generations (excluding sister generations), but during extremely hot and long summers the number of generations can reach three. In the mountains, especially at higher altitudes, as well as in the north of Eurasia, only one generation can develop. *Ips typographus* is considered to be one of the most important insect pests of spruce trees (*Picea* spp.), with the ability for rapid population increase, which results in outbreaks. The mortality of spruces (*Picea* spp.) can result in changes in the species composition of forests where spruce is an admixture, or in the decline of pure spruce stands, especially those that have been artificially introduced (Forestry Compendium)

Status: European species, occurring in The Netherlands.

Relation with climate change: drought makes trees susceptible, storm-felled trees form optimal breeding substrates.

Potential damage: secondary and primary pest, high mortality.

Green spruce aphid - *Elatobium abietinum*

This aphid sucks on the needles and is the most important defoliator of Sitka spruce and to a lesser extent Norway spruce in the U.K. and at present its population s appear to be limited primarily by cold winter temperatures. A rise in average winter temperatures is considered to lead to higher aphid populations and more frequent and intense defoliation. This may lead to weakening and mortality of trees (Evans et al. 2002). Populations are largely controlled by low winter temperatures and overwintering populations are therefore thought likely to increase with climate change. This effect of temperature on population dynamics has been clearly demonstrated and serious outbreaks are predicted to become more common. Research indicates that a serious outbreak reduces increment in the year of damage by 20-30% (Forestry Commission 2008).

Status: European species, occurring in The Netherlands.

Relation with climate change: increasing populations by mild winter temperatures.

Potential damage: primary pest, mortality.

Great spruce bark beetle - *Dendroctonus micans*

The female bores through the bark and establishes a brood chamber. When the female reaches the cambium, she bores upwards for approximately 2 cm and constructs an egg chamber. Newly hatched larvae feed gregariously, side by side, in a brood gallery that becomes larger as the larvae feed. The size of the brood gallery varies according to the number of larvae present. A large brood of larvae can construct a gallery that is 30-60 cm long and 10-20 cm wide. This can cause extensive injury to the tree. Adult flight and, more commonly, walking, play an important part in adult dispersal. This typically leads to small groups of attacked trees. In some countries, there appears to be an association between beetle attack and the occurrence of root disease caused by fungi such as *Heterobasidium annosum* or *Armellaria* sp. However, apparently healthy trees are also commonly attacked. Occasionally outbreaks do occur and result in widespread tree mortality. Trees are killed as a result of the girdling of larval feeding. This can take place over a period of several years. Normally, *D. micans* only colonizes green standing trees which are stressed by drought, poor soil nutrition and logging damage (Forestry Compendium; Roualt et al. 2006). The species is likely to benefit from an increased frequency of summer drought and climatic warming, although its specific predator (*Rhizophagus grandis*) might benefit to a greater extent, thus potentially reducing the impact of *Dendroctonus* (Forestry Commission 2008).

Status: European species, occurring in The Netherlands.

Relation with climate change: drought makes trees susceptible, storm-felled trees form optimal breeding substrates.

Potential damage: secondary pest, mortality.

Spruce budworm - *Choristoneura fumiferana*

The spruce budworm is the most destructive insect defoliator of forests in North America and Canada. It is observed that this species is sensitive to climate change with increased temperatures; it has resulted in a northwards shift (Evans et al. 2002). The adults appear in July or August, depending on geographical area, and females lay egg masses on the undersides of needles. Each female lays approximately 200 eggs. The eggs hatch in about 8-12 days, and the tiny larvae soon spin silken hibernation shelters in bark crevices. No feeding occurs before hibernation. The overwintered larvae emerge from the hibernation shelters shortly before the vegetative buds begin to expand, and mine within the old needles or into the unopened buds. As the shoots expand, the larvae spin loose webs among the needles, from which they move onto the new foliage.

Spruce budworm –airial spray application (photo: Jerald E. Dewey,USDA Forest Service, Bugwood.org)

Of the North-American *Choristoneura* species, it is probably the most dangerous as it attacks a rather large number of conifers which are present in Europe and can lead to tree mortality. The species is still absent in Europe but it presents a serious risk to European forests and plantations. Therefore, the species has recently been added to the European quarantine list (www.eppo.org).

Status: North-American species, not yet in Europe.

Relation with climate change: combined effects of climate change and increased global trade of timber and wood products are likely to result in invasive pests.

Potential damage: primary pest, high mortality. Of the North-American *Choristoneura* species, it is probably the most dangerous as it attacks a rather large number of conifers which are present in Europe and can lead to tree mortality. The species is still absent in Europe but it presents a serious risk to European forests and plantations. Therefore, the species has recently been added to the European quarantine list (www.eppo.org).

Small spruce bark beetle - *Pityogenes chalcographus*

After copulation, females begin to bore the mother galleries in a star-like arrangement, depositing about 40 egg niches on both sides of the mother gallery. After hatching, larvae generate larval galleries horizontally to the mother galleries, ending in a pupal chamber where development is completed. The beetle has one to two generations per year, while under especially favourable conditions a third generation may also be established. Drought makes trees susceptible and storm-felled trees form optimal breeding substrates (Roualt et al. 2006). The preference of *P. chalcographus* in the upper, thin barked parts of the trunk enables its association with *Ips typographus*, whose presence is located in the lower, thick barked parts. *P. chalcographus*, is associated with blue-stain fungi and has a negative impact on the timber quality (Forestry Compendium).

Status: European species, occurring in The Netherlands.

Relation with climate change: drought makes trees susceptible, storm-felled trees form optimal breeding substrates.

Potential damage: secondary pest, mortality.

Pine processionary moth - *Thaumetopoea pityocampa*

The females lay their eggs on the nearest pines. However, they can fly several kilometres, and quickly extend outbreaks over large areas. The young larvae aggregate in colonies and spin silken nests. In the Mediterranean region, the moth is considered one of the most important forest pests on pine. Defoliation damage is extremely serious in young reforested areas where it may lead to death of trees, directly or as a consequence of attack by bark beetles or other wood-boring insects. In mature forests trees are rarely killed but significant losses occur in volume growth. Defoliation damage and the presence of caterpillars are important on amenity trees in recreational and residential areas, where defoliation may also cause severe deterioration and greater maintenance costs. The species may have the potential to be invasive as a result of climate change. During the last decades, the moth has shown a substantial expansion northwards, such as in the Paris Basin in France, due to extreme climate events such as the summer of 2003. Also winter temperature may be a thriving force behind range expansion since hibernation takes place in the larval stage. The increase of the winter temperature may have allowed the survival of remaining larvae and the progress of the migration front. Thus, temperature limits larval survival directly through low, lethal temperatures (Roualt et al. 2006). In Italy, *Pinus sylvestris*, *Pinus mugo* and even *Pseudotsuga* are now attacked in mountain areas (Battisti 2008). The life cycle of *T. pityocampa* is normally annual but may extend over 2 years at high altitude or in northern latitudes. The caterpillars have irritating hairs which may cause allergies resulting in conjunctivitis and respiratory congestions (Forestry Commission 2008; Forestry Compendium).

Status: European species, not yet in The Netherlands.

Relation with climate change: expansion by elevated temperatures.

Potential damage: primary pest, mortality.

Engraver beetle - *Ips acuminatus*

This European beetle breeds in branches and tops of pine trees. Reports of serious damage are not common. It is largely a secondary pest on pine, but primary infestations have been reported, particularly at the young thicket stage on light soils. Primary attacks are linked to drought stress; so again, climate change may worsen the situation in some areas. Population build-up also occurs in areas of wind-blow, which may therefore present a future climate change impact should storm damage become more common (Broadmeadow & Ray 2005; Forestry Commission 2008).

Status: European species - occurring in The Netherlands.

Relation with climate change: warmth-loving insect, drought makes trees susceptible, storm-felled trees form optimal breeding substrates.

Potential damage: secondary pest, mortality of branches and tops.

Pine shoot moth - *Rhyacionia buoliana*

Moths lay their eggs on the buds in spring and early summer. Larvae mine base of needles then burrow into a bud to overwinter. Mining damage is usually accompanied by webbing and a flow of resin. Most damage is done in the spring, secondary injury is in the form of deformation of the tree axis, forking and bushing. Continued attack on terminal buds results in many secondary shoots which makes trees very bushy. This can result in serious economic losses in commercial forests. Serious infestations occur when trees are under stress. It is thought likely that its impact will increase with climate change (Forestry Commission 2008).

Status: European species - occurring in The Netherlands.

Relation with climate change: drought makes trees susceptible.

Potential damage: secondary pest, malformation of trees.

Pine stenographer beetle - *Ips sexdentatus*

The females produce egg galleries in dying trees. They defecate spores of blue stain fungi, for example, *Ceratocystis* spp. These spores germinate and the fungal hyphae grow throughout the outer sapwood, and block the conduction of water from the roots to the needles. Thus the tree is also weakened by dehydration, which increases the beetles' ability to colonize a living host and ultimately causes tree death. The species colonizes hosts simultaneously with other bark-beetles such as *Tomicus piniperda* (Forestry Compendium). Storm and drought may increase the populations (Roualt et al. 2006).

Status: European species, occurring in The Netherlands.
Relation with climate change: drought makes trees susceptible, storm-felled trees form optimal breeding substrates.
Potential damage: secondary pest, mortality.

Pine buprestid beetle - *Phaenops cyanea*

The pine buprestid beetle is ranked among the most aggressive and economically most important xylophagous insects affecting pine in Western Europe (Evans et al. 2004). In Switzerland, the drought of 2003 led to more tree mortality as a result of infestations by the pine buprestid beetle (Wermerlinger et al. 2008). The larvae of the beetle produce long zigzagging galleries under the bark of pine trees. The trees may die due to the girdling. The beetle lays its eggs on weakened trees, it can colonize slightly weakened trees in low densities without necessarily killing them (Wermerlinger et al. 2008).

Since 1997, the pine buprestid beetle has been established in The Netherlands (photo's: Leen Moraal).

Climate change scenarios for Europe, and in particular for Switzerland, predict an increase in temperature, drought periods, and heat waves. This suggests that infestations will become more prevalent in future and lead to more tree mortality as a result of *P. cyanea* and other aggressive species. As more frequent drought periods are likely as a result of climate change, even trees only slightly or temporarily weakened will be more subject to attack. This species seems to have increased its population levels in the past few years (Wermerlinger et al. 2008). In 1997, the beetle is recorded

for the first time in The Netherlands. In 2007, large numbers of larval galleries were found in storm-felled trees at Nunspeet (Moraal 2008).
Status: European species – occurring in The Netherlands since 1997.
Relation with climate change: warmth-loving insect, drought makes trees susceptible, storm-felled trees form optimal breeding substrates.
Potential damage: secondary pest, high mortality.

Pinewood nematode - *Bursaphelenchus xylophilus*

This is not an insect but a micro round-worm. It is an invasive species and originates from North-America and it has established in Japan and Portugal. It is not regarded as a dangerous pathogen in its native range, but millions of pine trees have been killed in Japan and recently in Portugal. The nematode feeds on wood cells and on fungi developing in the wood. Longhorn beetles of the genus *Monochamus*, which are present in our region, act as vectors for infection. A 'pest risk analysis' showed that the risks for other European countries may occur in areas where the July or August isotherm is > 20°C (Evans et al. 2002).
Status: North-American species, occurring in Portugal (and Japan).
Relation with climate change: combined effects of climate change and increased global trade of timber and wood products are likely to result in invasive pests.
Potential damage: primary pest, high mortality.

Common pine shoot beetle - *Tomicus piniperda*

In northern Europe and North America, the adults of the beetle hibernate in short galleries in the bark at the base of standing pine trees, but elsewhere they seem to hibernate mainly in the shoots. During the flight period, the females colonize suitable host material. Drought makes trees susceptible and storm-felled trees form optimal breeding substrates (Roualt et al. 2006). The beetle mainly attacks the lower stem, which is covered with thick corky bark. The female excavates the egg gallery, which runs along the wood grain. On standing trees, the galleries are oriented upwards, but on fallen stems they may be oriented towards the base or the top. The larvae feed on the phloem and construct their galleries. The pupal period is short, and the callow adults emerge via individual exit holes in the bark. The occurrence of sister broods increases from north to south. The adult beetles may hibernate for a second time, after a period of regeneration feeding within the shoots, and produce another brood the following year. The first severe frosts cause the beetles to leave the shoots and move to the base of standing pine trees, where they hibernate in short galleries made in the thick bark. The economic impact caused by the pine shoot beetles are growth losses caused by extensive shoot-feeding in the pine crowns and deterioration of timber quality may occur due to beetle-vectored blue-staining of saw logs and pulpwood (Forestry Compendium).
Status: European species, occurring in The Netherlands.
Relation with climate change: drought makes trees susceptible, storm-felled trees form optimal breeding substrates.
Potential damage: secondary pest, loss of increment.

Southern pine beetle - *Dendroctonus frontalis*

This bark beetle is one of the most damaging pests in the USA where it causes extensive mortality to pine trees. The beetle has three to five generations per year. The larvae produce egg galleries under the bark. The trees are killed due to the girdling. In general, compared with other species such as *Ips typographus*, they tend to be more aggressive and more host-specific. They mostly breed in coniferous hosts larger than 15 cm in diameter. In the USA, its populations and economic impact fluctuate considerably, probably because of climatic variation (e.g. drought). A blue-stain fungus, *Ceratocystis minor*, occurs symbiotically helping the beetle to infest a tree and reducing the value of the wood. Taking a direct interpolation of the latitudinal range of outbreak potential in the USA (35.4°N), the likelihood of damaging outbreaks is low and limited to southern Europe. However, the Mediterranean and mild oceanic climates of Europe would suggest that cold winter temperatures are not likely to be limiting, as is the case in the USA. Modelling with CLIMEX predictions, suggest that under a warmer climate, the beetle could establish populations in Western Europe, and that climatic warming could make forests susceptible to damage. *D. frontalis* has been used to illustrate that a pest, that initially would appear to offer low risk, may need to be considered under future climate scenarios (Evans et al., 2002). The beetle is an A1 quarantine pest for EPPO, within the category "non-European Scolytidae". Since it makes primary attacks on *Pinus* spp., it presents a definite risk to the EPPO region, where pines are important forest trees (Eppo).

Status: North-American species, not yet in Europe.

Relation with climate change: combined effects of climate change and increased global trade of timber and wood products are likely to result in invasive pests.

Potential damage: primary and secondary pest, high mortality.

Hornet moth - *Sesia apiformis*

The females lay their eggs at the base of poplar trees. The larva hatch and bore into the trunk where they produce their galleries. Infestation of young, recently planted trees can cause stem rupture or rapid death. In full-grown poplars the insect normally causes little damage. In heavily infested trees the risk of storm damage is increased.

Exit holes can often be seen near the base of poplar trees and there may be pupal cases nearby. This species is a stem borer of poplar, and its prevalence may be linked to climate. It is a secondary pest, and only presents a problem when trees are stressed by summer drought (Forestry Commission 2008).

Status: European species - occurring in The Netherlands.

Relation with climate change: drought makes trees susceptible.

Potential damage: secondary pest, mortality.

Douglas fir beetle - *Dendroctonus pseudotsugae*

The species occurs in USA and Canada. The main host is *Pseudotsuga menziesii* (Douglas fir). Like other bark-beetles, *Dendroctonus* periodically cause loss of wood (cut wood or standing trees) over extensive areas. In general, compared with other genera such as *Ips*, they tend to be more aggressive and more host-specific. They mostly breed in coniferous hosts larger than 15 cm in diameter. The species sporadically kills large quantities of mature *P. menziesii,* particularly following blow down from storms. The female initiates the boring of a new gallery by constructing a radial entrance tunnel through the bark into the wood. After pairing has occurred, the female is generally responsible for boring egg galleries and care of eggs and larvae.

Douglas fir beetle (photo: Mark McGregor,USDA Forest Service, Bugwood.org)

After completing one gallery system it is not uncommon for the parent beetles to construct a second, third or fourth system of tunnels to produce an equal number of broods. A few old adults may survive the winter and participate in the production of the spring brood. However, a majority of the adults die in their tunnels after producing one brood. *D. pseudotsugae* usually has only one generation per year, but may have two or more generations, correlated with seasonal change (Eppo).

Status: North-American species, not yet in Europe.

Relation with climate change: combined effects of climate change and increased global trade of timber and wood products are likely to result in invasive pests.

Potential damage: primary and secondary pest, high mortality.

Douglas-fir tussock moth - *Orgyia pseudotsugata*

The species is considered one of the most serious defoliators of North American forests. Repeated infestations may cause top-killing of the trees and tree mortality. Furthermore, stinging hairs of the larvae may cause allergic reactions of the skin and respiratory organs in man. The eggs are laid in clusters of 150-200 eggs. Adults appear in one yearly generation from August until November. Normally egg clusters are deposited in the higher parts of the trees, they overwinter and hatch in late spring. The young larvae move to the outer parts of the crowns of the threes and may be dispersed passively by the wind across long distances by means of spun threads. Young larvae prefer fresh growth, but from the second larval stage also older needles are consumed. In late summer pupation starts, usually among some older needles, and requires 1 to 2 weeks. The moth has recently been added to the

EPPO A1 quarantine list (www.eppo.org). Both *Abies grandis* and *Pseudotsuga menziensii* are frequently grown in forests in Europe and the number of pest species of these important timber trees is still relatively low. Introduction of *O. pseudotsugata* into the region could cause severe large-scale outbreaks, especially because of the lack of suitable natural enemies. In any case, tree mortality may cause great losses, not only in timber production areas, but also in nature reserves (Eppo).
Status: North-American species, not yet in Europe.
Relation with climate change: combined effects of climate change and increased global trade of timber and wood products are likely to result in invasive pests.
Potential damage: primary pest, high mortality.

Oak pinhole beetle - *Platypus cylindicu*

A secondary pest affecting the value of felled broadleaf timber, particularly oak (and beech). It was a 'red data-book' species in the early 1980s, but became a serious pest following the 1987 storms as a result of large quantities of lying timber. The beetle may form a problem after drought or storm (Forestry Commission 2008). It is a secondary pest affecting timber value but may have more impact, if tree mortality increases. The adults do not kill the tree but bore into the wood and introduce ambrosia fungi into their tunnels which serve as a food source for the adults and larvae. With that, the quality of timber will decrease (Broadmeadow & Ray 2005).
Status: European species - occurring in The Netherlands.
Relation with climate change: warmth-loving insect, drought makes trees susceptible, storm-felled trees form optimal breeding substrates.
Potential damage: secondary pest, affects timber quality.

Green oak leaf-roller moth - *Tortrix viridana*

The adults appear in late May and can fly until July; emergence from the cocoons can be prolonged in time. The adults fly around the crowns of oaks during the day and at twilight, and mate. The number of eggs laid on the tree increases with tree length. The eggs overwinter. Winter frosts do not kill the eggs during periods of either high or low population. Also egg parasitoids and predators do not control the dynamics of this pest. Weather is the population density regulator at the time of egg hatching. Cold weather from April to June can affect larval density. The species may be negatively affected by continuous high water stress but the populations increased in 2003 (and 2004), it may have benefitted from the warm spring, without suffering from the dry and hot summer (Roualt et al. 2006). There are usually one to two larvae developing in one bud, but the presence of as many as 12 larvae has been observed. When the food resource is depleted, the larvae look for a new feeding place. During outbreaks, the larvae can be observed suspended on their silk, looking for food. The larval development is strongly temperature-dependent. Thus, the duration of the larval development (five instars) is variable: in Italy it takes approximately 1 month and in Poland up to 38 days. The pupal stage last between 2 and 3 weeks, then the adult emerges. The pest often occurs in association with other oak defoliators, such as *Operophtera brumata* or *Erannis defoliaria*. The general result of defoliation is a change in tree condition and vitality. In the case of *T. viridana*, reduced tree growth and reduced wood increment were observed. In damaged stands, reduced oak fecundity and acorn crop were recorded. Defoliation is not too

serious for deciduous trees because the trees can sprout a second time in June, although the annual growth rate is reduced (Forestry Compendium). However, defoliated, weakened oaks may become infested by the wood-boring *Agrilus biguttatus* causing tree mortality (Moraal & Hilszczanski 2000).
Status: European species, occurring in The Netherlands.
Relation with climate change: increasing populations by elevated temperatures.
Potential damage: primary pest, healthy trees are susceptible, loss of increment and less seed production.

Small winter moth - *Operophtera brumata*
Adults emerge from pupation in autumn or winter. The adults are nocturnal. Males are weak fliers, females are wing-less and crawl up tree trunks. Mating usually occurs during the tree climb. Females lay 100-200 eggs singly or in small groups of between two and six in crevices in the bark of twigs and other similar places in the tree canopy. The larvae hatch in early spring simultaneous with the bursting of host tree buds. The larvae are polyphagous. The duration of larval feeding is usually about 6 weeks. The larvae descend to pupate in the upper layers of soil. There is one generation per year. The duration of the egg and pupal stages is genetically determined and varies with latitude. The egg stage is long in the north and short in the south, whereas the pupal stage is short in the north and long in the south *O. brumata* is considered as an economically important defoliator of deciduous trees in Western-Europe.

The small winter moth may cause a complete defoliation of oaks and many other broadleaved trees (photo: Leen Moraal).

Defoliation is not too serious for deciduous trees because the trees can sprout a second time in June, although the annual growth rate is reduced (Forestry Compendium). The species may be negatively affected by continuous high water stress but the populations increased in 2003 (and 2004), it may have benefitted from

the warm spring, without suffering from the dry and hot summer (Roualt et al. 2006). Defoliated, weakened oaks may become infested by the wood-boring *Agrilus biguttatus* causing tree mortality (Moraal & Hilszczanski 2000).
Status: European species, occurring in The Netherlands.
Relation with climate change: increasing populations by elevated temperatures.
Potential damage: primary pest, healthy trees are susceptible, loss of increment and less seed production.

Large winter moth - *Erannis defoliaria*

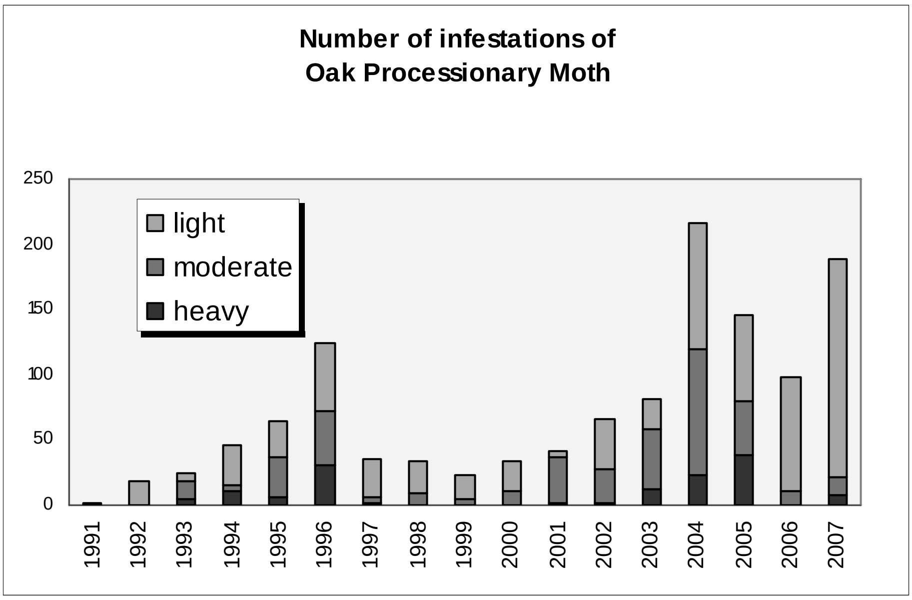
The biology and impact of this species is very similar to that of the Small winter moth – see above.

Gypsy moth - *Lymantria dispar*

The gypsy moth has one generation per year. Overwintering eggs hatch when oaks produce new leaves, depending on the climatic situation. Newly hatched larvae can remain on the egg masses for several days before climbing the trees to the branch tips and starting to feed on buds and new leaves. As larvae move upwards, they spin a thread of silk and suspend themselves from the threads that eventually fracture. The young larva is then carried by the wind. While most larvae will not move more than 200 m, some are reported to travel several kilometres. On average, during its entire life a single larva consumes a total of about 1m² of foliage. The larval stage lasts around 6-8 weeks. Pupal development is complete within 2-3 weeks. Males are good flyers, but in Europe and North America, females remain flightless, although their wings are fully formed. In Asia, however, females are capable of flight. Immediately after mating, oviposition of a single egg mass begins. In Eurasia, outbreaks are usually localized and of short duration. In experiments with temperatures of 15, 20 and 25°C, larval survival rate increased with increasing temperatures. This means that the larvae have a high tolerance to elevated temperatures. It can be expected that in warmer years or under conditions of global warming this insect species will be a potential threat to forests (Karolewski et al. 2007). Severe defoliation results in reduced growth increment. Tree mortality is only occasionally observed. Gypsy moth may also be a serious nuisance in urban environments. Ornamental trees and shrubs in gardens and recreation areas are often defoliated and migrating larvae crawl into houses, climb on fences, vehicles and people. Caterpillar hairs provoke allergenic reactions (Forestry Compendium).
Status: European species, occurring in The Netherlands.
Relation with climate change: increasing populations by elevated temperatures.
Potential damage: primary pest, healthy trees are susceptible, loss of increment and less seed production.

Oak processionary moth - *Thaumetopoea processionea*

The Oak processionary moth is a native species of central and southern Europe, where it is widely distributed, but its range has been expanding northwards, presumably in response to climate change (Moraal et al. 2004). It is now firmly established in The Netherlands. The larvae feed on the foliage of many species of oaks. They form a risk to human health because they have irritating hairs that contain a toxin and contact with these hairs, or their inhalation, can result in skin irritation and allergic reactions.



The Oak processionary moth has been established in The Netherlands since 1991 (source: Leen Moraal).

Since 1991, the oak processionary moth has been established in The Netherlands (photo: Leen Moraal)

These problems are significant because the oak processionary moth is often most abundant on urban trees, along forest edges and in amenity woodlands. Eggs are laid from July to early September. Each female lays between 100 and 200 eggs on twigs and small branches in the canopy and remain on the branches over the winter. The larvae hatch from the eggs in April and feed together in groups in long 'processions' to and from the nest. Pupation occurs in late June or early July. The adult moths emerge 1-2 weeks later.

Status: European species, since 1991 in The Netherlands.

Relation with climate change: expansion of populations by elevated temperatures.

Potential damage: primary pest, healthy trees are susceptible, loss of increment, annoyance to foresters and other people.

Oak buprestid beetle - *Agrilus biguttatus*

The Oak buprestid beetle is found throughout Europe. The primary hosts are *Quercus robur*, *Q. petraea*, *Q. pubescens*, *Q. ilex*, *Q. suber* and *Q. cerris*. In Europe, the American oak, Q. rubra is not infested. *A. biguttatus* may have one generation a year but a two-year cycle is more common. In northern Germany, the larvae hibernate over two winters. Adult flight occurs from May to July. After maturation feeding on foliage in the crowns of oaks, the females deposit clusters of 5-6 eggs in bark crevasses. The warm, south facing side of large oaks is preferred for egg-laying.

Larvae feed in the cambium layer in longitudinal, winding, zigzagging galleries and overwinter in side the bark. When feeding is completed, an individual larva may excavate a gallery up to 155 cm long. The pupae develop in the bark. The young adults escape by D-shaped exit holes. Larval activity can result in twig and branch dieback, thin crowns and epicormic branching.

Weakened trees become vulnerable for attacksof the oak buprestid beetle (photo: Leen Moraal).

Trees attacked for several successive years will die. Heavily infested trees are girdled and killed in a single season. In its native range, *A. biguttatus*, has been regarded as a

secondary invader of stressed and weakened trees. It is frequently found in trees that have been stressed by insect defoliation, frost damage or warm, dry summers. Recently, attacks have increased in several European countries including England, France, Germany, Hungary, Poland and the Netherlands. In England, for example, this species was regarded as endangered as recently as 1987 but is now a common tree killer in oak woodlands and parks. The increasing infestations of the warmth loving beetle are considered as a new element in oak decline and probably induced by warm summers (Broadmeadow & Ray 2005; Forestry Commission 2008; Moraal & Hilszczanski 2000).
Status: European species, occurring in The Netherlands.
Relation with climate change: increasing populations by elevated temperatures and drought-stressed trees.
Potential damage: secondary pest, mortality.

Asian longhorn beetle - *Anoplophora glabripennis*
The major hosts of *A. glabripennis* in China are species and hybrids of *Populus, Salix* spp. are also major hosts. Various other woody plants have also been recorded as hosts in China: *Acer, Alnus, Malus, Morus, Platanus, Prunus, Pyrus, Robinia, Rosa, Sophora* and *Ulmus*. Within the urban outbreak areas in North America, *A. glabripennis* has mainly been found on *Acer* spp. and on *Aesculus hippocastanum*. However, it has also been found on a range of other hardwood species: *Betula, Fraxinus, Liriodendron tulipifera, Morus alba, Populus, Robinia pseudacacia, Salix* and *Ulmus*. The beetle is indigenous to China. Its prevalence and range has increased as a result of widespread planting of susceptible poplar hybrids. The beetle has already established in some European countries such as Germany, Italy, Austria and The Netherlands (since 2007 and 2008). Due to climate change, the Asian longhorn beetle may become more prevalent (Evans at al. 2002). The larva feeds in the cambial layer of bark in the branches and trunk and later enters the woody tissues. Adults emerge from circular holes, 10 mm across, above the sites where the eggs were laid. Unlike many longhorn beetles, *A. glabripennis* can attack healthy trees as well as trees under stress. Several generations can develop within an individual tree, leading eventually to its death. In international trade, the beetle is most likely to be transported as eggs, larvae or pupae in packing material or dunnage made of the wood of host species. Over the last 30-40 years, there has been a policy in China to plant hybrid poplars in plantations, along roads, around farm buildings, etc. Some of these hybrids were imported from other continents, while others were bred in China. Some of them proved to be very susceptible to attacks. The beetle has proliferated on these susceptible hosts, becoming a common pest in many parts of China, also attacking a range of other hosts, especially *Salix* spp., fruit, ornamental and amenity trees. Since the 1980s, hybrids resistant to the pest have been used for new plantations of poplar, and there has been a corresponding decline in the importance of *A. glabripennis*. There is no indication that the beetle is a pest of natural forests in China. However, in Austria the infestations are found in a forest edge. Poplar wood damaged by *A. glabripennis* larvae can be downgraded and lose value by up to 46%. In the USA, suppressing a 1996 infestation in New York State cost more than 4 million USD. Hybrid poplars are widely planted in many countries, and it is probable that many of these hybrids

would be susceptible to the pest (Eppo). Due to climate change, the Asian longhorn beetle may become more prevalent in Europe (Evans at al., 2002).

Status: Asian species, recently in Europe, occurring in The Netherlands.

Relation with climate change: combined effects of climate change and increased global trade of timber and wood products are likely to result in invasive pests. Populations could establish in warmer coastal areas and they would benefit from climatic warming. Amenity and street trees are particularly susceptible, but climate Warming may enable development into woodland (Broadmeadow & Ray 2005; Forestry Commission 2008).

Potential damage: primary pest, mortality.

In 2007, the asian longhorn beetle has been discovered in The Netherlands (photo: Robert A. Haack-USDA, forestryimages.org)

White-spotted longhorn beetle - *Anoplophora chinensis (malasiaca)*

The species is polyphagous on woody hosts, having been recorded on at least 68 species of host trees belonging to 19 families. These include *Alnus, Casuarina, Citrus, Litchi, Melia, Moru, Populus, Malus, Salix, Acer*, and *Cryptomeria japonica.* In tropical and subtropical regions, there is a single generation per year, but the life cycle occasionally takes two years depending on climatic and feeding conditions. The adults live about a month between May and August. They feed on leaves, petioles and young bark of various trees. Egg deposition begins a week after copulation. The eggs, about 70 per female, are laid one by one under the bark of the trunk, from just above the soil surface to 60 cm higher. The feeding larva tunnels in the branches and trunk just under the bark and later enters the woody tissues of the lowest portions of the trunk and roots. Pupation takes place in the wood, often in the upper part of the feeding area. Larval tunnels are found under the bark and in the wood. *Anoplophora* spp. are most likely to be transported as eggs, larvae or pupae in woody planting material, including bonsai plants, and possibly in packing material. Individuals (larvae

and adults) have entered Germany and The Netherlands on bonsai plants of *Acer* and *Malus* from China and Japan. The species can cause serious damage to healthy fruit, ornamental and amenity trees. Damage to small young trees is most serious (Eppo).
Status: Asian species, recently in Europe, occurring in The Netherlands.
Relation with climate change: combined effects of climate change and increased global trade of timber and wood products are likely to result in invasive pests.
Potential damage: primary pest, mortality.