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Master's Thesis

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Windthrow risk assessment of Douglas-fir stands in Denmark

A comparison study of Douglas-fir (Pseudotsuga menziesii) and Norway spruce (Picea abies)

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Titel og undertitel Risikovurdering for stormfald i Douglas gran i Danmark
Et sammenligningsstudie mellem Douglas gran (Pseudotsuga menziesii) og Rødgran (Picea abies)

Subject description: The thesis aims to better understand the risk of wind and storm damage in Douglas-fir, hence a more precise economic calculation for a given stands rotation. The project uses data from different regions in Denmark. This data is provided by the nature agency. Further, the hypothesis around Douglas-fir being more stable as it develops in age, is investigated.

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Frontpage photo: Decker, L. (2016) Douglas-fir at the nature agency's district Søhøjlandet.

“To predict and reduce forest losses due to windthrow, it has long been recognised that data are required that describe the stability and anchorage of trees in relation to species, tree characteristics, site, soil, climate, and forest-management techniques”

- Bruce C. Nicoll

Preface

The work presented in this thesis is an analysis of the stand specific characteristics determining risk of windthrow in Douglas-fir. The study is meant to provide forest managers with the necessary knowledge about factors contributing to increased risk of storm felling in Douglas-fir. It has been prepared for Danish conditions, thus a tool for an improved forest management.

The subject of silviculture has always been of high interest throughout my studies of forest and landscape engineering and forest and nature management respectively. During my studies abroad at the Norwegian University of Life Science (NMBU) and in the course Applied economics of forest and nature, topics like risk management and adaption to, for example, climate change has been mentioned and discussed considerably and have gained my interest. Danish forestry is, due to geographical location, topography and soil conditions, significantly exposed to storms, which is why economic calculations considering the risk of storm is therefore highly pertinent and valuable for a more precise economic estimate of a given stand rotation. Previously, Norway spruce has been presented and used as a calculation example in the lectures for determining the loss in expectation value due to the risk of storm. In Danish forestry, Douglas-fir is a less significant tree species, yet a species which I find fascinating and consider having good prospects in Danish forestry. A practical experience learned from hosts at different forest districts and text books is furthermore that Douglas-fir is hypothetically becoming more stable as a function of age. It is the ambition of this study to confirm or deny this hypothesis, making it supported by empirical data and not just practical experience.

The personal incentive to carry out this study is to get a deeper insight to Douglas-fir as a silvicultural tree species in Denmark and hereby its limitations and strengths regarding storm stability. If wind-induced damage in Douglas-fir can be prevented due to a better understanding of the stand characteristics intensifying this risk, I feel the need to uncover this topic.

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- *Lauge Decker*

Copenhagen, August 2018

Abstract

The windthrow risk of Douglas-fir has been assessed by compiling stand characteristics, meteorological conditions and site classifications. The same assessment is done for Norway spruce for comparison of the wind stability between species. Four logistic regression models have been compiled and tested for their windthrow probability predictions. The dataset is based on the nature agency's forest inventories and subsequent registrations of windthrow for the consecutive years of 1999, 2005 and 2013. The inventory lists have been compiled with windspeed measurements of the winter storms from the three respective years together with the FK soil classification. The hypotheses tested was 1) whether correlations between stand, site and weather conditions for the risk of windthrow exist for the dataset, 2) whether Douglas-fir is less susceptible to windthrow than Norway spruce and 3) whether stability for Douglas-fir increase with height.

The findings of the study suggest that Douglas-fir is less susceptible than Norway spruce. This applies for all age classes yet exceeding heights of 30 meters makes stands of Douglas-fir more vulnerable to storms than stands of Norway spruce. The risk of windthrow was further shown to decrease by the age of 60 years for both species. Variables like height diameter ratios (taper) and standing volume per hectare where shown to be non-significant for the probability of windthrow. Soil classification on the other hand was. Higher content of clay was shown to significantly decrease the windthrow probability on a 5% level. However, differences between coarse and fine sand was not found significant. Height was found to be significant on a 0,1 % level for both species and further one of the individual variables best describing the probability of windthrow. The best describing variable was maximum windspeed based on fit statistics, however the variable itself was shown to be non-significant. Stands experiencing less than 32,5 ms^{-1} were significantly less likely to be overthrown than stands experiencing 37,5 ms^{-1}. Increasing the windspeed to 42,5 ms^{-1} further increased the relative risk of windthrow by a factor of 7.

In the dataset, windthrow is therefore shown to increase by height and higher windspeeds, while decreasing by maturity (>60 years). In relation to diameter, the windthrow probability increase by radial growth for Norway spruce. Douglas-fir stands on the other hand become more stable by diameter classes >50 cm. Among the four models, model D with the variables height, mean windspeed, soil classification, standing volume, taper and district yields the best predictions and is superior when tested against the other models.

It was further sought to evaluate the portfolio outcome and stumpage price for windthrown timber compared to deliberately harvested stands, yet this remains for future research.

Keywords: *Douglas-fir, Norway Spruce, storm, risk assessment, wind vulnerability, windthrow, logistic regression.*

Resumé

Risikoen for stormfald i Douglasgran er blevet vurderet ved at sammenstille bevoksnings karakteristika, meteorologiske data og jordbunds klassificeringer. Den samme undersøgelse er foretaget for Rødgran, med henblik på at sammenligne stormstabiliteten mellem de to arter. Fire logistiske regressions modeller er blevet sammensat og testet for deres prædiktive egenskaber i forhold til stormfaldsrisiko. Datasættet består af bevoksningsliter fra naturstyrelsen med oprindelse i årene 1999, 2005 og 2013. Bevoksningslisterne er efterfølgende sammenstillet med vindstyrke målinger fra de sammenhørende vinterstorme og den danske jordklassificering. De undersøgte hypoteser var 1) om der kan ses en sammenhæng mellem bevoksnings-, jordbunds- og vejrforhold for bestemmelsen af stormfaldsrisikoen i datasættet, 2) om Douglasgran er mindre overfølsom overfor stormfald end rødgran og 3) om stabiliteten i en Douglasgran bevoksninger stiger i takt med alder.

Det ses i resultaterne at Douglasgran er mindre overfølsom end rødgran. Dette gør sig gældende på tværs af alle aldersklasser. Ved højde der overskrider 30 meter ses der derimod, at Douglasgran bliver mindre modstandsdygtig overfor stormfald end rødgran. Risikoen for stormfald blev yderligere vist til at mindskes efter alder 60 år, hvilket gjaldt for begge arter. Variabler som højdediameterforholdet og den stående volumen per hektar var ikke signifikante for den prædikterede stormfaldsrisiko. Jordbundsklassificeringer var derimod signifikant. Større indhold af ler blev vist til at mindske stormfaldsrisikoen signifikant på et 5 % niveau. Forskellen mellem fint og groft sand blev derimod ikke vist til at være signifikant. Højde var signifikant på et 0,1 % niveau for begge arter og var yderligere en af de variabler som bedst beskrev risikoen for stormfald, på baggrund af model fit. Variablen der på baggrund af model fit, bedst beskrev stormfaldsrisikoen var derimod den maksimale vindstyrke, variablen i sig selv blev derimod ikke vist til at være signifikant. Bevoksninger der blev udsat for mindre end 32,5 ms^{-1} var signifikant mindre udsatte for stormfald end bevoksninger der blev udsat for 37,5 ms^{-1}. Ved en yderligere stigning i vindstyrke til 42,5 ms^{-1} steg den relative risiko for stormfald med en faktor 7.

Datasættet viser således at stormfaldsrisikoen stiger med større højde og større maksimal vindstyrke, mens den falder som følge af alder (>60 år). I forhold til diameter, stiger stormfaldsrisikoen med stigende diameter for rødgran. Bevoksninger af Douglasgran bliver derimod mere stabile ved diameter klasser >50 cm. Blandt de fire testede modeller var model D med variablerne højde, maksimal vindstyrke, jordklassificering, stående volumen per hektar, højdediameterforholdet og distrikt den som gav de bedst prædikterede syndsynligheder for stormfald. Modellen var yderligere overlegen i det den blev testet mod de andre modeller

Det blev yderligere søgt at evaluere sortimentsudfaldet og kubikmeter prisen for stormfældet tømmer sammenlignet med bevoksninger som bevidst var blevet fældet. Dette blev imidlertid ikke undersøgt, og emnet foreligger derfor stadig for fremtidig forskning.

Nøgleord: *Douglasgran, Rødgran, Storm, Risiko vurdering, vindpåvirkning, Stormfald, logistisk regression*

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Chapter I. Introduction

1 Introduction

This thesis is written in such a way that a forestry graduate should be able to understand it, given that they have some background within statistics, applied economics and meteorology.

1.1 Motivation

Within forestry in Denmark, as well as in the rest of Scandinavia, it is my impression that the extent and use of risk assessment and analysis for economic calculations is limited (Hanewinkel et al. 2011; Hildebrandt & Knoke 2011). Implicitly, some uncertainties are taken into consideration. This means that projects considered to be very risky are being discarded. General risk considerations however, in decision making and economic calculations are few.

These risk factors can be anything from changes in price, marketing, climate change and, in this case, the risk of a stand falling in storm. Due to the extended time horizon and long rotation periods one should be more interested in including various uncertainties as they increase over time. In managed forests, wind is a significant cause for economic loss since it reduces the yield of recoverable timber and increases cost of thinning and unscheduled clear cutting. By writing this thesis, I want to improve the foundation for appropriate management decisions under risk aversion. I have chosen to focus on Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) because present models for predicting windthrow do not include this species (Miller et al. 2000) and because:

1) I expect the abundance of this species to increase in Denmark (Da Ronch et al. 2016; Podrázský 2015; Skov- og Naturstyrelsen 1999) and
2) because it is seen as more stable than other coniferous spicies cultivated in Denmark (Bergstedt 2017; Møller 1977; Henriksen 1988; Jørgensen & Nielsen 2001).

I am therefore convinced that knowledge within this topic is desired and that making it available to the general forest manager in an easily tangible tool is requested.

1.2 Summary of the theoretical framework

This section is a short summary of the Theoretical framework described in Chapter II which leads to the proposed hypotheses.

According to the general knowledge regarding windthrow, a forest stands susceptibility to wind-induced damage is determined by: 1) the properties of the climate (e.g. windspeed, duration and occurrence) 2) site conditions (e.g. drainage, soil type and topography), 3) stand characteristics (e.g. species, height, diameter) and 4) management regime (e.g. species mixtures and thinning type). Storm damage in European forests is dominated by even aged mature stands which is also consequently taller and consisting of high percentage of conifers. This especially being Picea species. Recent thinnings especially strong thinnings increases the risk of windthrow, particularly within the first 5 years from thinning. Edge exposure is an additional risk factor contributing windthrow. The windthrow occurrence is on the other hand decreasing, with higher basal area, lower height and lower height to diameter ratio.

Unlike most species it is said that Douglas-fir becomes more stable as a function of age, thus windthrow probability is decreasing for mature and old stands of Douglas-fir. In contrast, the species is more vulnerable in the youth. However, different previous studies are contradictive when it comes to this conclusion.

1.3 Aims and Objectives

Based on the literature the aim and main hypothesis of this thesis is therefore to revise:

- Is there a correlation between stand structure, meteorological conditions and geographical location, describing the susceptibility of Douglas-fir to windthrow damage under Danish conditions?

Danish textbook material used during my studies further suggests that stability of Douglas-fir increase by age, yet other literature (including Danish) opposes this, hence the sub-question:

- Is there evidence in the data material for stability to increase with age?

According to the research questions, the main objectives of this thesis is therefore to analyse stand inventories including correlated soil, site and meteorological information for the occurrence of windthrow. The same studies are additionally made for Norway spruce (*Picea abies* (L.) Karst.) for comparison under the same prerequisites. Because much of the literature suggests Douglas-fir to be more stable, an additional sub-question is:

- How stable is Douglas-fir compared to Norway spruce under Danish conditions?

The different predicting variables effect on windthrow is further sought quantified or ranked so that possible cultivation recommendations can be made.

1.4 The project

The project analyses forest inventories of Douglas-fir and Norway spruce from the Danish nature agency (NST) (Ejlersen 2018). It relates stand specific characteristics with cross references of meteorological geological and geographical data. Variables such as diameter, height and maximum windspeed are thus examined for their individual impact and importance for whether a stand is affected by storm. Data is then used in a subsequent evaluation of future stands susceptibility to windthrow. The results are further used to incorporate the level of risk in economic stand rotation calculations to see its influence in a decision-making context.

1.5 Delimitation

The topic of windthrow is wide and many variables, approaches and relationships can be included and investigated. Determining causes of windthrow is therefore complex and very intangible, if not delimitated (Gardiner et al. 2008). The data material and registrations available do not allow for examination of thinning practice though this parameter is of great importance for the risk of windthrow. Furthermore, the sheltering effect of neighbouring stands and possible edge effect is not possible to investigate neither. The data is additional in relation to specific storm events and does not include analysis of smaller scattered storm events, as seen previously by e.g. Rahbek (2003). Though risk assessment in forestry also needs to concern the succeeding events affecting forest activities, it is not dealt with in this thesis.

Chapter II. Theoretical framework

Risk assessment and management in the context of windthrow is a complex topic. Chapter II describes the outline of the thesis in relation to literature and aspects used in the analysis sections. It starts by defining risk and to which degree risk is dealt with. Limiting the assessment only to handle windthrow, leads to an introduction and description of wind damage. This includes contributing factors, both those examined in the analysis section, but also, those that are not examined. This is due to data limitations and because it has previously been shown that some of the variables, not included, have a significant influence on the risk of windthrow. The different outcomes, both economically and biologically, are then described for further analysis and discussion with the results. The inclusion of risk in decision making processes is further looked upon. The different aspects are then seen in a Danish context and in relation to the two species investigated (Douglas-fir and Norway spruce).

2 Wind: a natural disturbance in forests

Windthrow is despite being a natural and recurrent ecosystem driver, often looked at, as an extraordinary catastrophic phenomenon (Mitchell 2013; Gardiner et al. 2008). A natural disturbance is commonly understood by discrete events that disrupt ecosystems and changes the resource availability (Battisti 2016). This makes wind a natural disturbance agent, as also stated by Rykiel (1985). In natural forests, windthrow furthermore plays an important role in the successional cycle of the forest (Bouget & Duelli 2004).

The wind-caused effects on trees ranges from being chronicle to acute. This means that the tree can either withstand the wind loading conditions it is exposed to (applied forces) or its biomechanical limits is exceeded (resisting forces), resulting in branch loss or windthrow (Telewski 1995). The parameters that distinguish the threshold of chronically from acute are therefore worth determining for the characteristics of a stand. Reasons to do so are to better anticipate possible windthrow and to improve management and decision making. This threshold is further the basis for the aim and objective of this thesis.

2.1 Chronicle

Shorter durations or intense long-lasting wind loads endured by the tree often results in altered growth responses and acclimation (*thigmomorphogenesis*) (Bonnesoeur et al. 2016). This among others include more flexible wood, thickening of stems, and the formation of reaction wood (Telewski 2012). This acclimation is previously shown to improve the wind stability of forest stands that later experiencing catastrophic wind (Everham & Brokaw 1996). The effect of chronicle wind exposure is therefore important in the further risk assessment.

2.2 Acute

When the wind loads on the other hand exceed the limitations of the stem and resistance of the roots and soil system, the trees either uproot or break (Mitchell 2013; Peltola 2006). The windthrown trees may further damage adjacent trees when falling through the canopy creating small gaps or even result in complete destruction of the overstory canopy (Mitchell 2013).

2.3 Sub conclusion

When predicting the risk of windthrow either to prevent or limit the damage, it must be seen in the context of it being a natural event, hence wind loads being recurring and inevitable. Wind is therefore continuously affecting the forest stand. This thesis only looks at acute events, however, chronicle effects, thus acclimation needs to be included in the predictive models. This is because, these influence the subsequent risk of windthrow. The two terms are therefore both described, though throughout the thesis risk only refers to acute events.

3 The concept of risk

However, how is this risk perceived? Risk is associated with uncertainty, though the terms are defined differently. Uncertainty describes conditions where future outcomes are not measurable, conversely risk refers to a possible loss hence measurable (Dow & Werlang 1992). Aven & Renn (2009) define risk as being the uncertainty about an activity's severity and consequences to something humans value. The definition is earlier adopted in risk assessment and management in forestry (Hanewinkel et al. 2011). Gardiner & Quine (2000) further define abiotic risk in forestry to be the probability of a hazard occurring, and a hazard to be a threat to humans or what they value.

In forestry we face different kinds of risk, both abiotic (e.g. windthrow and drought stress) and biotic (e.g. bark beetles and root rot) (Albert et al. 2015). Although several risk factors should be considered in forestry, this thesis only looks at the risk of windthrow. Risk of windthrow has economic and biological consequences for the forest management and for its consequential decision-making thus, assessment of risk is important. Kaplan & Garrick (1981) formulates 3 steps (questions) in assessing risk being 1) what can happen? (windthrow as stated in section 2), 2) How likely is it to happen? (probability) and 3) what are the consequences? (economically). Step 2 and 3 are dealt with in this thesis by deriving probabilities associated with windthrow, and later by including risk in economic calculations.

3.1 Wind-induced risk in forestry

In forestry, the risk of damage caused by wind is a combination of occurrence, exposure and vulnerability (Riguelle 2016). Furthermore, wind-induced damage is to be found on different levels which can be divided into three categories (Gardiner et al. 2010):

- Primary damage - Mechanical damage on the forest resource, expressed in area (ha), volume (m^3) or affected growing stock.
- Secondary damage - Subsequent damage linked with the windthrow event, on the forest resource (e.g. outbreaks of bark beetles and fires)
- Tertiary damage - Consequences for the forest growth and continuous forest management in a long-term perspective (e.g. market price regulations (Skogstyrelsen 2006) or subsidies for using sturdier trees (Matthesen 2000)).

Models already made to predict windthrow such as ForestGALES (Hale et al. 2015) and HWIND (Peltola, Kellomäki, Väisänen, et al. 1999) only look at primary damage and further require a large number of variables of high quality input data (Hanewinkel et al. 2004).

They calculate the critical wind speed (CWS) (vulnerability and exposure) and assess the probability of this windspeed to occur in a given stand (Gardiner et al. 2008), hence following the steps of Kaplan & Garrick (1981). The winter storm, colloquially known as “Gudrun” in 2005 however blew down 70 million m^3 of timber in Sweden, around twice the annual cut for the affected area (Skogstyrelsen 2006). This draws the attention to subsequent effects of such a storm (secondary and tertiary damage). Though these damage levels are crucial to include in relation to risk management, this thesis limits the concept to only address the primary damage.

3.2 Sub conclusion

Risk is a wide concept; hence delimitation is important. Risk has for this thesis been limited to the concept of mechanical damage of the forest resource, thus not including subsequent damage. The definition of risk is by Aven & Renn (2009) and Gardiner & Quine (2000) interpreted in this study to be a potential loss of the forest resource due to wind. Further, it is assumed it does not influence market prices and demand (used for economic calculations).

4 Windthrow contributing features

Windthrow in northern Europe and especially extensive windthrows is often caused by winter storms generating high wind speeds of more than 30 ms^{-1} (Riguelle 2016). The level of damage however is not only correlated to wind speed but also to site and stand specific characteristics (Lohmander & Helles 1987; Mitchell 2013; Díaz-Yáñez et al. 2017). Factors influencing the probability of windthrow may therefore be divided in four categories 1) meteorological conditions, 2) topographic conditions, 3) site conditions and 4) tree and stand characteristics (Schindler et al. 2012). While site and topography are quasi-static weather and stand characteristics shows dynamic behaviour.

4.1 Meteorological conditions

The intensity and therefore the severity of wind-induced damage is shown to be highly depending on the maximum sustained wind speed and the duration of the wind exposure (Gardiner et al. 2010). The Danish windspeed charts rank extreme winds as storms (25-28 ms^{-1}), strong storms (29-32 ms^{-1}) and hurricanes (>32 ms^{-1}), with Beaufort values of 10, 11 and 12 respectively (Cappelen & Rasmussen 2013). Together with the intensity of the wind, the frequency of the storms to recur in a region is very central for understanding wind as a natural disturbance in forestry (Mitchell 2013). For a midlatitude temperate zone as Denmark, extreme winds are often a result of extra-tropical cyclones developing over the Atlantic Ocean (Ulbrich et al. 2009; Frame et al. 2017). These are termed European windstorms (Jones et al. 2003; Martínez-Alvarado et al. 2012). The development of European windstorms, such as the winter storms of 1999, 2005 and 2013, respectively (Hewson & Neu 2015) is a consequence of decaying tropical cyclones (Jones et al. 2003; Frame et al. 2017). On the Northern hemisphere these cyclones rotate counter clockwise, placing the strong winds to the right (south) of the cyclones centre (the low atmospheric pressure) (Hewson & Neu 2015). Denmark lies within the prevailing westerlies wind belt between 30-60^{o}N. Because of that, these cyclones more commonly pass north of Denmark, bringing high wind speeds (Martínez-Alvarado et al. 2012).

4.2 Topography and shelter

The movement of these cyclones and other large-scale air systems change depending on local and regional topography (Mitchell 2013). Topography is referred to as surface features, most commonly terrain contours, but also neighbouring stands, windbreaks and other sheltering obstacles affects the winds speed, direction and gustiness.

Wind exposure accounts for 77 % of the total score on the British storm hazard rating system, and topography alone accounts for 23 % making exposure a vital contributing factor of windthrow (Ruel et al. 2002). The reason why topography is included in such a huge proportion of the rating system is due to the location of the strongest regional windspeeds is determined by the topography (Quine 1995). Ridge tops and especially west-facing slopes experience stronger wind speeds (Ruel et al. 1998).

While some studies report no relation between topography and wind damage, a study with 159 windthrown areas found that 45 % where located at windward slopes and only 7 % where found on flat areas (Everham & Brokaw 1996). Depending on the wind direction, valleys both amplify the disturbance due to constricted and accelerated winds (Ruel et al. 1998) but also provide protection (Everham & Brokaw 1996). Though topography influences wind damage it may be due to correlations with edaphic characteristics, such as soil depth and water saturation (Everham & Brokaw 1996).

4.3 Site conditions

In addition to wind as a meteorological influence, precipitation therefore also affects the damage level due to waterlogging (Lohmander & Helles 1987; Schmidt et al. 2010), reducing the anchorage of trees (Peltola, Kellomäki & Väisänen 1999; Sanderson & Armstrong 1978). Differences in soils, being the medium in which trees are anchored, has long been evident for limitations of rooting, hence affecting tree stability and subsequent windthrow (Quine 1995). Wind-induced damage is often higher for species with shallow root systems or due to incorrect root development caused by waterlogging or impermeable soil layers (Sanderson & Armstrong 1978; Everham & Brokaw 1996; Peltola 2006). Nicoll & Ray (1996) however, found that Sitka spruce (*Picea sitchensis* (Bong.) Carr.) showed adaptive root system morphology because of shallow rooting, which improved anchorage. Root deformation could on the other hand also be due to incorrect planting techniques or wrong choice of stock type (Nørgård Nielsen 2014c; E. K. Hansen 2013). Depth and also the mass of the roots are therefore closely correlated with the resisting forces (Peltola 2006; Quine 1995).

Nicoll et al. (2006) found Douglas-fir to have significantly better anchorage than Sitka spruce on medium-depth mineral soils. However, the same study found uprooting to be more frequent on mineral soils compared to peat soils. This was due to the roots being held more firmly in mineral soils leaving no incentive for wind adaptive root development. In Germany Klaus et al. (2011) showed that poor quality soils with high erodibility and large grain size where more sensitive to windthrow. Soil frost duration is further decreasing due to rising temperatures as a consequence of climate changes (Peltola, Kellomäki & Väisänen 1999). Anchorage is therefore weakened resulting in increasing risk of windthrow in northern latitude forests (Peltola, Kellomäki & Väisänen 1999).

Analyses of the storms Lothar and Martin in 1999 further showed a relationship between acidifying depositions of sulphur and nitrogen and the susceptibility to windthrow (Mayer et al. 2005). The same study however, showed that the proportion of coniferous species had a significant impact on storm damage. Since coniferous species causes soil acidification together with these being more prone to windthrow, storm damage may not be correlated with low soil pH but with the proportion of conifers (Mayer et al. 2005). Nitrogen fertilization in Scandinavia has on the other hand been shown to increase windthrow probability (Mayer et al. 2005). This gives indices for higher windthrow risk of the examined species in Denmark.

4.4 Stand characteristics and species

Stand characteristics are highly correlated with the above-mentioned differences in climate, topography and soil conditions. This alters the vulnerability against wind-induced damage. Despite the differences in earlier studies (e.g. different soil type and climates), some general conclusions are still drawn for most forest stand characteristics and across species.

4.4.1 Single tree level

When looking at single tree conditions, earlier studies have found that stem resisting forces are shown to significantly increase by radial growth (Pukkala et al. 2016; Díaz-Yáñez et al. 2017; Peltola 2006; Rich et al. 2007). Though the stem resisting forces increase by stem size, applied forces from tree tip displacement due to wind, increase as a function of height. The root resisting forces is therefore often surpassed making height a critical factor of windthrow (Schmidt et al. 2010).

4.4.2 Stand level

When looking at the damage occurrence on stand level, windthrow is on the other hand positively correlated with an increase in diameter (Lohmander & Helles 1987; Valinger & Fridman 2011; Wallentin & Nilsson 2013; Peltola 2006). While the relationship between windthrow and stem size is linear for the individual tree it is unimodal for the stand (Mitchell 2013). The smallest trees are often sheltered while the tallest trees have acclimated to the windy conditions (Mitchell 2013; Díaz-Yáñez et al. 2017). This also makes the proportion of broken trees larger in these groups since better anchorage of large trees makes these break instead of uprooting and afterwards break the smallest trees when falling (Mitchell 2013; Díaz-Yáñez et al. 2017). Stand grown trees are additionally sheltered by neighbouring trees (high social stability) but is also competing with these for growing space making the stems slender as a function of density (Lohmander & Helles 1987; Mitchell 2013; Long et al. 2004).

4.4.3 Slenderness

Slenderness refers to the ratio between height and diameter. Many earlier studies have found that increased height diameter ratio (termed h:d, h/d or taper) increases the probability of damage (Lohmander & Helles 1987; Peltola, Kellomäki, Väisänen, et al. 1999). A 20 meters high stand of Scots pine with a taper of 1:100 was in a Finnish windspeed simulation shown to be overthrown with a mean wind speed of 13,2 ms^{-1} and even lower wind speeds would be critical for stands with a taper of 1:120 (Peltola, Kellomäki & Väisänen 1999).

Where less tapering trees (very slender, thin trees) are more likely to break, highly tapering trees (thicker trees) are more likely to uproot (Peltola, Kellomäki, Väisänen, et al. 1999). Schütz et al. (2006) and Valinger & Fridman (2011) on the other hand, did not find significance between increase in taper and increase in storm damage. Though a high taper is a consequence of dense stands, unthinned stands are found to be highly resistant to heavy storms (Wallentin & Nilsson 2013; Lohmander & Helles 1987). However, this only applies if the canopy is intact. The uniformity of the stand regarding crown and stem size can by edge exposing or gap openings result in substantial damage during extreme wind events, especially if this happens late in the rotation period (Mitchell 2013; Wallentin & Nilsson 2013).

4.4.4 Age development

Talking about rotation period, risk of windthrow has furthermore been proven to increase by age (Nicoll et al. 2006; Lohmander & Helles 1987; Valinger & Fridman 2011; Rich et al. 2007). Stands in particularly windy areas are often harvested prior to the economically optimal rotation age, to reduce the risk of damage (Nicoll et al. 2006). For coniferous stands this trend seems to decrease for old and very old stands (>100 years old), whereas 90 year old stands are the most sensible (Valinger & Fridman 2011; Rich et al. 2007). This is discussed to possibly be a consequence of older stands having reached their top height, having acclimated and not having experienced thinnings for a long period which are shown to increase the damage level.

4.4.5 Reduction in basal area

Thinnings reduce the basal area of the stand and makes the distance between the trees larger. This results in wind passing through the canopy, thus exposing the individual tree to higher wind loads (Wallentin & Nilsson 2013; Lohmander & Helles 1987). As mentioned earlier, higher wind loads for slender trees leads to windthrow, hence thinning being a windthrow contributing factor. Thinning is on the other hand carried out to improve radial growth of the remaining trees. This decreases the height diameter ratio together with increasing its roots strength and mass (Peltola, Kellomäki & Väisänen 1999). Thinning therefore affects windthrow in two ways, negatively and positively (Lohmander & Helles 1987).

The following increase in diameter of the remaining trees, therefore makes stands most vulnerable immediately after thinning (Pukkala et al. 2016; Lohmander & Helles 1987; Wallentin & Nilsson 2013). This also means that the negative effect is temporarily and earlier studies suggest a recovery period for coniferous species of 5-6 years before the same stability as before the intervention is reached (Pukkala et al. 2016; Díaz-Yáñez et al. 2017; Lohmander & Helles 1987). This recovery period however, increases by time (Nørgård Nielsen 2014b). Some authors however, did not find this relationship (Schütz et al. 2006). High thinning volume and intensity has further been proven to affect windthrow damage significantly, especially in older stands (Wallentin & Nilsson 2013; Lohmander & Helles 1987). Increased recovery period and higher risk with strong thinnings have therefore led to the suggestion of excluding thinnings late in the rotation period (Nørgård Nielsen 2014c). The Southern Swedish forest owner's organisation (Södra) also recommends members to thin stands of Norway spruce early and relatively severely to reduce the risk of windthrow (Keskitalo et al. 2016).

4.4.6 Tree species

The probability of windthrow for deciduous trees are shown to be generally lower than those of conifers (Schmidt et al. 2010; Mayer et al. 2005). Valinger & Fridman (2011) showed that an admixture of 25-30 % deciduous trees in a Norway spruce stand would decrease the risk of windthrow by 50 % in southern Sweden. For both Danish and Swedish conditions, the strongest storms happen in late autumn and winter time, which means deciduous trees are leafless making them less susceptible to strong wind loads (Schmidt et al. 2010; Valinger & Fridman 2011; Mayer et al. 2005). Schütz et al. (2006) further showed that an admixture of 10 % deciduous species or 10 % Douglas-fir in a spruce stand significantly decreased the stands vulnerability by more than three times. This admixture is also suggested under Danish conditions (Møller 1977; Henriksen 1988). In general, shade intolerant species are shown to be more prone to windthrow (Rich et al. 2007). Shade intolerant species also being early successional species allocate most of its resources to rapid growth. This is often height growth instead of structural strength, which makes them less firm against wind (Givnish 1995).

A series of tree species trials in Denmark (the F.65 series) has revealed some of the differences between species cultivated in Denmark. At Lindet state forest district, the trial with 12 different species was severely hit by the cyclone Anatol in 1999. Only European beech, sessile oak and cypress remained unharmed while Douglas-fir were partially preserved. Other conifer species mainly spruce and pine were overthrown (Jørgensen & Nielsen 2001). Conclusions made based on all the trials were, that young Douglas-fir and Norway spruce are unstable, while older Douglas-fir are particularly stable (Jørgensen & Nielsen 2001). Modelling single tree storm damage in Germany after the winter storms in 1999, further showed Norway spruce to have the highest risk of being damaged by wind, followed by Douglas-fir and Scots pine (Schmidt et al. 2010). Lohmander & Helles (1987) in contrast found that Douglas-fir was significantly more unstable than Norway spruce but also conclude that the observations of Douglas-fir was few and that the dummy variable used in their model was not significant.

In a study from southern Germany Albrecht et al. (2013) further suggests that the two species are equally vulnerable to wind induced damage, under present German management conditions, hence Douglas-fir not having higher storm damage resistance

4.5 Sub conclusion

Windthrow is complex and many variables can be examined for predictive abilities. This thesis looks at four different European windstorms and meteorological terms have therefore been presented (see section 6). The windstorms are altered in strength by sheltering and topographic features and these variables have a large impact on the stability of a given stand. However, the examined data set does not make it possible to examine all variables thus, variables not examined has been described for their influence for further discussion.

General stand characteristics have been described for their influence on the risk of windthrow, since the analysis is made on stand level. The effect on single tree level however, is important for the understanding of management actions, such as thinning and subsequent slenderness. This thesis looks at Douglas-fir together with Norway spruce why differences in these species are described.

5 Consequences of windthrow

Windthrow has few benefits (Gardiner et al. 2010). For the forest owner windthrow reduces prices due to demand and supply interactions. While this is a loss of income for the forest owner, it is positive for the industries now being able to buy cheaper raw material. Windthrow also accumulates deadwood improving habitats for some species (Andersson et al. 2006) but also increases the abundance of pests, like bark beetles (Schelhaas et al. 2001).

5.1 Biological consequences

Even though the CWS has not been exceeded, some significant changes may occur, such as branch, stem and root movement, making the tree more vulnerable under future events (Quine & Gardiner 2007). Though movement of roots have a wearing effect on the roots, it also stimulates the acclimating of the tree (e.g. root thickening) (Quine & Gardiner 2007). When the CWS is exceeded, vegetation and forest soil components is affected on both microsite, stand and landscape level (Mitchell 2013).

5.1.1 Stand composition dynamics

If socio-economic consequences are ignored, but only structural and ecological consequences are looked upon, windthrow, especially gap openings, possess essential values for the structural dynamics in forests (Nicoll et al. 2006). The gaps enhance advanced growth at the forest floor, changing stand structure and age (Quine & Gardiner 2007). Also, species diversity can change depending on seed sources from seedbanks and neighbouring trees. The overturning of trees, furthermore mixes the soil horizons favouring better conditions for advanced growth (Nicoll et al. 2006). Windthrow might even accelerate succession since shade intolerant species are shown to be more prone to fall under wind loads (Rich et al. 2007).

5.1.2 Fungi, insects and soil dynamics

Windthrow further results in the accumulation of dead, downed and broken trees (Wichmann & Ravn 2001; Schmidt et al. 2010). This increases the amount of coarse woody debris providing habitats for many species, such as lichens and fungi (Paillet et al. 2010). The weakened and dead trees however, pre-dispose stands to subsequent damage like the spruce bark beetle *Ips typographus* (L.) (Wichmann & Ravn 2001; Schmidt et al. 2010). Schelhaas et al. (2003) also showed that damage from bark beetles was highly correlated with previous storm damage. Windthrow however, often causes uprooting of trees which expose and invert mineral soils at the forest floor (Pawlik 2013). The uprooting leaves pit mounds which are both warmer and drier during the growing season, promoting diversity in the understory flora (Quine & Gardiner 2007).

Mounds and pits following windthrow are shown to increase soil features such as available nutrients and biomass of earthworms (Kooch et al. 2015). Ulanova (2000) found that pit and mound topography was highly associated with spatial distribution of trees and that tree uprooting was important for stable population structures in forest. Windthrow or windthrow imitation has even been suggested to be carried out to maintain soil productivity levels in temperate forests (Mitchell 2013; Bormann et al. 1995).

5.2 Economic consequences

Though biological consequences possess positive and negative values, windthrow is only negatively correlated with the forest owners' economy (Gardiner et al. 2010). The profitability of forest stands managed for timber production is greatly reduced due to lower values of the windthrown timber (Nicoll et al. 2006). Severe storms further have financially huge subsequent consequences, affecting both forest owners, wood-industries and other employees in the forestry sector (earlier referred to as secondary and tertiary damage) (Skogstyrelsen 2006; Haanpää et al. 2006).

5.2.1 Decision making under risk consideration

In general, financial risk aversion often leads to the decision of shortening the rotation length, which further reduces production and financial returns (Buongiorno et al. 2017; Gardiner & Quine 2000). Forest owner organisations in Sweden even recommends cutting the rotation lengths of spruce dominated forests by 10 to 15 years to avert the risk of windthrow (Keskitalo et al. 2016). The presence of a partial or destructive risk is further shown to involve earlier thinnings and because of this the economically optimal, rotation age would be prolonged (Loisel 2011) which on the other hand, contradicts with the actual management decisions.

The risk of windthrow thus lowers the value of an investment project so much that it to some degree discourage investment in forestry (Yin & Newman 1996). Brunette et al. (2015) shows that harvest amount increases with greater risk of windthrow and when the forest owners risk aversion increase, harvest amount is reduced. The study further suggests, that a higher risk leads to a higher willingness to pay for coverage. The forest owner is thus willing to pay for prevention or coverage strategies (shorter rotation length or windthrow insurance). Blennow et al. (2013) suggests that risk is both subjective and objective and that management of forests are vastly based on personal risk assessment of the forest owner. This further means that risk management and also decision making is often facilitated by heuristic methods. Meilby et al. (2001) further notes in their study of optimal spatial harvest planning under risk of windthrow, that despite the study being the first of its kind the results are in accordance to present silvicultural practice and decisions. Much of the present risk management is therefore often based on intuition and personal experience, yet easy measurements and calculations can be done (Bright & Price 2000). The only practical problem is to obtain realistic estimates of windthrow probabilities (Bright & Price 2000), which is the aim of this thesis.

5.3 Sub conclusion

While windthrow in the context of the chosen definition of risk is negative (loss), it might possess positive values in other contexts. The perception and aversion of this risk could therefore differ depending on the forest management and owner. In accordance to the chosen definition the biological benefits of windthrow will however not be dealt with but only discussed. This also means that the consequences of windthrow is only looked upon as negative economic consequences in forests managed for timber production, though other management aims could benefit from potential windthrow. Previously, risk management is based on intuition and experience, while calculations are easily done if realistic probabilities are obtained.

6 Wind-induced damage in Danish forestry

In temperate maritime regions like Denmark, wind stress on forests is regularly having major disturbance effects (Quine & Gardiner 2007). Schelhaas et al. (2003) reported that 53% of the total damage in European forest was caused by wind, and that the Sub-Atlantic region, including Denmark and The British Isles, was among the most severely hit regions. An estimate of the last 100 years of Danish windthrows shows an average frequency of 5 years between major windthrow events and an average of about 10 years between windthrows greater than 250.000 m^3 (Skov- og Naturstyrelsen 2010; Dansk Skovforening 2014; Jørgensen & Nielsen 2001) (see appendix 1).

The windspeed in 45 m height for Denmark is seen in Figure 6.1 and is estimated by compiling topographic and geographic features (EMD 2001). It was originally made for wind energy planning but is used here in relation to what windspeed stands are regularly exposed to. It shows higher mean windspeeds for the entire western coast of Jutland together with western faced coastlines of Funen, Zealand and the remaining islands. As mentioned in section 2.1, regular wind impact acclimates the trees, improving anchorage. However, there is a large difference between average wind speed and the wind speeds during cyclones (Cappelen & Jørgensen 1999).

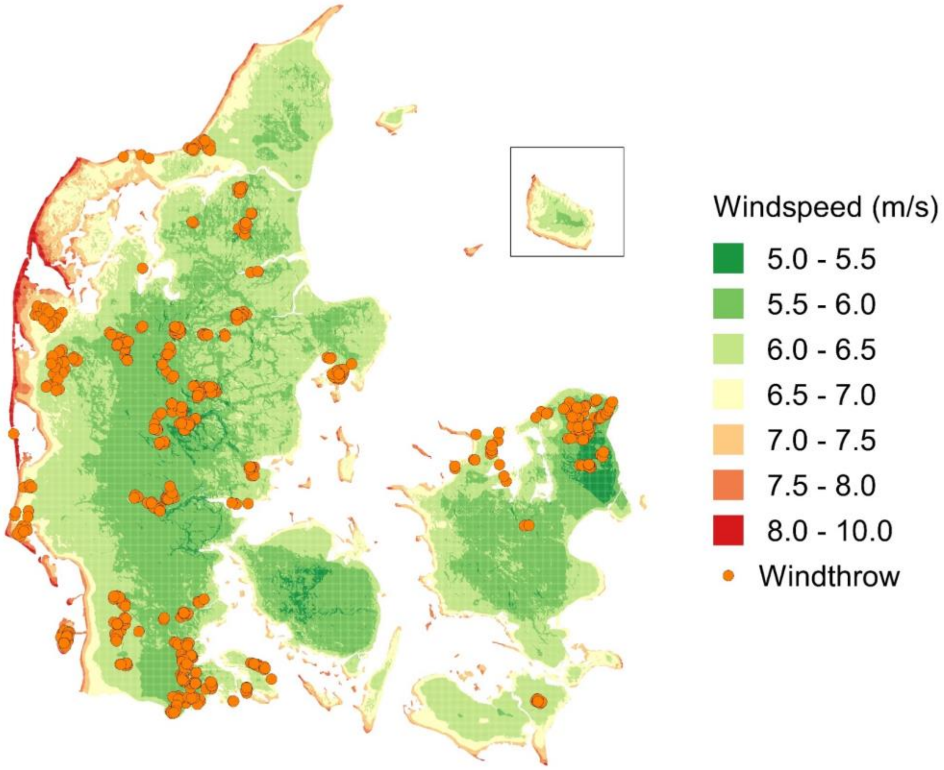


Figure 6.1: Wind resource map of Denmark at 45 meters above the ground, mean windspeed measurements. Data derived from EMD (2001). Orange plots marks forests experiencing windthrow in the data material.

6.1 Storms and storm development in Denmark

The Intergovernmental Panel on Climate Change (IPCC) predicts extratropical cyclones to become more intense and having larger windspeed peaks (Solomon et al. 2007). The number of cyclones however, is projected to decrease, though this estimate is rather uncertain.

The Danish meteorological institute (DMI) also confirms this trend, that the frequency of storms will be less, but more severe (Christensen & Hess 2013). Emission models (greenhouse gas concentrations) from the IPCC further predicts the largest windspeed increases in Europe to be across Danish latitudes. Though these predictions are very uncertain, a wide variety of models predict the same outcome (Christensen & Hess 2013).

This thesis study uses data from four severe cyclones. Their characteristics are shown in Table 6.1. In the table national storms refer to an affected area larger than 30 % of the total area of Denmark and the classification from 1 to 4 equals a Beaufort value of 9-12 (Cappelen 2017). Under Finnish conditions an earlier study suggest that thresholds for the occurrence of wind damage in spruce are already exceeded with regional windspeeds of more than 15 ms^{-1} and with gusts of more than 30 ms^{-1} (Kellomäki et al. 2005). These thresholds are all exceeded for certain regions during the analysed storms.

Table 6.1: Storm events information: time, classification and windspeeds.

Name	Time of event	Classification	Highest windsp.	Sustained windsp.
Anatol[1]	December 3rd, 1999	National cl. 4	51,4 ms^{-1}	38,1 ms^{-1}
Gudrun[2]	January 8th, 2005	National cl. 3	46,0 ms^{-1}	35,0 ms^{-1}
Allan[3]	October 26th, 2013	Regional cl. 4	53,5 ms^{-1}	39,5 ms^{-1}
Bodil[4]	December 4th, 2013	Regional cl. 4	44,2 ms^{-1}	36,6 ms^{-1}

[1] Further reading: Hansen (2013); Ulbrich et al. (2012); Woetmann & Hansen (2003)

[2] Further reading: Haanpää et al. (2006); Carpenter (2005); Skogstyrelsen (2006); Suursaar & Sooäär (2006)

[3] Further reading: Haeseler & Lefebvre (2013); Cappelen (2013)

[4] Further reading: Deutschländer et al. (2013); Eriksen (2014); Nielsen (2014)

The highest windspeeds of the four storms together with locations of the affected forests for the individual storms are shown in Figure 6.2 to Figure 6.5. A somehow clear pattern shows higher concentrations of affected stands within regions with increasing windspeeds for the specific storms. Data depicting forests affected by storms during the late months of 2013 do not distinguish between the cyclone Allan and its successor cyclone Bodil. Looking at Figure 6.4 however, data plots from northern and central Jutland is presumably a cause of cyclone Bodil and plots from southern Jutland a cause of cyclone Allan. For the data analysis the highest experienced windspeed of the two (Allan and Bodil) were used.

During cyclone Allan, many deciduous trees were still in leaf (October) increasing the amount of damage (Haeseler & Lefebvre 2013). In Denmark severe storms during autumn is a rare event and only a few has occurred earlier (Cappelen 2017). The track of the storm (marked with a red dotted line on Figure 6.4) also shows an unusual path for an Atlantic storm, crossing the southern parts of the British Isles (Haeseler & Lefebvre 2013).

The European commission has previously categorised the potential level of damage related to wind by maximum gust wind speeds (Gardiner et al. 2010). No considerable damage is expected for windspeeds <30 ms^{-1}, a moderate damage level is expected between 30 – 40 ms^{-1}, a high damage level is expected between 40 – 45 ms^{-1}, and a severe damage level is expected for wind speeds >45 ms^{-1}.

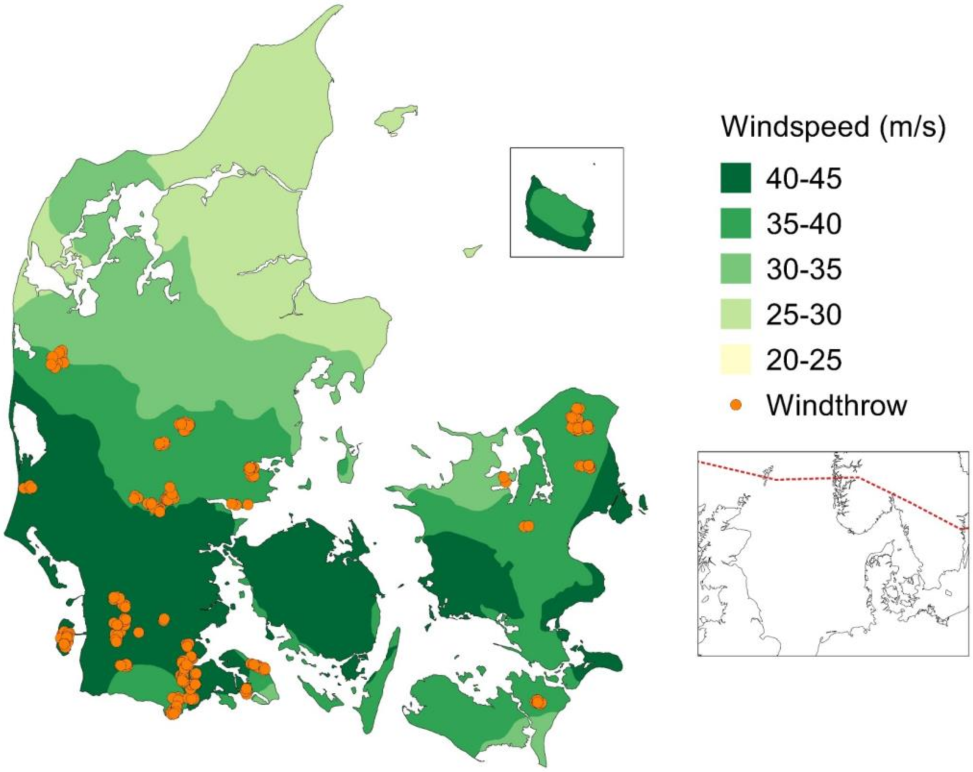


Figure 6.2: Maximum windspeed (gusts) during the storm Anatol on December 3rd, 1999.
Orange plots marks forests experiencing windthrow. Red dotted line shows the eye of the cyclone.
Data provided by DMI NST and GST.

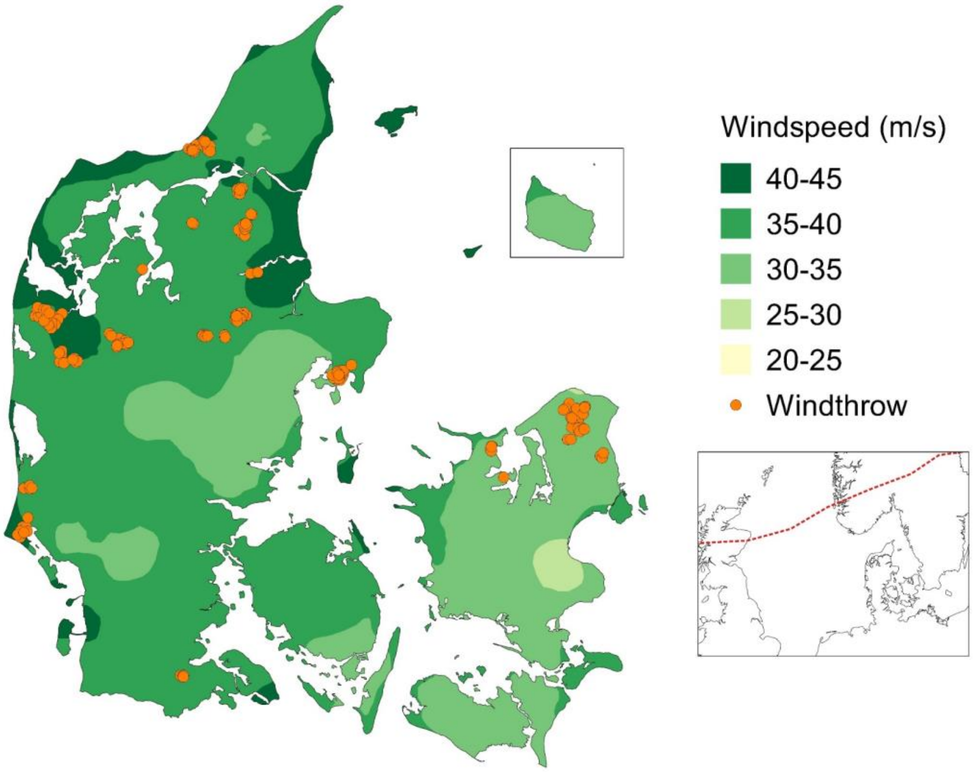


Figure 6.3: Maximum windspeed (gusts) during the storm Gudrun on January 8th, 2005.
Orange plots marks forests experiencing windthrow. Red dotted line shows the eye of the cyclone.
Data provided by DMI NST and GST.

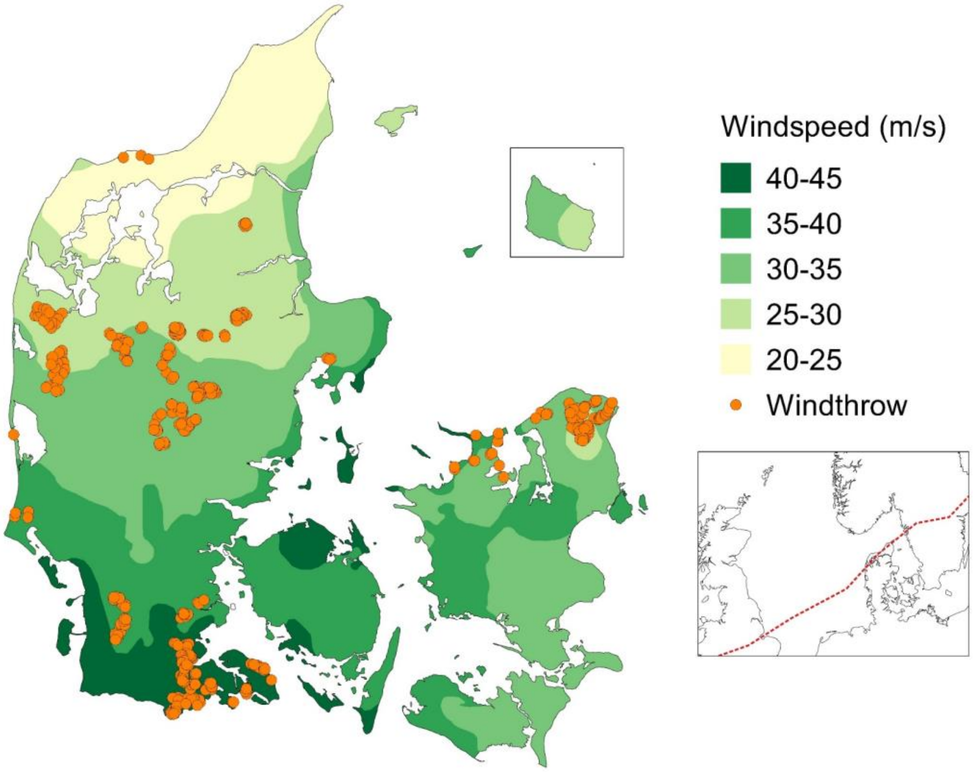


Figure 6.4: Maximum windspeed (gusts) during the storm Allan on October 28th, 2013.
Orange plots marks forests experiencing windthrow. Red dotted line shows the eye of the cyclone.
Data provided by DMI NST and GST.

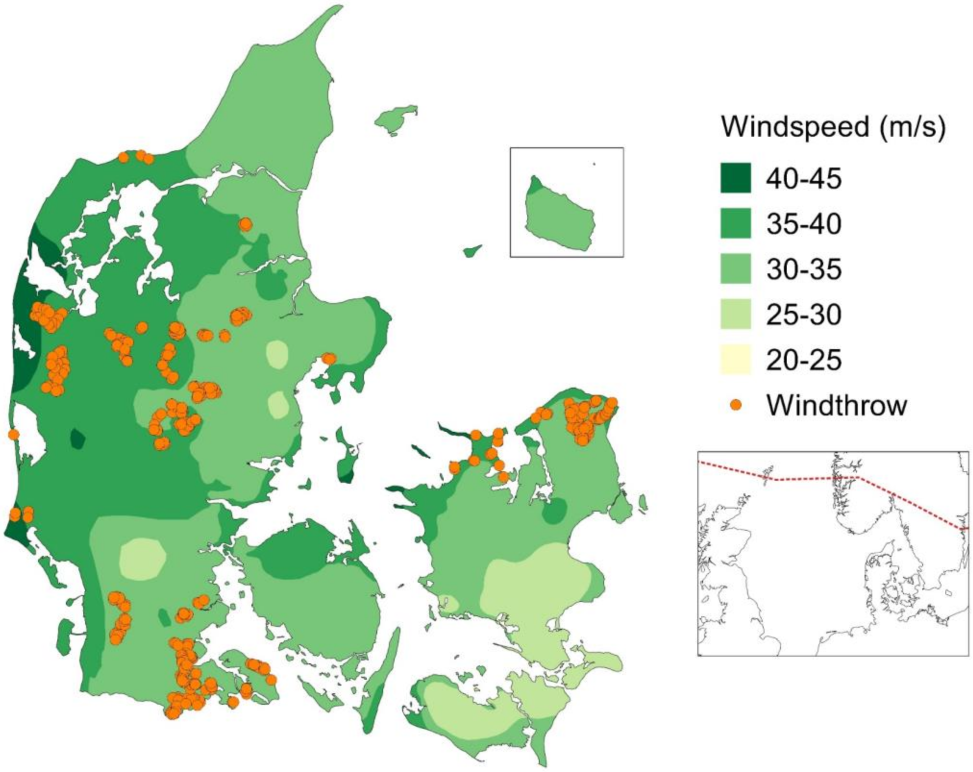


Figure 6.5: Maximum windspeed (gusts) during the storm Bodil on December 5th, 2013.
Orange plots marks forests experiencing windthrow. Red dotted line shows the eye of the cyclone.
Data provided by DMI NST and GST.

6.2 Stand characteristics and species composition

The Danish forest cover has experienced a steady increase the last century and especially the abundance of coniferous species shows a large development (Nord-Larsen et al. 2017). The forest statistics of 2016 further shows, that Norway spruce equals 18 percent of the total growing stock in the Danish forests. It is further the individual species covering most forest land. The substantial share of spruce however, are shown to increase the risk of windthrow as also seen in Sweden, especially during extreme wind events (Valinger & Fridman 2011).

6.2.1 Danish thinning practice

The common Danish thinning practice in coniferous stands is a basal area of 67% compared to the unthinned stand, also termed C-thinning (Bergstedt 2017). This practice potentially increases the vulnerability against wind loads since extensive thinnings reduce the stability of the stand (section 4.4). The time between thinnings (often <10 years apart (Madsen 1990)) also gives little incentives for the stand to recover (approximately 5-6 years, mentioned earlier) before the next thinning. Furthermore, the recovery period increases as a function of age due to decreasing volume increment, which additionally increases the susceptibility to wind loads (Nørgård Nielsen 2014b). Coniferous stands under common Danish management is thus continuously exposed to the risk of windthrow throughout their rotation period.

6.2.2 Tree species

Though the risk of windthrow has indirectly been a part of the decision-making basis in Denmark when selecting tree species, the practise seems to have increased since the winter storm in 1999 (Jørgensen & Nielsen 2001). The windthrow act (Act 349 of May 17, 2000 on storm surge and windthrow) recommends among other species; Beech, Oak, Douglas-fir and Larch, as being wind firm. Cultivation with these species are also subsidized by the state, whereas Norway spruce is not according to the windthrow act. In this thesis Douglas-fir is analysed together with Norway spruce as comparison reference and the two species is therefore described in the following sections.

6.3 Douglas-fir

The North American coastal Douglas-fir have since its introduction to the European forestry, managed to become an economically important tree species because of good quality timber and its fast growth rate, even outperforming the native Norway spruce on some sites (Herman & Lavender 1990). The highest abundance of a cultivated non-native tree species in Central European forests is further the Douglas-fir, giving it substantial importance, especially in France and Germany (see Figure 6.6) (Da Ronch et al. 2016). European planted stands however, differ from the native coastal Douglas-fir by having a more rapid growth. This is particularly seen in the difference of initial height growth (Hermann & Lavender 1999).

In its native range coastal Douglas-fir is a deep-rooting species with a profound heart root system including taproots. However, as with many other species the morphology of the roots varies according to the soil (Klinka et al. 1999). In deep soils taproots can grow up to 50 % of their final depth within 5 years and 90 % before the age of 8 (Herman & Lavender 1990).

Shallow soils and soils with high water tables on the contrary, develop flat root systems (Herman & Lavender 1990). Though the same deep reaching root systems is developed under European conditions, taproots were not shown in a Czech study by Mauer & Palátová (2012). While the initial root growth in North America is rapid, it seems opposite for the European stands. Root systems with anchorage potential similar to that of the taproot, was shown to be established at the age of 20 instead of 5 (Mauer & Palátová 2012). The roots however increased both in range and dimensions with age and in relation to the above ground part of the tree. The initial increase in height growth and decrease in root growth for European stands, compared to those of North America, therefore has the potential to reduce the storm stability of young Douglas-fir (based on the statement by Givnish (1995), see section 4.4.6).

A study in the genetic variation in susceptibility to windthrow in young Douglas-fir also showed that windthrow was significantly related to initial height growth and root anchorage between families (Silen et al. 1993). The study suggested breeding for more resistant trees on the expense of a reduction in height growth. However, it also notes that this would be expensive compared to the silvicultural means that can be performed to improve stability, such as mixtures and thinning practice. Douglas-fir therefore has the potential to be managed towards a greater storm stability. However, this is a relative measure unless it is seen in relation to other species.

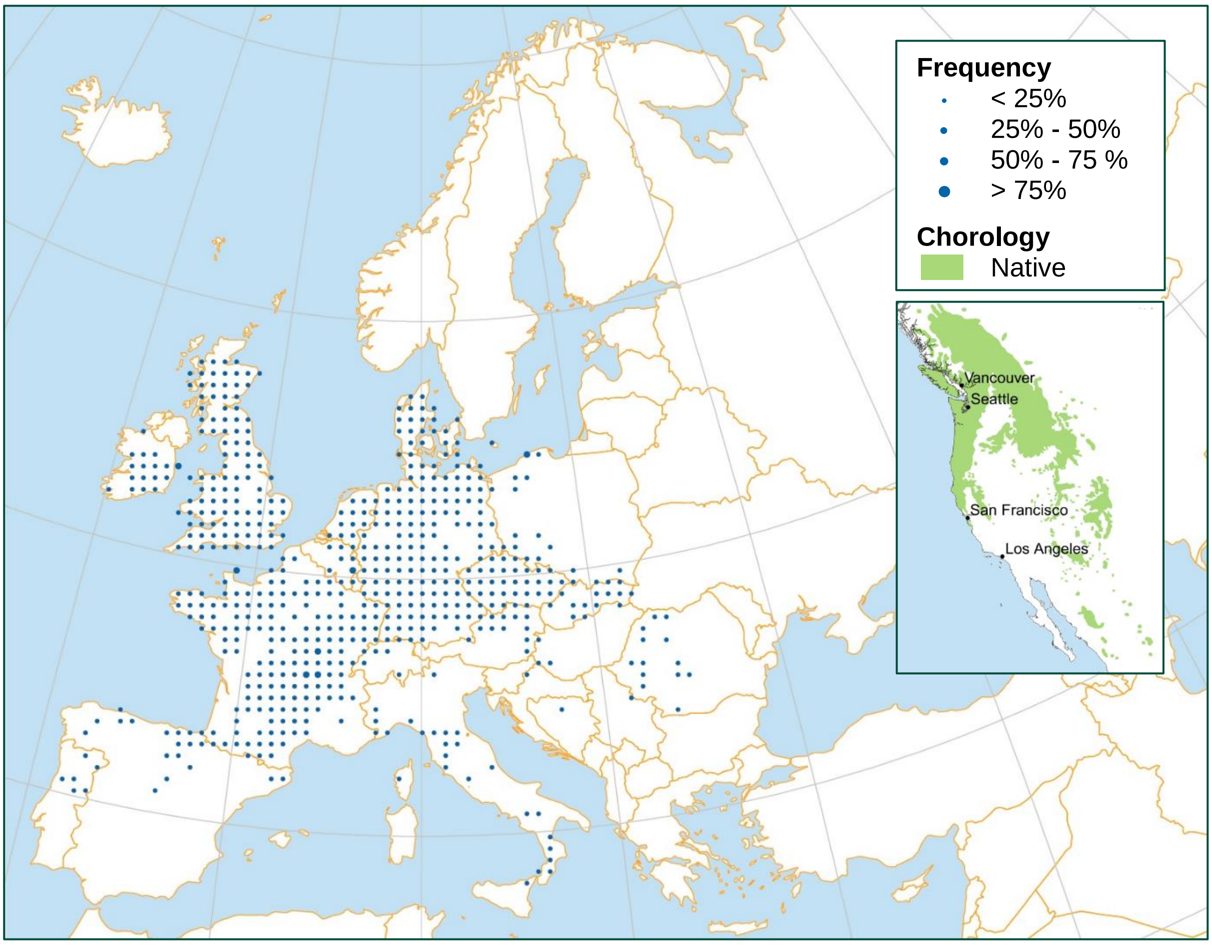


Figure 6.6: Plot distribution of Douglas-fir in Europe with a simplified chorology map (Da Ronch et al. 2016). Based on field observations as reported by the national forest inventories. Chorology derived from (Little 1999).

6.4 Norway spruce

To better understand the susceptibility of Douglas-fir to wind-induced damage, the same study is therefore made for Norway spruce for comparison. Norway spruce is among the most important coniferous species cultivated in Europe, both in relation to economy and ecology (Caudullo et al. 2016). The highly productive species have thus been introduced to many sites beyond its native range in Europe including Denmark and has a long cultivation tradition (see Figure 6.7). As already stated, the species appears to be extremely sensitive to wind damage which, together with the high abundance of the species in Denmark, makes it worth comparing.

Climate change predictions featuring increasing temperatures additionally makes Norway spruce a subject to increasing biotic risks (Hanewinkel et al. 2011). The increase in drought periods as a consequence of higher temperatures creates environments suboptimal for Norway spruce (Kellomäki et al. 2005; Albert et al. 2015). It further increases the activity of damaging pathogens, like the root rot fungi *Heterobasidion* (Keskitalo et al. 2016). Due to this, Norway spruce is expected to cease as a productive species in most of England (Broadmeadow 2002), and partly in southern Finland and Sweden (Keskitalo et al. 2016; Kellomäki et al. 2005). The incentive for comparing with Norway spruce is therefore also due to recommendations for adaptive management, including species change (native and exotic) to increase resistance and resilience of forests to climate change (Subramanian et al. 2016).

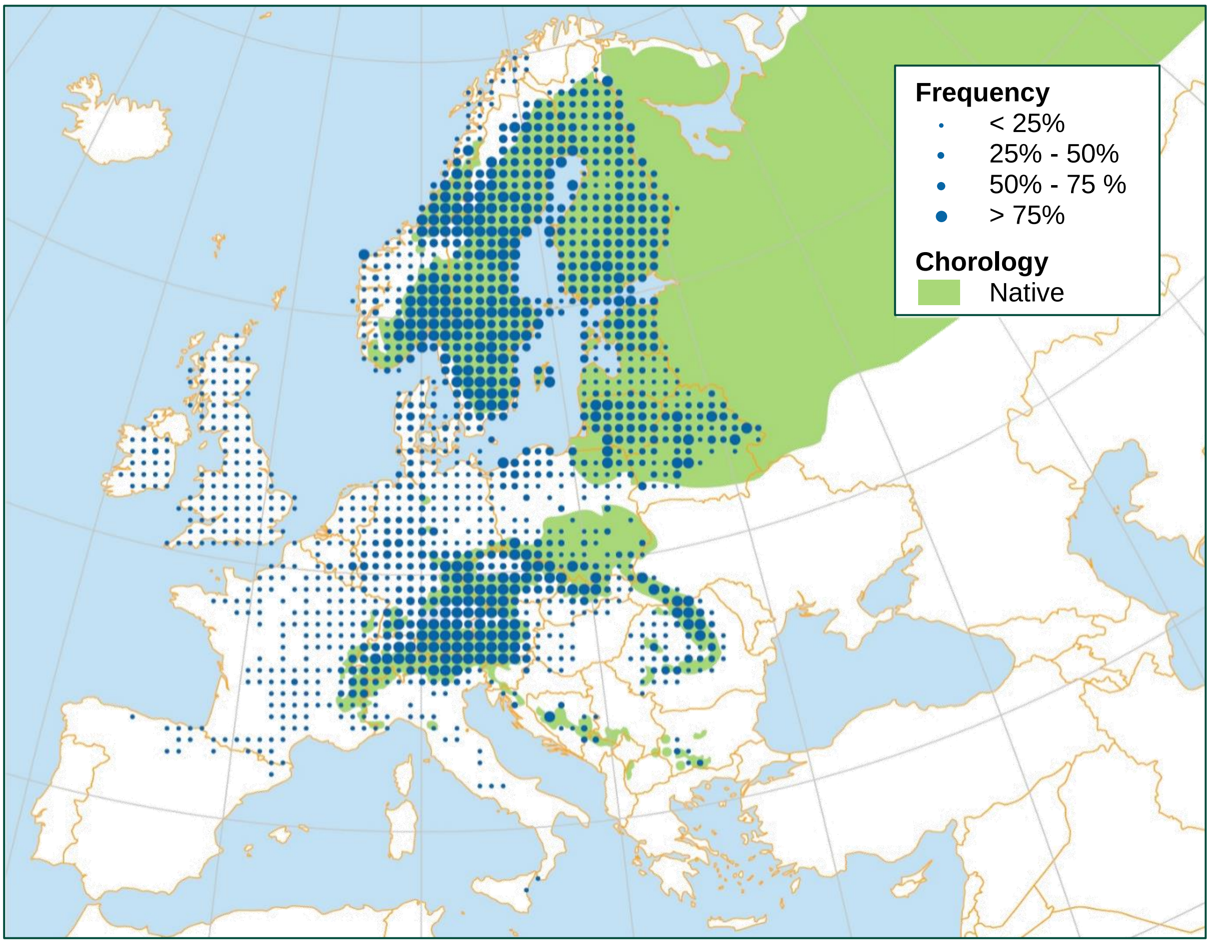


Figure 6.7: Plot distribution of Norway spruce in Europe with a simplified chorology map (Caudullo et al. 2016). Based on field observations as reported by NFI data. Chorology derived from EUFORGEN (2013).

6.5 Douglas‑fir as a partial substitute for Norway spruce

Unlike Norway spruce, facing problems with root rot, Douglas-fir have been imported to the European forestry without its specific antagonists, hence not facing present biotic threats (Hanewinkel et al. 2011). Douglas-fir therefore possesses an advantage, yet this could be temporarily. Neither of the species is native to Denmark and whereas Norway spruce is distinguished in the boreal forest region (Caudullo et al. 2016) Douglas-fir is a temperate forest region species (Klinka et al. 1999), similar to Denmark.

In relation to Danish forest management, the use of Douglas-fir could therefore be expected to increase in Denmark. This is due to somehow similar traits in timber quality, production and better habitat amplitude which induce for its abundance in Sweden to increase (Keskitalo et al. 2016), hence possibly also in Denmark. However, Norway spruce have bright wood, whereas Douglas-fir develops heartwood (Lund Johansen 2014), which causes problems with the production of e.g. paper products. Czech forestry also promotes Douglas-fir as a substitute to Norway spruce especially in lower altitudes somehow similar to Denmark (Podrázský 2015). Studies of different site fertility in the Czech Republic between the two species further showed Douglas-fir to be less sensitive to site nutrient conditions based on allometric relationships (Urban et al. 2013). On a European level, species like Silver fir (*Abies alba*) however, has been suggested to substitute the drought sensitive Norway spruce instead of Douglas-fir (Da Ronch et al. 2016).

Though Douglas-fir previously tested under Danish and German conditions (Lohmander & Helles 1987; Albrecht et al. 2013) does not have scientific evidence of being steadier than Norway spruce, mixed stands showed different root development. Thus, Douglas-fir having better root development and larger share of fine roots especially in deeper soils than did Norway spruce (Schmid et al. 2014). Together with increasing the soil anchorage this difference in root morphology also helps reduce competition for nutrients with other species (Schmid et al. 2014). Higher soil anchorage however, increases the stem breakage frequency, resulting in higher economic losses than with uprooted stems (Wallentin & Nilsson 2013). The Danish tree species trials, nevertheless showed Douglas-fir to rarely break but instead uproot across all ages while Norway spruce was shown to easily break (Jørgensen & Nielsen 2001). Augusto et al. (1998) further showed that Norway spruce enhanced the soil acidification more than Douglas-fir, potentially increasing its susceptibility to windthrow in Scandinavia (Mayer et al. 2005).

Increased focus on biodiversity along with an aim of securing the supply of good quality coniferous timber (Miljøstyrelsen 2018) could also benefit to an increase in the cultivation of Douglas-fir. Podrázský et al. (2014) for instance showed that cultivation of Douglas-fir compared to Norway spruce exhibited a high increase in species diversity, though this was still lower compared to stands with deciduous species like sessile oak and European beech.

The presumably higher stability against wind as a function of age, also offers good opportunities for implementing a gradual shelterwood cut of the old stand if appropriate light and humidity conditions allows it (Bergstedt 2017). Douglas-fir however, is often both bitten and swept by deer, and it is a condition for self-rejuvenation that the deer stock is kept under control e.g. by fencing (Henriksen 1988).

The nature agency's transition to close-to-nature management, which applies for the examined forests and stands, also promotes the use of Douglas-fir and the species is included in 5 out of 20 forest development types (FDT's) (Larsen 2005). With its good ecological properties (good in blends and good self-rejuvenation) and high growth it is the non-native tree species said to have the greatest potential in close-to-nature forestry (Bergstedt 2017).

The previous tree species politic of the nature agency from 1999 also promoted Douglas-fir as substitute for Norway spruce (Skov- og Naturstyrelsen 1999). This was mainly to ensure a certain spread of risk, both species wise but also in relation to windthrow (Skov- og Naturstyrelsen 1999).

6.6 Present management towards more stable stands

To prevent windthrow Møller (1977) suggests that cultivation of Douglas-fir should not be made in pure stands, but instead in mixed stands with Norway spruce, which for many forest districts and estates are the preferred cultivation strategy (Hintz & Dahl 2017). However, unless measures are done, the height growth between the two species differs making Douglas-fir overgrow the spruce, thus exposing it to unnecessary wind loads. Also subsequent planting in beech are shown to have good prospects (Henriksen 1988; Bergstedt 2017).

Larger spacing between plants are also recommended to enhance stability, but is on the expense of timber quality (Nørgård Nielsen 2014a). The spacing further leads to subsequent thinnings which is recommended to follow a D to A harvest (Nørgård Nielsen 2014b) thus, a relatively hard thinning in the youth (D-harvest) and harvest peace in the last third of the rotation (A-harvest, i.e. no harvest). Pukkala et al. (2016) further showed in a comparison study of different thinning types, that continuous cover management is an efficient approach to reduce the risk of wind damage. This is consistent with the previous statements regarding thinning practice and subsequent recovery periods.

6.7 Sub conclusion

Windstorms are thus expected to increase in severity, especially in Denmark compared to the rest of Europe. Danish forest management practice however, urge for major risks of windthrow. The two species compared in this thesis possess similar traits and Douglas-fir has been suggested as an alternative to Norway spruce under climatic changes. Douglas-fir however has some disadvantages which makes it unstable in the youth. Management practices like mixed stands and changed thinning practice could however offset these.

Chapter III. Materials and methodology

7 Materials and data collection

Data has been gathered from the Danish Nature agency (NST), the Danish meteorological institute (DMI), the Danish Geodata agency (GST), the Geological survey of Denmark and Greenland (GEUS) the National Center for Food and Agriculture (DCA) and EMD International A/S (EMD).

7.1 Stand and inventory data

Characteristics for stands with Norway Spruce and Douglas-fir is provided by the NST's forest inventories from the consecutive years of the four storms (1999, 2005 and twice in 2013) (Ejlersen 2018). The inventories include notations of the four specific storms with remarks of whether the stand was affected or not, enabling a direct linkage between windthrow and storm specific measurements (gusts and windspeed). The inventory data consists of geographical data (forest name, department number and division, etc.) stand parameters (height, diameter, basal area, volume, stem number etc.) and attribute codes which among other, refers to whether a stand is planted after windthrow.

The data consists of Excel spreadsheets with the inventory data together with vector files for subsequent GIS analysis and comparison with weather and soil data.

7.2 Wind and soil data

Windspeed registrations were extracted from DMI (N. Hansen 2013a) and EMD (EMD 2001). The variables consist of maximum windspeed (ms^{-1}) and mean wind speed in 45 meters height (ms^{-1}) respectively. Soil maps were extracted from GEUS (Schack Pedersen 2011) and DCA (Institute of agroecology 2016a; Institute of agroecology 2016b). Soil maps are shown in appendix 5.

8 Data preparation and processing

The inventories do not directly show which stands are affected by windthrow. The stands experiencing windthrow are therefore located by comparing two inventory lists, the year of the event (1999, 2005 and 2013), and the lists 3 years after the event. This is done since the registration of attribute codes in NST's planning and GIS software Proteus, documents whether new stands are established after windthrow.

The attribute codes are a result of the specific events being so severe, that they incited for subsequent subsidies for regeneration and processing of the windthrown trees. Thus, making the registrations important documentation. The specific windthrow registrations are therefore linked to the investigated storm events. The comparison period of 3 years is a result of the following windthrow inventory reports, relying on the documentation of all areas to be assured and checked for possible windthrow in the years 2002, 2008 and 2016 respectively.

8.1 Locating stands affected by storm

Locating the stands are done by the following procedure:

1. The attribute code for windthrow is looked for in the comparison inventories for the individual stands. Windthrow attribute codes are 104, 113 and 183 for the years 1999, 2005 and 2013 respectively.
    - Example W2016=IF(ISNUMBER(SEARCH("183";Attribute code));"1";"0")
2. An identification variable is generated for all stands experiencing windthrow. It consists of District no., forest part no., forest no., Department no. and Stand litra (letter division). This is done for the storm event inventory and the comparison inventory.
    - Example ID=334_101_240_c
3. The identification variable is looked for in the storm event inventories, creating the variable Windthrow with the value 1 if hit and 0 if not (see section 10.1 for explanation).
    - Example W2013=VLOOKUP(ID;W2016;FALSE)

Upon request to the author, spreadsheet examples may be provided with formulas and proceedings. The full material cannot be handed out due to official document rules of the NST.

8.2 Complications

Though the procedure for locating stands is simple, many complications occur. Among these, some districts have been given new names and numbers and their geographical extension has further been altered between the comparison period. In 1999 the Nature agency consisted of 26 districts while in 2016 it was reduced to 18. This reduction makes changes in the numbering and administrative boundaries. Forest names and numbers has also changed. This make the comparison between years even more complicated since the identification variable would give a syntax error. Number and name of the individual forests in the comparison inventory, not showing linkage with the event inventory, are therefore investigated for their syntax mistakes.

8.2.1 Spelling and prefixes

For most errors it has been possible to update the values making the comparison possible. For instance, many forests within a forest part, was numbered 1,2,3 etc. in 1999 while in 2002 they were given the prefix 10. This changed the forest numbers to 101, 102, 103 etc. Though changed, they still had the same department numbers and litra division. Small differences in names also occurred e.g. *Humble skov* was later named *Humble Byskov*. Some forests had also been sold making them disappear from the comparison inventory. Since the forests sold, potentially possess the probability of being windthrown, they have been excluded from the datasets. This due to that no linkage could be made.

8.2.2 Numbering and division

Larger implications occurred when both department numbering and litra division had been altered. Table 8.1 and Table 8.2 shows a bad case where both forest name, forest no. and department no. has changed within the comparison period. While the number of departments for the individual forest are the same the numbering is different (e.g. 9 departments for *Myrdeskov* but numbered 600-609 in 1999 and numbered 503-512 in 2002),

Table 8.1: Section of Ravnsholte forest part no. 5, Odsherred district (1999)

No.	Forest name	Department no.	Area (ha)
501	Storskov	1001-1037, 1350	150,8
504	Tåstrup skov	1260-1267, 1354	40,2
505	Myrdeskov	600-609	55,5
506	Vrangeskov	610-619	54,1

Table 8.2: Section of Ravnsholte forest part no. 005, Odsherred district (2002)

No.	Forest name	Department no.	Area (ha)
501	Bidstrup del, Ravnsholte	501	583,3
504	Vrangeskov	520-529	54,1
505	Myrdeskov	503-512	55,5
506	Langesø eng	550	3,1

Clear differences are seen in the tables above however, changing the department numbers so that they can be linked for all cases like this is difficult and linked with mistakes. Geographic inventory data for the year 1999 does not exist thus, this could have been used for an overlaying process and analysis in a GIS tool. These cases are therefore left out in the continuous analysing process. This however, affects the overall possibility of windthrow since some observations are left out of the data material. Some forests have also merged, an example is *Gribskov* which was previously formed by the forests *Strøgårdsvang*-, *Maarum*- and *Nødebo skov* but is now only one forest administration. However, numbering remains identical giving no comparison problems.

8.3 Geographical information processing

Data for regional wind (mean wind), strongest consistent gusts and soil types are transformed using the GIS tool Quantum GIS. The intersecting tool is used to combine the respective layers from DMI, EMD, DCA and GEUS with the inventory data from NST.

DMI: Data from DMI consists of raster files. These has been georeferenced with vector files for the outline of Denmark (GST) (Kortforsyningen 2018). Next, they are transformed to vector files (polygons) and given the variable MWIND (maximum windspeed, ms^{-1}). For the year 2013, the highest of the two windspeeds is used in the analysis.

EMD: Data from EMD consist of vector files. The variable, regional windspeed at 45 meters height (renamed RWIND) is used for further intersect with inventory data.

DCA: Data from DCA consists of vector files with text classifications of soil types (renamed SOIL) which is further used for intersecting with inventory data. Two datasets are used. One depicts whether the soil is mostly clay (normally >15 % clay) or mostly sand (normally <10 % clay and often <5 % clay) (variable: SOIL1) and the other includes the FK soil classifications from 1-8 (Holst 1992) (variable: SOIL2).

The variables MWIND, RWIND and SOIL1 and SOIL2 are then added to the data sets for the individual stands by intersecting the different spatial layers with the stand inventory. All variables with descriptions used in the following data analysis is shown in appendix 2.

9 Modelling material

The three processed datasets (1999, 2005 and 2013) are all combined. The preparation of the datasets before the logistic regression analysis has cut away a proportion of the initial observations (stands). This is done due to the previously mentioned implications with the inventory comparison. All observations with positive correlation between year of event and comparison year have been included in the final dataset. The statistical analyses are thus made within these limits for NST's total forest area, excluding forests that have syntax errors. In total 1875 observations have been excluded, which equals 3,8 % of the initial dataset.

9.1 The dataset

Mean values and standard deviation together with minimum and maximum values for the chosen dataset are given in Table 9.1 and Table 9.2 for Douglas-fir and Norway spruce respectively. It must be kept in mind that the observation number *n* represents the combination of three individual inventories hence a higher value than the actual number of stands of the two species managed by the NST.

The variables stem number and basal area was originally thought used but does not exist for all inventories. Attempts to include these by calculating the values based on e.g. volumes were not possible due to complications, such as area shares of 0. It would further yield unrealistic values and be linked with mistakes. Class variables are shown in Table 9.3.

Table 9.1: Mean max and minimum values for the modelling material of Douglas-fir.

Variable	*n*	Mean	Std. deviation	Min	Max
Age (year)	7751	40,95	28,02	3,00	177,00
Diameter (cm)	7751	24,14	18,53	0,60	106,00
Height (m)	7751	16,85	11,00	0,60	46,70
Taper (H/D)	7751	82,44	22,67	28,13	166,67
Mean windspeed (ms^{-1})	7751	5,86	0,43	5,25	7,75
Max. windspeed (ms^{-1})	7751	36,10	3,47	27,50	42,50
Volume (m^3/ha)	7751	150,95	176,06	0,00	866,60
Windthrown / Unharmed					84 / 7667 (1,1%)

Table 9.2: Mean max and minimum values for the modelling material of Norway spruce.

Variable	*n*	Mean	Std. deviation	Min	Max
Age (year)	40313	49,80	25,21	1,00	196,00
Diameter (cm)	40313	21,21	10,56	0,40	232,60
Height (m)	40313	16,31	7,13	0,30	38,10
Taper (H/D)	40313	79,03	12,13	8,90	175,00
Mean windspeed (ms^{-1})	40313	5,77	0,42	5,25	9,00
Max. windspeed (ms^{-1})	40313	36,02	3,52	27,50	42,50
Volume (m^3/ha)	40313	191,66	150,50	0,00	989,20
Windthrown / Unharmed					941 / 39372 (2,3%)

Table 9.3: Class variables with different class names and total number of classes.

	District	**Region**	**Soil classification 1**	**Soil classification 2**
n	18	4	2	8
Classes	Blåvandshuk	REG1 (East)	Clayey	FK1 Coarse sand
	Bornholm	REG2 (West)	Sandy	FK2 Fine sand
	Fyn	REG3 (Heathland)		FK3 Clayey sand
	Himmerland	REG4 (Dunes)		FK4 Sandy clay
	Hovedstaden			FK5 Clay loam
	Kronjylland			FK6 Clay
	Midtjylland			FK7 Organic
	Nordsjælland			FK8 Calcareous
	Storstrøm			
	Søhøjlandet			
	Sønderjylland			
	Thy			
	Trekantsområdet			
	Vadehavet			
	Vendsyssel			
	Vestjylland			
	Vestsjælland			
	Østsjælland			

9.2 Graphically presentation of data material

The observed mean windthrow frequencies for age and diameter classes of the two species, Norway spruce and Douglas-fir are shown in Figure 9.1 and Figure 9.2. Other variable's mean frequencies in relation to classes and class variables are shown in appendix 6. The graphically presentation is meant as a help to determine possible irregularities or special conditions within the different variables.

Figure 9.1. Plot of the percentage of windthrown stands in the data material in relation to age classes.

As seen in Figure 9.1 in relation to Table 9.1 and Table 9.2 most age classes are represented in the dataset, hence no missing values. The general windthrow percentage is slightly higher for Norway spruce than Douglas-fir despite the aberrant data in the age classes 90-130 years of Douglas-fir (classes 90-99 and 120-129).

In relation to diameter classes (Figure 9.2) Norway spruce in larger diameter classes however, becomes less susceptible to windthrow than Douglas-fir. The two species on the other hand are not equally represented in all diameter classes (data not shown) which is the case for age classes. Norway spruce observations with diameters >55 cm is 176 (0,4 % of all Norway spruce observations) and Douglas-fir observations are 276 (3,6 % of all Douglas-fir observations). Despite knowing Douglas-fir having a higher production than Norway spruce and therefore possibly a higher Diameter at the same age this might also be a consequence of the two species being managed differently within the nature agency's forests.

Norway spruce is mainly managed for production (rotations of approx. 60 years and dimensions of ≤ 40 cm (e.g. Rold Skov savværk A/S (2018)) whereas Douglas-fir stands of large dimensions and high age are also wanted for recreational and biological purposes (Skov- og Naturstyrelsen 1999; Skov- og Naturstyrelsen 2008). This also applies for the height distributions where 11,6 % of the Douglas-fir stands are >30 meters and less than 1 % of the Norway spruce stands are >30 meters.

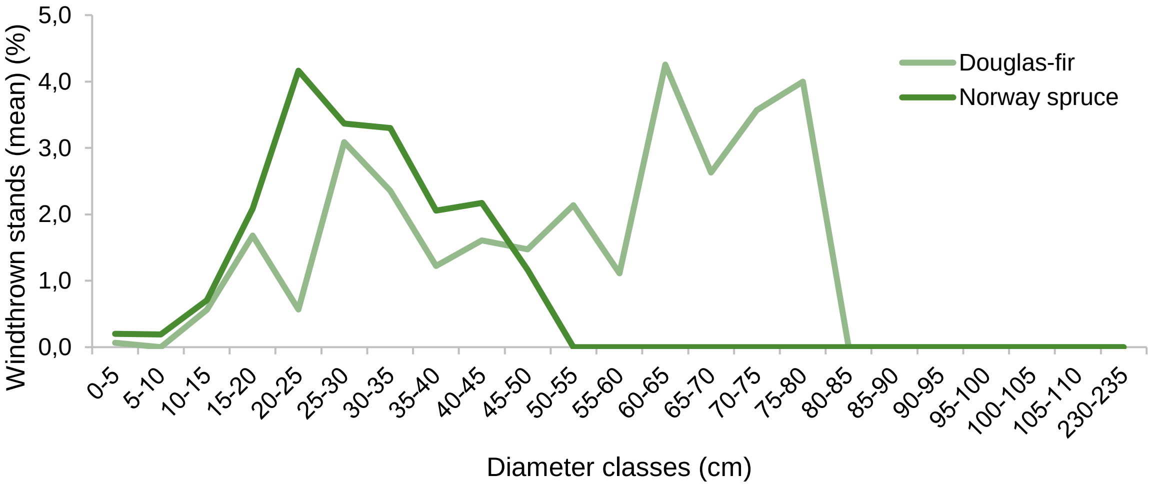


Figure 9.2. Plot of the percentage of windthrown stands in the data material in relation to height classes.

From the data in appendix 6 it is further seen that most soil classifications are represented for the two species except calcareous soils (FK8, in Danish “Atypisk”) and Clay (FK6, in Danish “Svær lerjord”). The highest windthrow frequency is found on organic soils (FK7) followed by fine and coarse sand (FK1 and FK2). On the contrary, looking only at whether the soil consist of mostly sand or clay does not show any clear differences. In relation to District the highest mean frequencies are found for the districts; *Vadehavet*, *Sønderjylland*, *Himmerland*, *Trekantsområdet* and *Vestjylland* and the lowest for the districts; *Thy*, and *Vendsyssel*. On regional level *Heathland*s (Region 3 in Danish “Hede”) are found to have higher mean frequencies and Dunes (Region 4 in Danish “Klit”) have the lowest frequency on regional level.

10 Regression analysis

The base calculus to assess the risk is the probability of an event occurring (windthrow) depending on values from independent variables (e.g. height, diameter and age).

For a situation with dichotomous data like this, logistic regression models are appropriate. This is because the response only have two possible outcomes, often represented by the absence or presence of an attribute (Rodrıguez 2007). The logistic regression procedure is based on the methods described by Hosmer (2013). Analyses are done through the logistic procedure in the SAS® software package (SAS Institute Inc. 2010) (scripts shown in appendix 4).

10.1 Logistic models

The dependent variable, y, in this case is whether the stand has experienced windthrow or not, and can be expressed as:

$$y = \begin{cases} 1 & \text{if the stand is harmed} \\ 0 & \text{otherwise} \end{cases}$$

The response y is a realization of the variable Y, only taking values between 1 and 0 (since the predicted value is a probability) with the probabilities p and $1-p$ respectively. Thus, the distribution of the dependent variable Y is binomial following the Bernoulli distribution given by:

$$Y \overset{Bern}{\sim} (p) \tag{10.1}$$

The unknown probability p is then to be estimated for any given linear combination of independent variables (e.g. height, diameter and age), linking these with the Bernoulli distribution which is done by taking the natural logarithm of the odds also called logit:

$$logit(p) = ln(odds) = ln\left(\frac{p}{1-p}\right) = \beta_0 + \sum_{i=1}^{n} \beta_i x_i \tag{10.2}$$

Where n is the number of variables β_0 is the intercept and the independent variables x_i have the regression coefficients β_i. The logit function has the probability (0,1) on the x-axis. However, we want it to be on the y axis (eq. (10.1)) so we take the inverse of the logit function:

$$logit^{-1}(\alpha) = \frac{e^{(\alpha)}}{1+e^{(\alpha)}} \tag{10.3}$$

where α equals the linear combination of independent variables and their coefficients (The righthand side of equation (10.2)). Inserting equation (10.2) in (10.3) gives:

$$p = \frac{e^{\left(\beta_0 + \sum_{i=1}^{n} \beta_i x_i\right)}}{1+e^{\left(\beta_0 + \sum_{i=1}^{n} \beta_i x_i\right)}} \tag{10.4}$$

this is the function for the probability of a given stand to experience windthrow.

10.2 Choosing variables for logistic regression

Given different developments of the independent variables, as seen by the mean frequencies in Figure 9.1 and Figure 9.2 and appendix 6, all variables have been transformed to squared values and natural logarithm values. The different variables were then chosen in case of meeting Akaike's information criterion (AIC) (Akaike 1974). AIC indicates the goodness of fit by the log likelihood method with the lowest AIC values giving better fit statistics (Hosmer 2013). The lowest AIC value for the tested variables e.g. Diameter, Diameter x Diameter^2 and LN(Diameter) were then chosen for the following models. All chosen and tested variables with AIC values and statistical significance are shown in appendix 3. Only looking at AIC values; District, Maximum windspeed and Height were the variables with the lowest values, while mean windspeed and taper had the highest.

When choosing models, the Receiver operating characteristic (ROC) are further used to evaluate model fit. The ROC value is the estimate of the area under a plot of true positives versus false positives (SAS Institute Inc. 2010). The true positives are events predicted to be events, whereas false positives are non-events predicted to be events. This means that a ROC value of .50 is regarded as failing since the predictive abilities are 50/50. A ROC value of 1.00 on the other hand represents a perfectly predicting model. This also means that models with ROC values up until .70 can be regarded as poor or at least having low predictive abilities. The variable SOIL1 only distinguishing between sand or clay was with only to classes found not to be significant for Douglas-fir (appendix 3). The variable is therefore left out of the dataset.

11 Model building and selection

Since the selected variables can have collinearity, they are divided into different categories as shown in Table 11.1. This is meant as a help with the selection of variables for the individual models to avoid this problem. As with linear regression, fitting models by logistic regression is very sensitive to collinearities among independent variables (Hosmer 2013). This is expressed through extraordinarily large standard errors and estimated coefficients (Hosmer 2013). This means that one or more predictors must be excluded. However, no information is lost by doing this, though interpreting parameters becomes more complex (Weisberg 2005).

Table 11.1: Different variables divided into groups of their descriptive abilities.

Classes	Stand development	Management	Wind
Soil classification 2	Age	Taper (H/D)	Regional wind (mean wind)
Region	Diameter		Maximum wind (max wind)
District	Height		
	Volume		

While soil, region and district are class variables, all other variables are continuous variables. The use of event year in the models would make these descriptive rather than predictive which is desired. Despite there being differences in the different years of this variable it is not used since the data is based on specific events as opposed to if it were regularly scattered windthrows.

11.1 Testing for correlation between variables

Since variables describing stand development (age, diameter and height) is expected to be highly correlated (Rahbek 2003), correlation coefficients have been calculated for these. This is done in SAS® using the Pearson correlation procedure. Correlation coefficients take values between -1 and 1. The relationship between the variables is positive if the correlation is 1 and negative if the correlation is -1 (SAS Institute Inc. 2010). If the variables have no linear predictability between the two, the correlation is 0 (H_0: Rho=0). Correlation coefficients and coherent significance levels are shown in Table 11.2 for the two species.

Table 11.2: Pearson Correlation Coefficients for variables describing stand development of Douglas-fir.

	Douglas-fir			**Norway spruce**		
	Age	**Diameter**	**Height**	**Age**	**Diameter**	**Height**
Age	1,00000	0,93159 <,0001	0,90479 <,0001	1,00000	0,74737 <,0001	0,73181 <,0001
Diameter	0,93159 <,0001	1,00000	0,96049 <,0001	0,74737 <,0001	1,00000	0,93327 <,0001
Height	0,90479 <,0001	0,96049 <,0001	1,00000	0,73181 <,0001	0,93327 <,0001	1,00000

As also assumed, there is a strong correlation between the three variables. Highest correlations are between diameter and height, while the lowest is between age and height. In a silvicultural aspect stand height is often used as site index for a given reference age (Skovsgaard & Vanclay 2008), therefore the lower correlation is probably due to differences in site productivity. However, the three variables are highly correlated which means that they cannot be used in the same model assuming that the variables are to be independent.

Intersecting the geographical location of the class variables district and region with maximum windspeed in QGIS also shows correlation (data not shown, however see Figure 6.2 - Figure 6.5 and appendix 6). As mentioned in section 9.2, lower frequencies were found for the region Dunes and the districts *Thy* and *Vendsyssel*. Both districts represent this region and both districts are further the ones experiencing less powerful windspeeds. On the contrary the districts *Vadehavet, Sønderjylland,* and *Trekantsområdet* are the districts experiencing the most powerful windspeeds. These districts are further also the districts experiencing the largest mean frequency of windthrow. Again, using these variables in the same models is not possible under the assumption of mutual independence.

Where MWIND is a continuous variable DISTRICT and REGION are administrative divisions based on, for example, municipal- and geographical boundaries (e.g. streams and rivers). Consequently, they are not necessarily coupled with the risk of windthrow. However, the management carried out by the local forester of the individual districts could be altering the probability of windthrow which makes the variables DISTRICT and REGION worth including in the final dataset to examine whether this effect exists.

11.2 Selection of models predicting windthrow

The selection of variables for 12 different models to assess the windthrow probabilities are then made based on the following strategies before models are tested:

1. Variable or combinations used in previous models (or earlier found highly significant)
2. Variables easily available to the forest manager
3. Variable combinations which does not imply implications (collinearity and correlation)
4. Variable combinations combining all or most groups of Table 11.1.
5. Preferably variables with higher individual fit statistics (section 10.2, appendix 3)
6. As minimum one variable describing stand characteristics

Models, their combination of variables and goodness of fit statistics are shown in Table 11.3.

Table 11.3: Goodness-of fit measurements for different models predicting windthrow in Douglas-fir stands.

		Douglas-fir	**Norway spruce**	
No.	**Model variables**	**AIC value** **ROC value**	**AIC Value** **ROC value**	**Remarks**
(1)	Max wind Diameter Soil2	708.316 0.901	7166.914 0.845	Model A
(2)	Max wind Height Soil2	688.008 0.912	7087.842 0.850	Model B *Ranked 3rd*
(3)	Max wind Age Soil2	733.112 0.882	7217.510 0.838	
(4)	District Diameter Mean wind Taper	710.530 0.924	6723.762 0.884	
(5)	District Mean wind Height Taper	690.845 0.934	6630.060 0.886	Model C *Ranked 2nd*
(6)	District Volume Age	721.191 0.917	6514.962 0.896	 *Ranked 4th*
(7)	Max wind Diameter	750.485 0.864	7421.799 0.824	
(8)	Max wind Height	729.936 0.881	7302.738 0.833	
(9)	Volume Soil2 Diameter	827.300 0.812	7925.999 0.792	
(10)	Soil2 District Mean wind Taper Height Volume	649.169 0.946	6234.399 0.902	Model D *Ranked 1st*
(11)	Region Taper Mean wind	853.250 0.786	8281.543 0.739	
(12)	District Diameter	706.712 0.920	6805.325 0.882	
	AIC Intercept only L(0)	929.246	8933.451	

As seen most models include the variable Maximum windspeed (5/12) and district (5/12). This is due to these being the individual variables with best fit statistics. The maximum windspeed on the other hand is directly linked with the independent storms. Future predictions including this variable could therefore be difficult to make since the variable itself is unpredictable to some degree. Height is often underestimated due to personal bias, whereas diameter at breast height (DBH) is not (Omule 1980). Therefore, even though height previously is shown to be significant for the probability of windthrow, diameter has been preferred in the models (strategy 2 above). Models with few (2) predictor variables (model 7, 8 and 12) had lower AIC and ROC values than models with many predicting variables (e.g. model 4 and 5 with 4 variables). However, including Mean wind and Taper in model 4 compared to model 12 had little effect (even increasing AIC for Douglas-fir). Taper and mean wind were also the individual variables with lowest decrease of AIC compared to the Intercept values.

In general, most models predict the probability quite well (decrease in AIC compared to L(0) value). Model 10 was ranked 1st (lowest AIC value for both species models) with AIC decreases from 929 to 649 and from 8933 to 6234 with ROC values of 0,946 and 0,902 for Douglas-fir and Norway spruce respectively.

11.2.1 The chosen models

For the further analysis four different models has been chosen. The decision is mainly based on the goodness-of-fit measures including AIC and ROC values. Ranking the different models across the two species (Table 11.3) gives the four best fit statistics for the models 10, 5, 2 and 6. However, model 1 is chosen instead of model 6. Based on the previous statement of height often experiencing personal bias when measured, model 1 are chosen instead to test whether using diameter rather than height (model 1 and 2) gives similar predictive abilities. Model 1 and 2 are further simple models which meets the criteria of the 6 strategies mentioned in section 11.2. The chosen models are therefore:

Model A)	Max wind, Diameter, Soil2.
Model B)	Max wind, Height, Soil2.
Model C)	Mean wind, District, Height, Taper.
Model D)	Mean wind, District, Height, Taper, Volume, Soil2,

The goodness-of-fit values for models of Norway spruce in Table 11.3 however, are very high. This indicates that there are problems with getting the model to correctly describe the observations (Rahbek 2003). These problems might be due to the inclusion of vital variables like volume of last thinning and time since last thinning (shown to be significant in previous studies, see section 4.4).

11.3 Comparing models

However, despite all models (A-D) showing a decrease in AIC values and having ROC values >.70 the 4 models are tested to determine which model is relatively more superior. Due to the earlier selection based on AIC values, a test is used which further relies on these.

Since the chosen models are non-nested (models are not versions of a larger model) the Akaike likelihood ratio index is used to test and later choose between alternative models (Ben-Akiva & Swait 1986). The test (termed the Ben-Akiva and Swait test), is based on the AIC values of two tested models. Under the null hypothesis that model 2 is the true model, it estimates the probability p that model 1's fitness measure, P_i^2(adjusted Rho sq.), is greater than that of model 2. The fitness measure of each model (adjusted Rho sq.) takes the form:

$$p_i^2 = 1 - \frac{L_i - K_i}{L(0)} \tag{11.1}$$

Where L_i is the AIC value (Log-Likelihood) of model i, K_i is the number of variables and $L(0)$ is the AIC value for constants only (the intercept). The test assumes $K_1 \geq K_2$ for the two models and that the two sets of variables are different by at least one element. The test then takes the functional form of:

$$p \leq \Phi\left(-\sqrt{-2\left(p_2^2 - p_1^2\right)L(0) + \left(K_1 - K_2\right)}\right) \tag{11.2}$$

Where Φ is the standard normal cumulative distribution function (CDF). The part $P_2^2 - P_1^2$ is further assumed to be ≥0 under the assumption of model 2 being the true model.

Equation (11.2) therefore sets an upper bound for the probability of wrongly choosing model 1 although model 2 is the true model (Shen 2009). It can therefore be considered a conservative proxy for the significance (p-value) of differences in model fit (Chorus 2012).

12 Interpreting results

The results of the models are interpreted through odds ratios (OR). The OR shows how much bigger (or smaller) the risk is under some given conditions. The ratio for a variable represents the odds change with a variable increase of 1 unit, while all other variables is held constant. Thus, the function is the relationship between two odds:

$$OR = \frac{odds_1}{odds_2} = \frac{p_{REF}}{1 - p_{REF}} / \frac{p_{ALT}}{1 - p_{ALT}} \tag{12.1}$$

here p_{REF} is the probability under a specific set of conditions (The reference), and p_{ALT} is the probability under a different set of conditions (the alternative). Since the odds ratio is a relative value, confidence intervals are particularly important to verify the statistical significance of the OR. To obtain the 95% confidence intervals for the OR the estimate must be converted to the natural log (ln) scale:

$$ln(OR) = ln\left(\frac{p_{REF}}{1 - p_{REF}} / \frac{p_{ALT}}{1 - p_{ALT}}\right) = \left(\beta_{REF} + \sum_{i=1}^{n} \beta_{REFi} x_{REFi}\right) - \left(\beta_{ALT} + \sum_{i=1}^{n} \beta_{ALTi} x_{ALTi}\right) \tag{12.2}$$

Equation (12.2) is similar to equation (10.2) except with the variables x_i which are not examined are held constant (12.2). This leads to the function for the odds ratio OR to be:

$$OR = e^{\left(\left(\beta_{REF} + \sum_{i=1}^{n} \beta_{REFi} x_{REFi}\right) - \left(\beta_{ALT} + \sum_{i=1}^{n} \beta_{ALTi} x_{ALTi}\right)\right)} \tag{12.3}$$

Chapter IV. Results and analysis

13 Age development

When looking only at the variable age in relation to the sub-question whether stability increases with age, the logistic regression of the variable age in Figure 13.1 shows the differences in predicted windthrow of the two species, Douglas-fir and Norway spruce. The average relation between age and windthrow probability is found to be unimodal and ranges from a windthrow probability of 0 % to around 4 %.

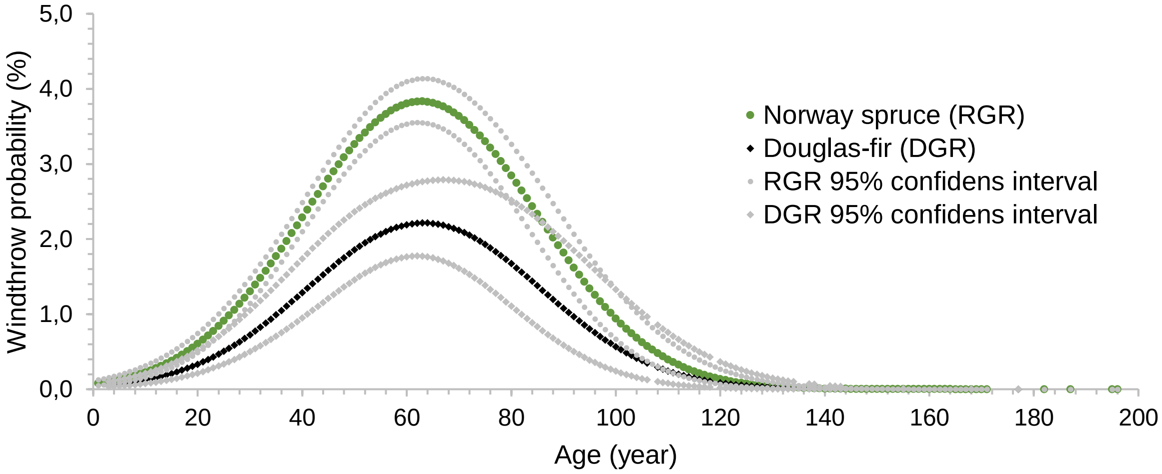


Figure 13.1: Predicted windthrow probability modelled with the variables AGE and AGE2 for both species.

Douglas-fir in general shows less susceptibility than Norway spruce across all ages (almost half the windthrow probability when highest from 3,8 % to 2,2 %). This even applies within the 95 % confidence intervals. For both species the windthrow probability decreases by age. Despite including the effect of species on age in the regression model, both species are shown to have the highest windthrow probability around 60 years. For Douglas-fir however, this could be slightly higher within the confidence level (Y(max)=67 for the upper 95% confidence interval of Douglas-fir).

14 Models

The four models are described below (model A, B, C and D) with examples and interpretations of results through Odds ratios. The full model outputs from the logistic procedure in SAS® are shown in appendix 7. Comparing of the models are done with the Akiva and Swait test seen in section 15 on page 57.

14.1 Model A

Model A predicts the probability based and the stand diameter at breast height the maximum experienced windspeed and the soil classification. This means that variables describing management (Taper) are not used. The overall reason for selecting and analysing this model is based on comparing it with Model B which instead uses the height of the stand.

14.1.1 Douglas-fir

As seen in Table 14.1 both variables describing diameter (D and D2) are significant on a 0,1% level, However the variables describing the maximum windspeed are not. The individual soil type estimates show the comparison with Fine sand (FK1). By the sign of the estimate it is seen that most soil types are less susceptible to windthrow than fine sand (negative values) and only organic soils are shown to be more susceptible. Both Coarse sand and Organic soils on the other hand, are not significant, compared to Fine sand on a 5 % level. This means that they are not necessarily more or less likely to experience windthrow than fine sand. Soils containing more clay however, are significant on a 5 % level and soils with 5-15 % clay (clayey sand and sandy clay) are significantly less susceptible on a 0,1 % level.

Table 14.1: Analysis of maximum likelihood estimates of model A for Douglas-fir.

Parameter	Estimate	Standard error	P-value
Intercept	-10,0505	14,2238	0,4798
MWIND	-0,2029	0,7415	0,7844
MWIND2	0,00750	0,00963	0,4363
D	0,1616	0,0282	<,0001
D2	-0,00151	0,000415	0,0003
Coarse sand	-0,3844	0,3421	0,2611
Organic	0,00480	0,4285	0,9911
Clayey sand	-2,2266	0,5902	0,0002
Clay loam	-2,6466	1,0646	0,0129
Sandy clay	-2,1665	0,5211	<,0001

By model A for Douglas-fir it is further shown that increasing diameter increases the risk of windthrow (positive estimate sign of the variable D). However, the development is shown to be unimodal (including D2 increased AIC) and therefore experiencing a peak in the relation between diameter and windthrow probability. For this model the logistic analysis gives the following linear function following equation (10.2):

$$logit\left(p\right)=\beta_0+\beta_{SOIL2}+\beta_{MWIND}+\beta_{MWIND2}+\beta_D+\beta_{D2}$$

Where β_0 is the intercept -10,0505, β_{SOIL2} is the effect of the class variable SOIL2 that has the following parameter estimates: fine sand = 0, Coarse sand = -0,3844 Organic = 0,00480 etc. and β_{MWIND}, β_{MWIND2}, β_D and β_{D2} is the effect of the different variables (estimate x variable).

Example 1.

The average stand for both species in the dataset experienced 37,5 ms^{-1} had a diameter of 25 cm and grew in Coarse sand. When estimating the windthrow probability of a stand with these characteristics for Douglas-fir the linear function takes the form:

$$logit\left(\hat{p}\right)=-10{,}0505-0{,}3844+\left(-0{,}2029\cdot 37{,}5\right)+\left(0{,}00750\cdot 37{,}5^2\right)+\left(0{,}1616\cdot 25\right)+\left(-0{,}00151\cdot 25^2\right)=-4{,}4005$$

By inserting the linear function in equation (10.4) we get the predicted windthrow probability:

$$\hat{p} = \frac{e^{(-4,4005)}}{1+e^{(-4,4005)}} = 0,012$$

The windthrow probability is therefore approximately 1,2 % under the given circumstances.

The further development for stands on Coarse sand experiencing 37,5 ms^{-1} are shown in Figure 14.1 including 95 % confidence intervals. The highest windthrow probability are shown to be at a diameter at breast height of 53,4 cm. However, the data material for diameter classes >50 cm is limited which means that predictions outside the data material (>50 cm) is rather uncertain and conclusions based on model A outside the dataset should be used with caution.

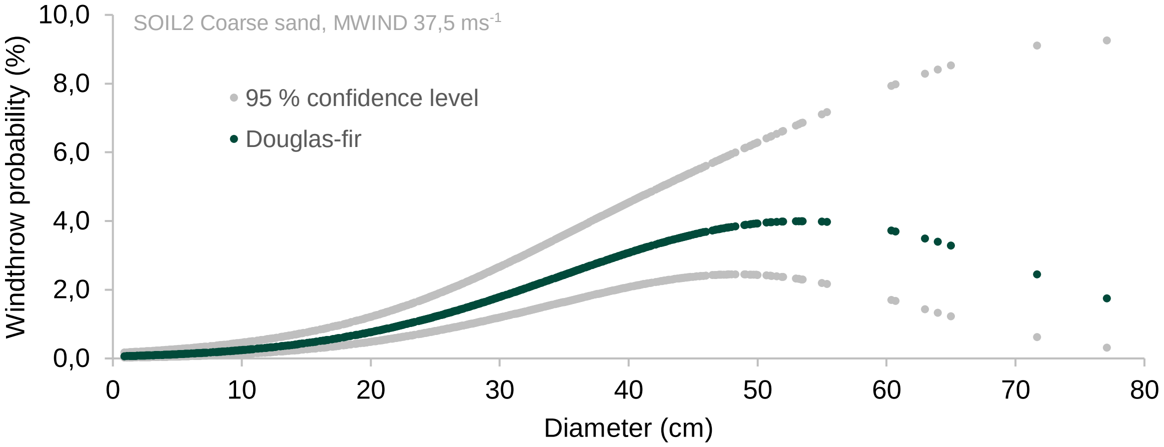


Figure 14.1. Model A. Predicted windthrow probability of Douglas-fir at 37,5 ms^{-1} on coarse sand.

14.1.2 Norway spruce

For Norway spruce the model uses the natural logarithm of the diameter and only the maximum windspeed not the maximum windspeed to the power of 2. This means that the windthrow probability increases by both parameters and does not decrease at some point as seen by the parameter and estimates in Table 14.2 (positive estimate signs). Also, for Norway spruce observations in the range of diameters >50 cm is few. Both variables however, are significant at a 0,01 % level.

Table 14.2: Analysis of maximum likelihood estimates of model A for Norway spruce.

Parameter	Estimate	Standard error	P-value
Intercept	-20,0694	0,5571	<,0001
MWIND	0,3259	0,0117	<,0001
LND	1,5087	0,0899	<,0001
Coarse sand	-0,3493	0,1358	0,0101
Organic	0,0356	0,1656	0,8298
Clayey sand	-1,4167	0,1729	<,0001
Clay loam	-1,2668	0,2795	<,0001
Sandy clay	-1,9123	0,1945	<,0001
Calcareous	-10,7474	691,2	0,9876
Clay	-11,7778	211,1	0,9555

For the different soil classifications calcareous and clay soils are shown not to be significant compared to Fine sand, however observations of these soil types are few for the overall dataset which is also seen by the huge standard errors compared to the estimates (Table 14.2). Coarse sand for Norway spruce is found to be significantly less susceptible to windthrow than fine sand, which was not the case for Douglas-fir and almost at a 1 % level. Again, greater content of clay shows less risk of windthrow, yet not in a linear context (Clay loam smaller effect than both Clayey sand and Sandy clay). This was also the case for Douglas-fir.

Example 2.

Following example 1 the same calculus for the average stand of Norway spruce in the dataset gives an expected probability of:

$$logit(\hat{p}) = -20{,}0694 - 0{,}3439 + (0{,}3259 \cdot 37{,}5) + \left(1{,}5087 \cdot ln(25)\right) = -3{,}3357$$

$$\hat{p} = \frac{e^{(-3{,}3357)}}{1 + e^{(-3{,}3357)}} = 0{,}034$$

The risk of windthrow for the same stand of Norway spruce is therefore around 3,4 % compared to 1,2 % for Douglas-fir using model A for both species

14.1.3 Comparison of species for model A

Only by looking at the variables, used for the two species variations of model A, it is seen that diameter is affecting the windthrow probability of Norway spruce more than Douglas-fir. In Figure 14.2 the diameter classes up until 80 cm are shown for two soil types, organic and coarse sand. It shows the windthrow probability at a maximum windspeed of 37,5 ms^{-1} for the two species.

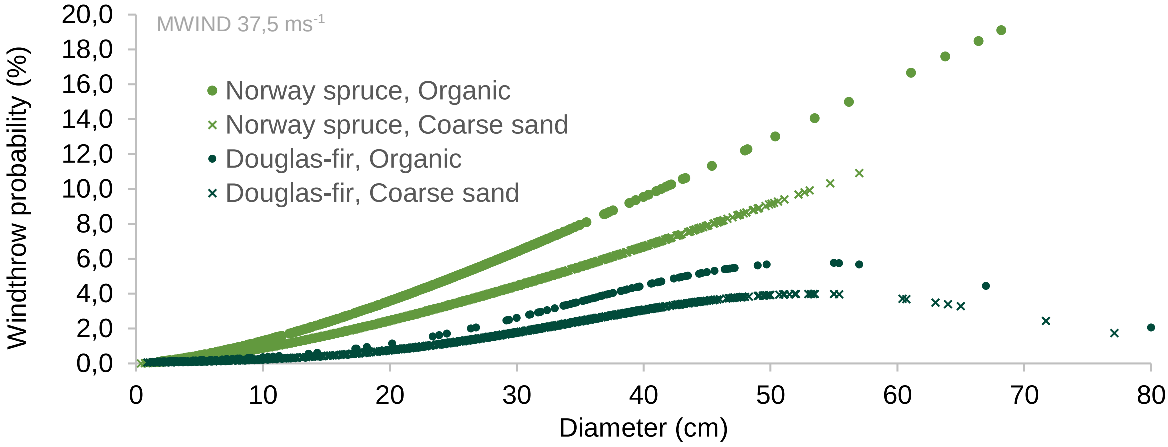


Figure 14.2: Model A. Predicted windthrow probability at different diameters for Douglas-fir and Norway spruce.

The windthrow probability for Organic soils (•) are shown to be higher than Coarse sand (×) for both species. For both soils Norway spruce has higher predicted windthrow probability than Douglas-fir. Across a wide range of diameter classes Norway spruce is more than twice as likely to experience windthrow on both soil types with windspeeds of 37,5 ms^{-1}. However, this must be seen in the context of limitations of data exceeding a diameter of >50 cm.

Figure 14.3 shows the windthrow probability for organic soils at different windspeeds for Douglas-fir for diameters <80 cm. Whereas windspeeds of 37,5 ms^{-1} had probabilities of <6 % an increase in windspeed to more than 40 ms^{-1} increases the windthrow probability dramatically. At diameter 40 cm the windthrow probability increases to 25 % from earlier 4 % at windspeeds of 37,5 ms^{-1}. By looking at Figure 14.3 it is further seen that windspeeds <32,5 ms^{-1} does not affect the windthrow probability particularly. Model A further makes it possible to illustrate the importance of higher windspeeds for the risk of windthrow with odds ratios. This is dealt with in example 3.

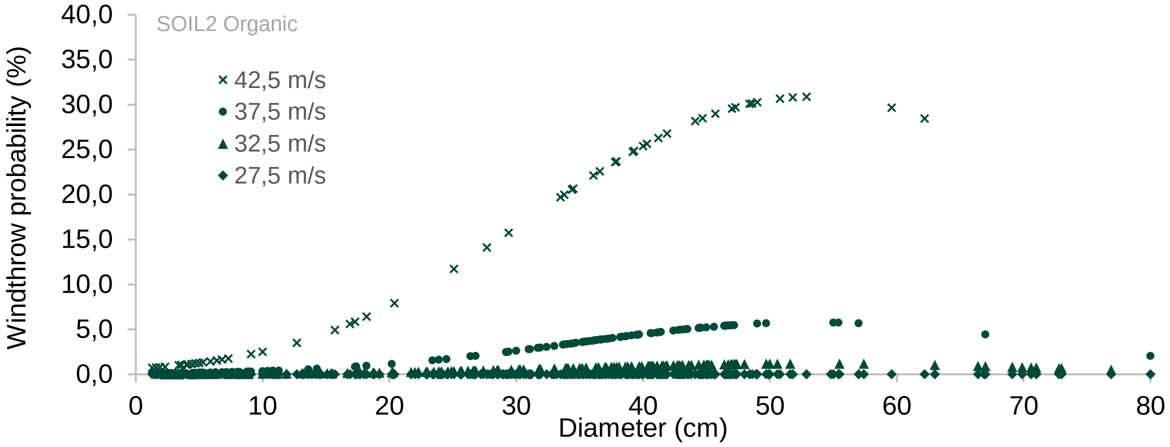


Figure 14.3: Model A. Predicted windthrow probability of Douglas-fir at different Windspeeds on Organic soils.

Example 3.

How much higher would the risk of windthrow be if the maximum windspeed was 42,5 ms^{-1} instead of 37,5 ms^{-1}? When following equation (12.2) and (12.3) increasing the windspeed from 37,5 ms^{-1} to 42,5 ms^{-1} in a Douglas-fir stand would increase the risk by:

$$ln(OR)=\left(\beta_0+\beta_{SOIL2}+\beta_{MWIND(42,5)}+\beta_{MWIND2\left(42,5^2\right)}+\beta_D+\beta_{D2}\right)-\left(\beta_0+\beta_{SOIL2}+\beta_{MWIND(37,5)}+\beta_{MWIND2\left(37,5^2\right)}+\beta_D+\beta_{D2}\right)$$

$\Downarrow$

$$ln(OR)=\left(\beta_{MWIND(42,5)}+\beta_{MWIND2\left(42,5^2\right)}\right)-\left(\beta_{MWIND(37,5)}+\beta_{MWIND2\left(37,5^2\right)}\right)$$

$\Downarrow$

$$ln(OR)=\left(\left(-0,2029\cdot(42,5-37,5)\right)+\left(0,00750\cdot(1806,25-1406,25)\right)\right)$$

$\Downarrow$

$$ln(OR)=-1,0145+3=1,9855$$

$\Downarrow$

$$OR=e^{(1,9855)}=7,283$$

There is thus a 7 times higher likelihood that the stand will be damaged or experience windthrow if the windspeed increases from 37,5 ms^{-1} to 42.5 ms^{-1}. This effect equals an increase of 13,3 % in windspeed. Regardless of whether the increase is estimated from a windspeed of 20 ms^{-1} or 30 ms^{-1} the 7 times higher risk applies to all increases of 13.3%.

14.2 Model B

This model is like model A but uses height as stand characteristic instead of diameter. Still no management variable (taper) is used in this model.

14.2.1 Douglas-fir

Like that of model A, variables describing maximum windspeed are not shown to be significant (Table 14.3). Variables describing height however, is significant on a 0,1 % level. The same traits in the relation between soil types occur in model B (sandy soils having higher probability of experiencing windthrow than soils containing clay, seen by the estimate values). As also seen in model A no observations are found for FK7 and FK8 (clay and calcareous).

Table 14.3: Analysis of maximum likelihood estimates of model B for Douglas-fir.

Parameter	Estimate	Standard error	P-value
Intercept	-11.5943	13.8964	0.4041
MWIND	-0.2737	0.7235	0.7052
MWIND2	0.00859	0.00941	0.3612
H	0.4764	0.0974	<.0001
H2	-0.00848	0.00224	0.0002
Coarse sand	-0.3106	0.3436	0.3660
Clayey sand	-2.1835	0.5895	0.0002
Sandy clay	-2.0451	0.5183	<.0001
Clay loam	-2.6601	1.0650	0.0125
Organic	0.0726	0.4287	0.8655

In Figure 14.4 the windthrow probability of Douglas-fir on fine sand experiencing maximum windspeeds of 37,5 ms^{-1} are shown in relation to stand height together with 95 % confidence intervals. Under these circumstances and with this model a stand of 22 meters has between 1,6 % and 6,0 % chance of experiencing windthrow. Again, as for model A, larger classes (here height compared to diameter) contains fewer observations. For Douglas-fir 84,4 % of the stand data are less than 30 meters tall and predicting windthrow for stands exceeding this height using this model must be done with care and without excessive conclusions.

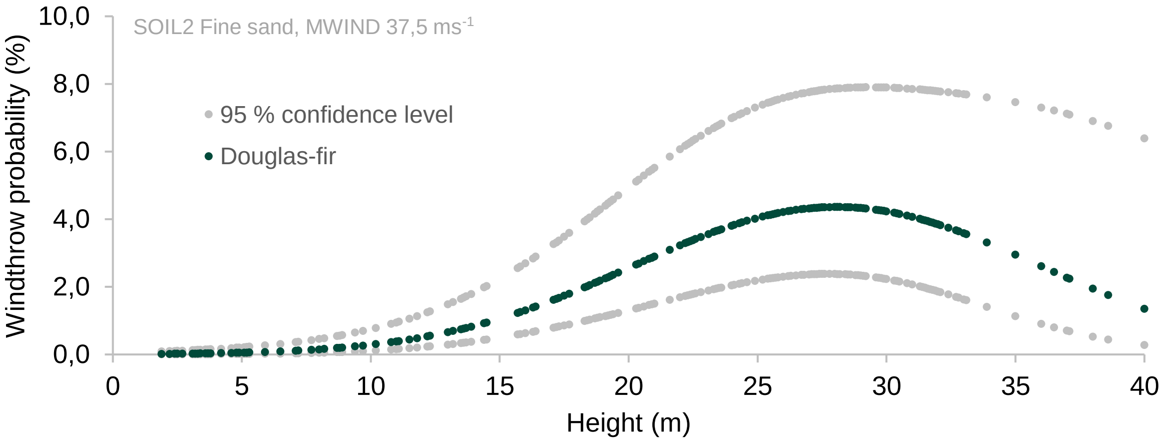


Figure 14.4. Model B. Predicted windthrow probability of Douglas-fir at 37,5 ms^{-1} on fine sand.

14.2.2 Norway spruce

The same traits as for model A occur for model B. Again, neither clay nor calcareous soils are shown to be significant. Both variables describing height and maximum windspeed are shown to be significant on a 0,01 % level.

Table 14.4: Analysis of maximum likelihood estimates of model B for Norway spruce.

Parameter	Estimate	Standard error	P-value
Intercept	-20.5194	0.6140	<.0001
MWIND	0.3303	0.0118	<.0001
H	0.4533	0.0427	<.0001
H2	-0.00952	0.00114	<.0001
Coarse sand	-0.2966	0.1368	0.0301
Clayey sand	-1.2319	0.1727	<.0001
Sandy clay	-1.7615	0.1944	<.0001
Clay loam	-1.1450	0.2789	<.0001
Clay	-11.8586	211.0	0.9552
Organic	0.0894	0.1663	0.5909
Calcareous	-10.9512	691.6	0.9874

The observed height classes of Norway spruce exceeding 30 meters are even less than Douglas-fir, less than 1 % of the total data set. As for Norway spruce the windthrow probability of the same stand of 22 meters experiencing windspeeds of 37,5 ms^{-1} can be read from Figure 14.5 to be between 4,6 % and 7,4 %. Compared to a windthrow probability of 1,6 – 6,0 % for Douglas-fir, Norway spruce is considered to have a higher probability of being windthrown under these circumstances and when estimated with this model.

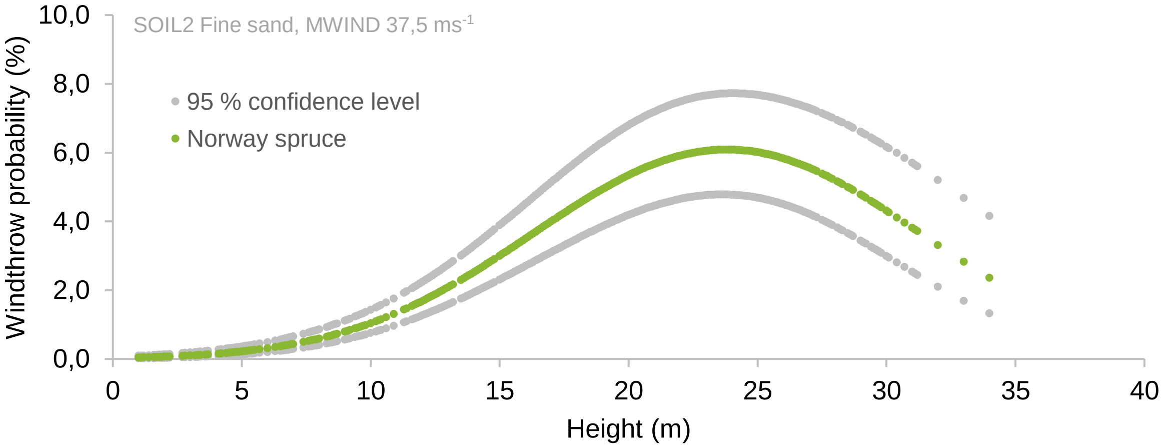


Figure 14.5. Model B. Predicted windthrow probability of Norway spruce at 37,5 ms^{-1} on fine sand.

14.2.3 Comparison of species models

By comparison with model A, the main difference in this model seems to be that a better match is obtained between the predicted probabilities and the observed responses (see Figure 9.2 and appendix 6). This is also supported by the AIC and ROC values of the two models.

On Figure 14.6 the windthrow probability of three soil types, Fine sand, Coarse sand and sandy clay are shown for the two species at a maximum windspeed of 37,5 ms^{-1}. DGR represents Douglas-fir and RGR represents Norway spruce. It is seen that the most critical point (highest windthrow probability) for Norway spruce occurs for stands with a height of 24 meters. For Douglas-fir this point occurs for stands of 28 meters. Up until a stand height of 30 meters Douglas-fir is less susceptible than Norway spruce but then becomes more likely to be windthrown.

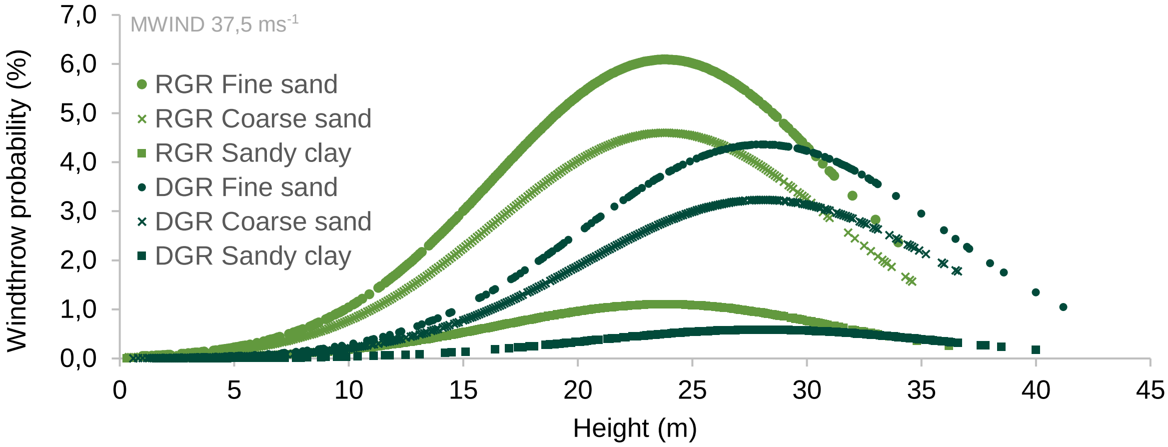


Figure 14.6. Model B. Predicted windthrow probability for Douglas-fir and Norway at windspeeds of 37,5 ms^{-1}.

The graphical presentation of the three soil types further, clearly indicates the differences in clay content and the subsequent windthrow probability of both tree species. If still looking at Coarse sand soils but at different windspeeds it is seen in Figure 14.7 that increasing the windspeed to more than 40 ms^{-1} makes predictions of windthrow larger than 20 % by heights of 25 m. As also seen for model A windspeeds <32,5 ms^{-1} does not affect the windthrow probability particularly in relation to stand height.

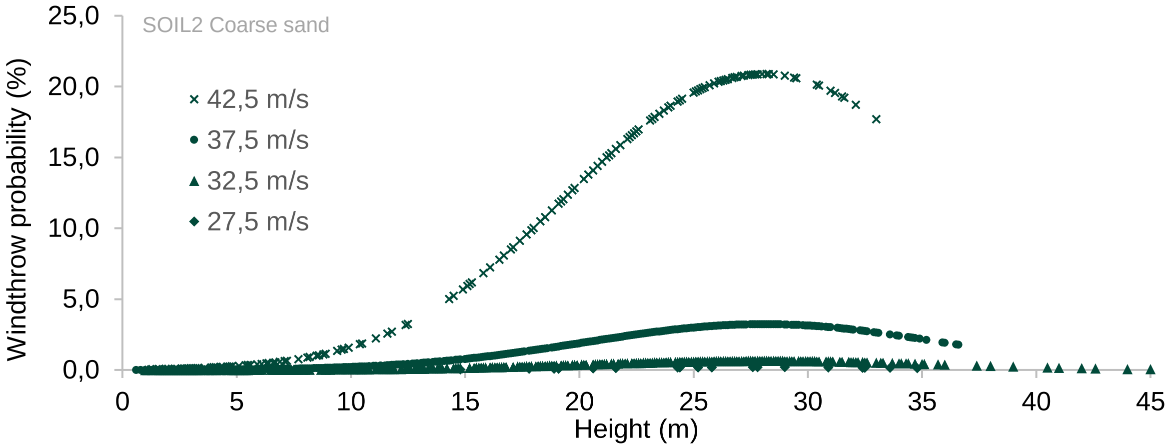


Figure 14.7. Model B. Predicted windthrow probabilities of Douglas-fir at different windspeeds on Coarse sand.

This increasing windthrow probability for high windspeeds already appears for stands with a low height. At a height of 15 meters, the windthrow probability of a stand experiencing over 40 ms^{-1} is already up to almost 6 %.

14.3 Model C

Model C predicts windthrow in relation to the individual district and uses the regional mean windspeeds in 45 meters height instead of the maximum windspeed as seen in model A and B. Like model B height is used to describe the stand. Further, management is described by the variable taper.

14.3.1 Douglas-fir

For Douglas-fir no observations of windthrow was found at the districts; Bornholm, Blåvandshuk, Fyn, Kronjylland, Midtjylland, Storstrøm, Thy, Vendsyssel and Østsjælland. In Table 14.5 they are therefore left out (see appendix 7, Model C DGR instead). The individual estimates for the district show the comparison with the district Himmerland, this therefore having the value 0. The wind and management variables are all shown to be non-significant for the model. For districts, only Nordsjælland, Søhøjlandet, Vadehavet and Vestsjælland are shown to be significantly different from Himmerland whereas Sønderjylland, Trekantsområdet and Vestjylland cannot be distinguished from Himmerland. Vadehavet is shown to be the district most likely to experience windthrow (high positive estimate sign) and Vestsjælland the least likely. Large differences in windthrow probabilities between districts therefore occur.

Table 14.5: Analysis of maximum likelihood estimates of model C for Douglas-fir.

Parameter	Estimate	Standard error	P-value
Intercept	-1,4722	4,8901	0,7634
Hovedstaden	-1,9744	1,0694	0,0649
Nordsjælland	-2,8794	0,7864	0,0003
Søhøjlandet	-2,7689	0,7831	0,0004
Sønderjylland	-0,0827	0,4065	0,8388
Trekantsområdet	0,0654	0,4351	0,8805
Vadehavet	1,1094	0,3937	0,0048
Vestjylland	-0,5203	0,8244	0,5280
Vestsjælland	-3,2767	1,0525	0,0019
LNRWIND	-2,9416	2,5946	0,2569
H	0,5789	0,1118	<,0001
H2	-0,012	0,00253	<,0001
HD	-0,0753	0,0549	0,1697
HD2	0,000466	0,00036	0,1964

Example 4.

Since the risk of windthrow for stands of Douglas-fir depends on which district the stand is located at it is possible to estimate how much more or less likely Douglas-fir is to experience windthrow between two districts. One thought example could be that planning, and choice of species is done across districts. This means that two districts want to determine which is more suited for cultivating Douglas-fir than the other hence which district should aim for cultivating other species.

The two districts Vadehavet and Trekantsområdet shares boarders and a thought example like this could apply between these. Again, following equation (12.2) and (12.3) we get:

$$ln(OR) = \left(\beta_0 + \beta_{DISTRICT(Vad.)} + \beta_{LNRWIND} + \beta_H + \beta_{H2} + \beta_{HD} + \beta_{HD2}\right) - \left(\beta_0 + \beta_{DISTRICT(Tre.)} + \beta_{LNRWIND} + \beta_H + \beta_{H2} + \beta_{HD} + \beta_{HD2}\right)$$

$$\Downarrow$$

$$ln(OR) = \left(\beta_{DISTRICT(Vad.)}\right) - \left(\beta_{DISTRICT(Tre.)}\right)$$

$$\Downarrow$$

$$ln(OR) = (1{,}1094) - (0{,}0654) = 1{,}0440$$

$$\Downarrow$$

$$OR = e^{(1{,}0440)} = 2{,}840$$

There is thus almost 3 times higher relative risk that the stand will be damaged or experience windthrow if cultivated on the district Vadehavet rather than on the district Trekantsområdet.

The difference between districts is further shown on Figure 14.8, which shows the predicted windthrow probability for the districts Vadehavet, Trekantsområdet and Vestjylland. The plot is done for all tapers (Height diameter ratios) with regional windspeeds of 6,25 ms^{-1} and shows the development between heights of 10 to 40 meters.

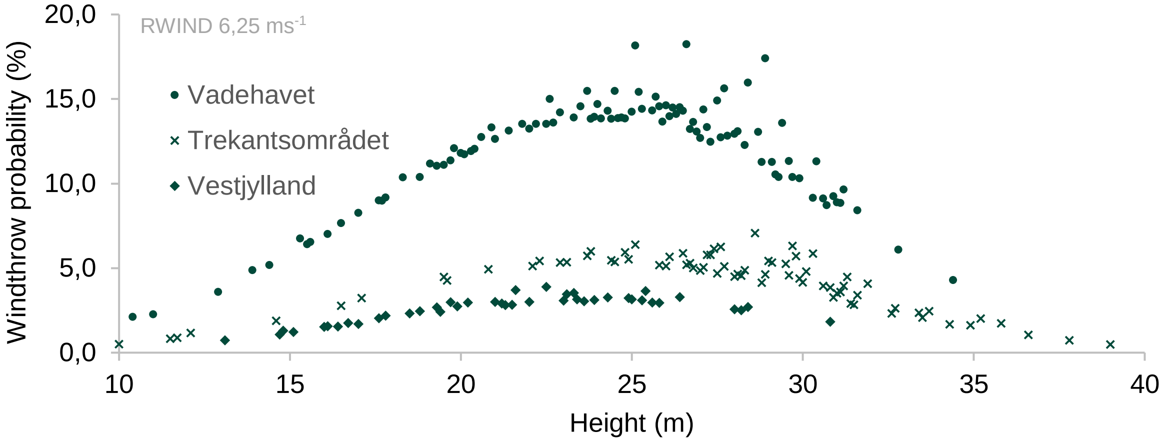


Figure 14.8. Model C. Predicted windthrow probabilities of Douglas-fir for all tapers at 6,25 ms^{-1}.

Higher windthrow probabilities are found for all height classes for the district Vadehavet. Compared to Trekantsområdet the most critical height for both Vestjylland and Vadehavet is lower (around 25 meters compared to almost 30 meters).

14.3.2 Norway spruce

For Norway spruce the amount of observations is much higher and the districts Blåvandshuk, Kronjylland, Midtjylland and Østsjælland are all represented whereas, on the other hand, they were not for Douglas-fir for model C. The remaining five districts Bornholm, Fyn, Storstrøm, Thy and Vendsyssel are still without observations of windthrow for Norway spruce as also for Douglas-fir. In Table 14.6 Districts are once again compared to the district Himmerland. For Norway spruce only Vestjylland district are shown not to be significantly different from Himmerland of the districts shown in Table 14.6. In contrast to Douglas-fir the variables for regional windspeeds are found significant on a 0,01 % level for Norway spruce.

Table 14.6: Analysis of maximum likelihood estimates of model C for Norway spruce.

Parameter	Estimate	Standard error	P-value
Intercept	10,8023	30.435	0,0004
Blåvandshuk	-1,7576	0,7331	0,0165
Hovedstaden	-2,9444	0,7332	<,0001
Kronjylland	-2,5005	0,443	<,0001
Midtjylland	-2,3544	0,2589	<,0001
Nordsjælland	-1,9389	0,2153	<,0001
Søhøjlandet	-1,7499	0,3109	<,0001
Sønderjylland	0,5583	0,1841	0,0024
Trekantsområdet	0,4215	0,2014	0,0364
Vadehavet	1,9810	0,1837	<,0001
Vestjylland	-0,2606	0,232	0,2613
Vestsjælland	-1,9370	0,3944	<,0001
Østsjælland	-4,3278	1,0159	<,0001
RWIND	-5,8301	0,8716	<,0001
RWIND2	0,4377	0,0637	<,0001
H	0,6140	0,0463	<,0001
H2	-0,0139	0,00123	<,0001
HD	-0,0244	0,0221	0,2698
HD2	0,000101	0,000134	0,4522

Vadehavet is also for Norway spruce the district predicted to experiencing most windthrows while Østsjælland is least likely to do so. This however is under the consideration of leaving out districts which does not have observations of windthrow.

Figure 14.9 shows like Figure 14.8 the differences in 3 districts for Norway spruce. At windspeeds of 6,25 ms^{-1}, following the same calculus as in example 4, Norway spruce is 4,75 times more likely to experience windthrow at Vadehavet district than on Trekantsområdet. For the plotted districts, stands are most vulnerable around a height of 22 meters compared to 25-30 meters for Douglas-fir.

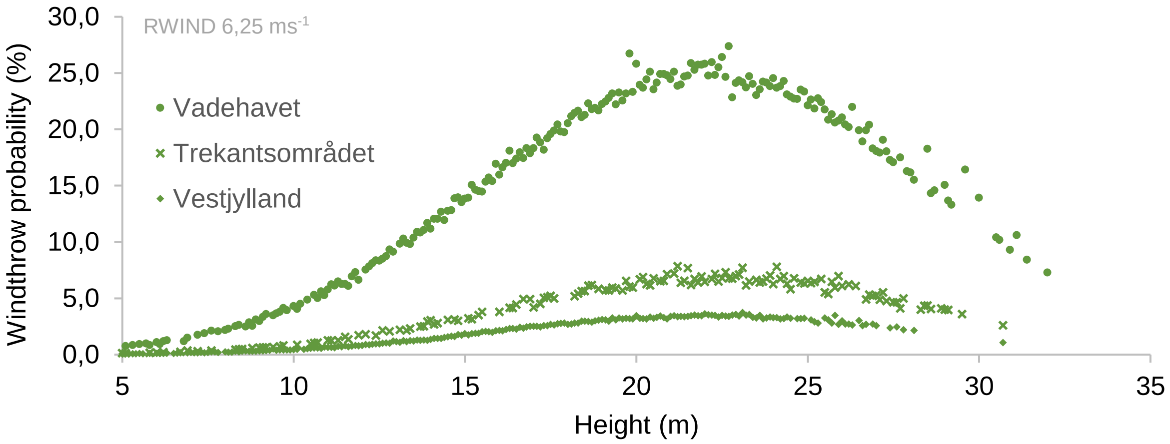


Figure 14.9. Model C. Predicted windthrow probabilities of Norway spruce for all tapers at 6,25 ms^{-1}.

14.3.3 Comparison of species models

In Figure 14.10 and Figure 14.11 the predicted windthrow probability in relation to taper is shown for stands with heights of 15 and 20 meters for both species, at regional windspeeds of 6,25 ms^{-1}. The figures depict this relation for the two districts Vestjylland and Vadehavet respectively. For both figures all predicted observation for all heights are shown (•).

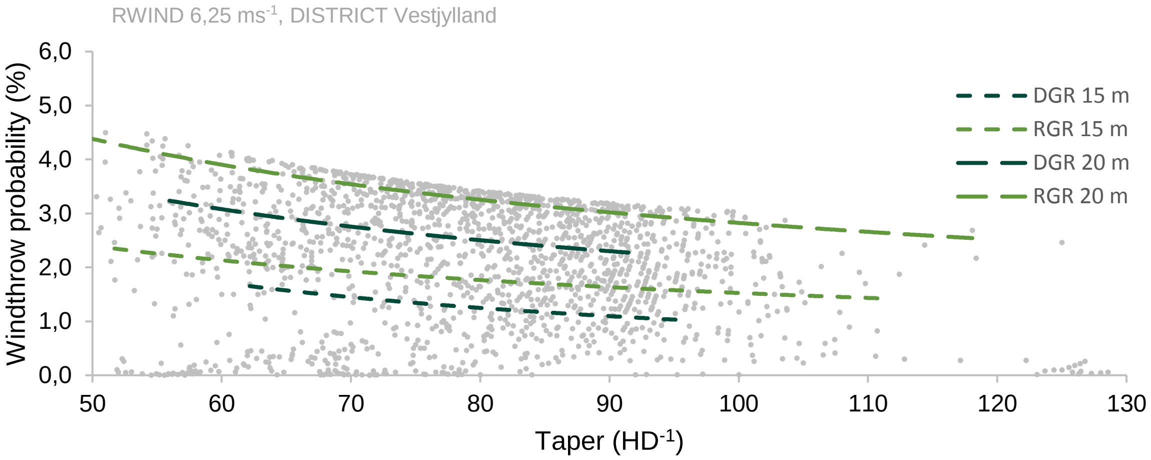


Figure 14.10. Model C. Predicted windthrow probability in relation to Taper for the district Vestjylland.

Rough polynomial trendlines for heights of 15 and 20 meters for the two species shows a decreasing risk of windthrow as an effect of higher taper. This trend is further seen across all height classes. However, the variables for taper were not shown to be significant and the differences (the decrease) can therefore not necessarily be seen as true for the dataset. The trend as, also seen when comparing Figure 14.8 and Figure 14.9 with Douglas-fir being less susceptible, is also seen here for the district Vestjylland.

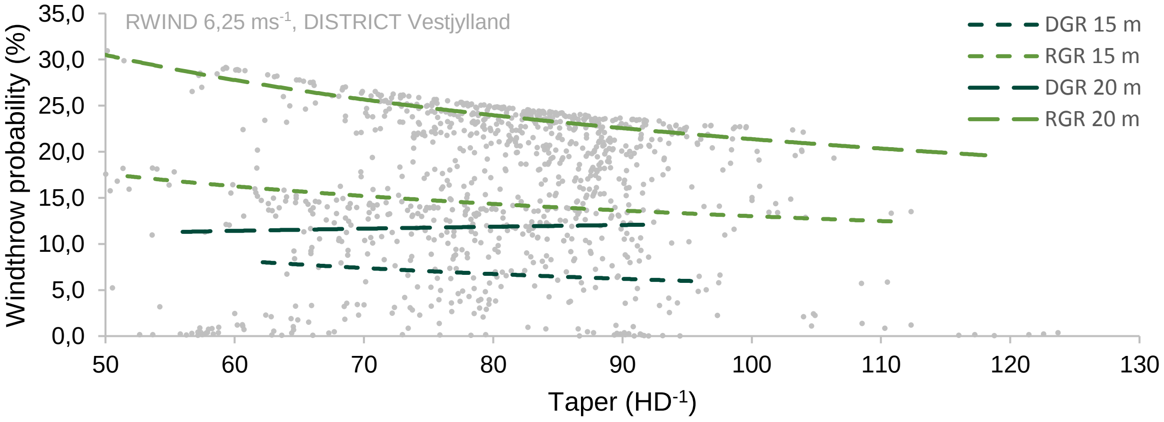


Figure 14.11. Model C. Predicted windthrow probability in relation to Taper for the district Vadehavet.

For Vadehavet district Douglas-fir stands of 20 meters are shown to be less susceptible than Norway spruce stands of 15 meters across all height diameter ratios. This trend contrasts with Norway spruce at height 20 meters by slightly increasing the windthrow probability with increase in taper. It is further worth mentioning the differences in the y axis values, which for Vadehavet district goes up until 35 % as opposed to 6 % for Vestjylland district.

14.4 Model D

Model D is similar to model C (using mean wind, district, height and taper) but further uses the stand volume per hectare and the soil classification.

14.4.1 Douglas-fir

For Douglas-fir only Vadehavet district showed to be significantly different from Himmerland and further districts with p-values lower than 0,5 (far from significant) were only Søhøjlandet, Sønderjylland and Trekantsområdet (see appendix 7). Including soil classifications in model D compared to model C it is seen in Table 14.7 that only Sandy clay and clayey sand is significantly different from Fine sand (reference value) on a 5% level.

Table 14.7: Analysis of maximum likelihood estimates of model D for Douglas-fir.

Parameter	Estimate	Standard error	P-value
Intercept	8,9512	8,4180	0,2876
Coarse sand	-1,3353	1,4519	0,3577
Clayey sand	-4,2302	1,5776	0,0073
Sandy clay	-2,9130	1,4314	0,0418
Clay loam	-3,0418	1,6924	0,0723
Organic	-0,2739	1,4706	0,0625
LNRWIND	-7,5446	4,6702	0,1062
HD	-0,1477	0,0479	0,002
HD2	0,000883	0,000295	0,0028
H	0,604	0,1106	<,0001
H2	-0,0124	0,00254	<,0001
VHA	-0,00036	0,00195	0,8544

Compared to model A and B that also includes soil classifications the same trend in content of sand applies to some degree. Clayey sand having higher content of sand than sandy clay decreases the predicted windthrow probability more using this model. Volume per hectare are further not shown to be significant and the same goes for the regional windspeeds.

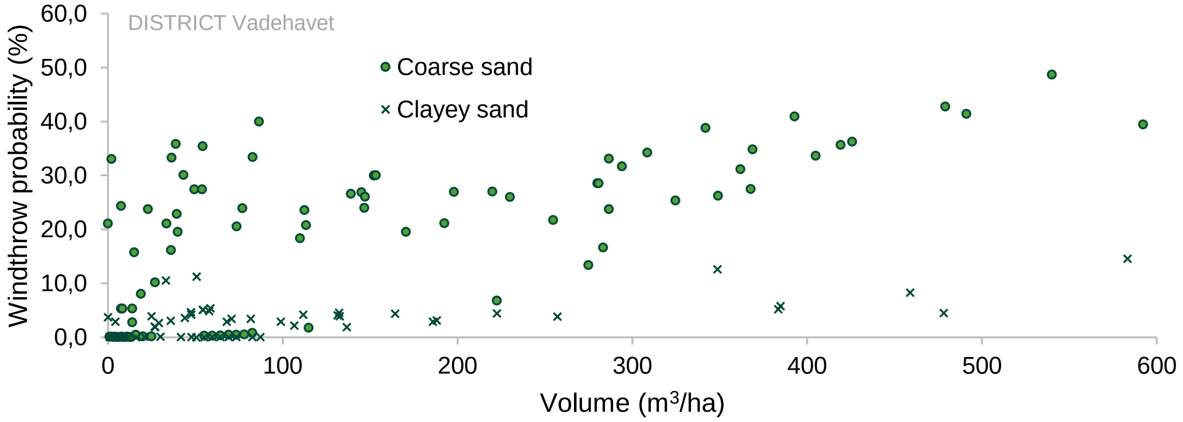


Figure 14.12. Model D. Predicted windthrow probability of Douglas-fir for Vadehavet district.

Looking at the two different soil types for Douglas-fir in relation to standing volume on Figure 14.12 on the previous page, both shows slight increases in windthrow probability as standing volume increases. Higher probabilities are found for coarse sand, while a higher content of clay reduces this probability. Coarse sand compared to clayey sand also shows larger increases as standing volume increase when using this model (Coarse sand roughly ranges from 0-50 % probability while clayey sand ranges from 0-15 %). This however does not apply for all districts (data not shown).

Example 5.

Model D includes more variables than model A to C. Being quite like model C it is possible to see the differences in predicted windthrow probability between the two models. Having a stand with height 22 meters, a volume of 210 m^{3}ha^{-1}, a taper of 1:100 experiencing regional windspeeds of 5,75 ms^{-1} growing on the district Himmerland on fine sand would give the respective probabilities for model C and D of:

Model C:

$$logit(\hat{p}) = -1,4722 + (-2,9416 \cdot ln(5,75)) + (0,5789 \cdot 22) + (-0,012 \cdot 22^2) + (-0,0753 \cdot 100) + (0,000466 \cdot 100^2) = -2,5599$$

$$\hat{p} = \frac{e^{(-2,5599)}}{1 + e^{(-2,5599)}} = 0,072$$

Model D:

$$logit(\hat{p}) = 8,9512 + (-7,5446 \cdot ln(5,75)) + (0,604 \cdot 22) + (-0,0124 \cdot 22^2) + (-0,1477 \cdot 100) + (0,000883 \cdot 100^2) + (-0,00036 \cdot 210) = -2,9750$$

$$\hat{p} = \frac{e^{(-2,9750)}}{1 + e^{(-2,9750)}} = 0,049$$

The predicted windthrow probability for model C (7,2 %) is thus 2 % higher compared to the same stand predictions using model D (4,9 %) which further includes soil classification and standing volume per hectare. Since Himmerland and Fine sand are reference values they both equal 0 in the equation. Results from example 5 are shown in Figure 14.13 for all height classes together with observations for model D for all tapers and stand volumes (•). It is seen that model C predicts higher windthrow probabilities of Douglas-fir than model D.

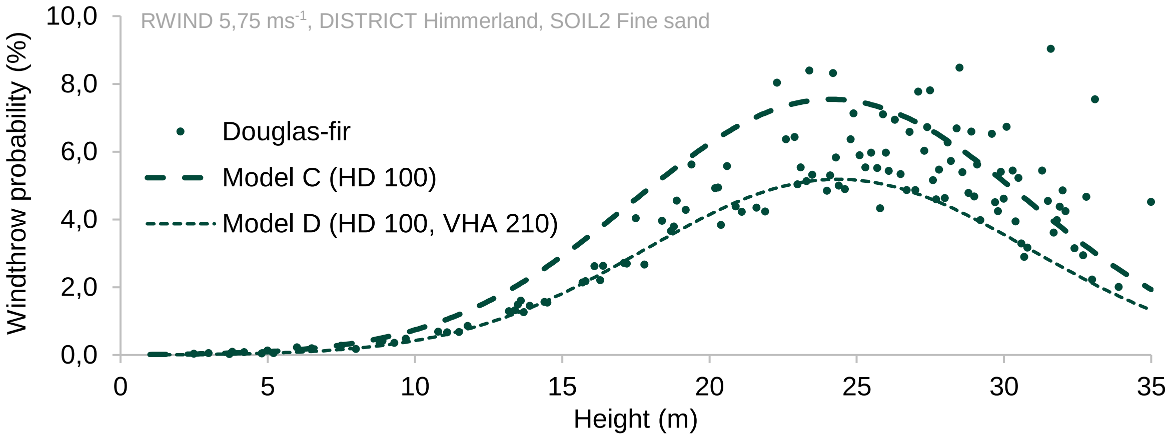


Figure 14.13. Model D & C. Predicted windthrow probability of Douglas-fir on Himmerland district on Fine sand.

14.4.2 Norway spruce

For Norway spruce both regional wind variables, height and volume are found to be significant on a 0,01 % level (Table 14.8). In relation to districts there are larger differences across districts for Norway spruce than Douglas-fir (more are found significantly different from Himmerland). Out of the 12 included districts 9 were shown to be significant.

Table 14.8: Analysis of maximum likelihood estimates of model D for Norway spruce.

Parameter	Estimate	Standard error	P-value
Intercept	6,7344	3,4789	0,0529
Clayey sand	-1,8386	0,3882	<,0001
Sandy clay	-1,2161	0,3855	0,0016
Organic	-0,8221	0,3836	0,0321
Blåvandshuk	-1,7282	0,7892	0,0285
Hovedstaden	-1,6739	0,8200	0,0412
Kronjylland	-2,403	0,5768	<,0001
Midtjylland	-2,2048	0,4392	<,0001
Vadehavet	2,5267	0,4128	<,0001
Søhøjlandet	-1,5386	0,4584	0,0008
Sønderjylland	0,9633	0,4057	0,0176
Vestsjælland	-1,0739	0,4997	0,0316
Østsjælland	-2,6818	1,0764	0,0127
RWIND	-4,8377	1,0106	<,0001
RWIND2	0,3662	0,0751	<,0001
HD	-0,0462	0,0224	0,0395
HD2	0,0002	0,000134	0,1362
H	0,5411	0,0478	<,0001
H2	-0,0116	0,00126	<,0001
LNVHA	0,4234	0,0393	<,0001

Example 6.

Compared to the predictions done with model D for Douglas-fir in example 5, the same stand of Norway spruce would have a windthrow probability of:

$$
\begin{aligned}
logit(\hat{p}) = {} & 6{,}7344 + (-4{,}8377 \cdot 5{,}75) + \left(0{,}3662 \cdot 5{,}75^2\right) \cdot (0{,}5411 \cdot 22) + \left(-0{,}0116 \cdot 22^2\right) \\
& + (-0{,}0462 \cdot 100) + \left(0{,}0002 \cdot 100^2\right) + \left(0{,}4234 \cdot ln(210)\right) = -3{,}0411
\end{aligned}
$$

$$
\hat{p} = \frac{e^{(-3{,}0411)}}{1 + e^{(-3{,}0411)}} = 0{,}046
$$

With a windthrow probability of 4,6 % Norway spruce would under these circumstances and at the same stand characteristics be less susceptible than Douglas-fir (4,6 % compared to 4,9 %) yet the difference is small (0,3 %).

14.4.3 Comparison of species models

Like Figure 14.13 the results of example 6 for all heights are shown in Figure 14.14 for Norway spruce together with results from example 5 of Douglas-fir. It is seen that by a height of 20 meters Norway spruce becomes less susceptible than Douglas-fir which up until this height has been less susceptible than Norway spruce. However, the developments are bound to a standing volume of 210 m^3ha^{-1} which for some plots of height classes in Figure 14.14 are not realistically possible. The difference between the two species in relation to example 5 and 6 is further insignificant if corrected for standard errors (data not shown). For this example district one species is therefore not superior to the other in relation to windthrow susceptibility.

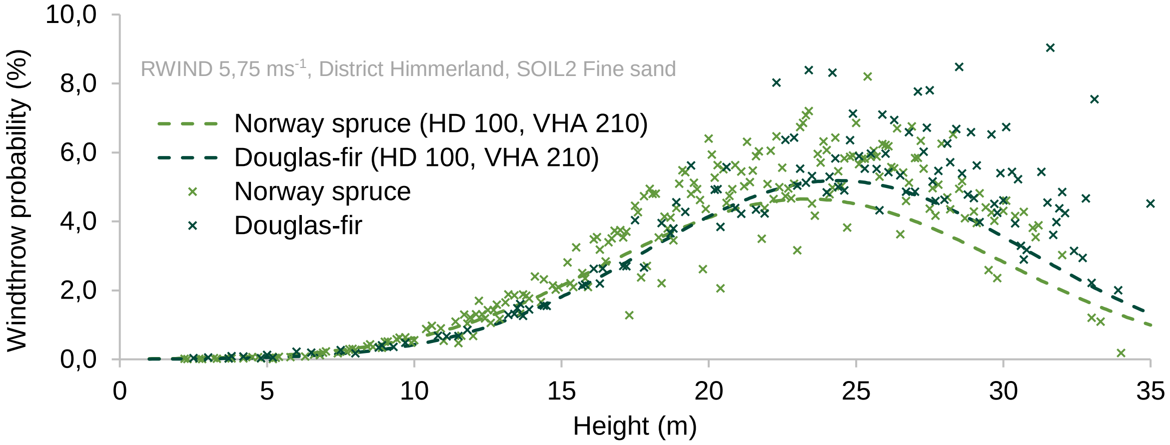


Figure 14.14. Model D. Comparison of Predicted windthrow probability of Norway spruce and Douglas-fir.

15 Comparing models

From equation (11.2) on page 41 values of x, for $p \le \Phi(x)$, are shown in Table 15.1 together with adjusted Rho sq. values, $P_i^{\,2}$, the number of variables, K, AIC values and the AIC for the intercept only $L(0)$. True models (models with the value $P_2^{\,2}$) are listed horizontal and false models (models with the value $P_1^{\,2}$) are listed vertical. Under the assumptions of $K_1 \ge K_2$ and $P_2^{\,2} - P_1^{\,2}$ some comparisons of models where not possible (left blank in Table 15.1).

Table 15.1: Ben-Akiva & Swait test results from comparing models A, B, C and D of both species.

	Douglas-fir				**Norway spruce**			
	Model A	**Model B**	**Model C**	**Model D**	**Model A**	**Model B**	**Model C**	**Model D**
L(0)	929,246	929,246	929,246	929,246	8933,451	8933,451	8933,451	8933,451
AIC	708,316	688,008	690,845	649,169	7166,914	7087,842	6630,060	6234,399
K	5	5	6	9	3	4	7	9
p_i^2	0,2431	0,2650	0,2630	0,3111	0,1981	0,2070	0,2586	0,3031
Values of x								
Model A	0,00	-6,37	-6,16	-11,41	0,00	-12,69	-32,95	-43,39
Model B		0,00		-9,47		0,00	-30,41	-41,50
Model C		-1,64	0,00	-9,61			0,00	-28,24
Model D				0,00				0,00

Under the assumption that values of x, follows the standard normal cumulative distribution function (CDF) the calculated probabilities $p \leq \Phi(x)$ are all except one ≈ 0 since they range from -6,16 to -43,39 (values <-4 ≈ 0 (Van Laar & Akça 2007)). For Douglas-fir when model C is compared with model B it is associated with incorrectly choosing the wrong model. This is because $p \leq \Phi(-1{,}64) = {,}0505$ which means one has 5 % chance of choosing the wrong model (in this case model C instead of model B, seen by lower AIC for model B). Distinguishing between the two is therefore difficult and one is not superior to the other.

15.1 Models ranking

From Table 15.1 it is seen that model D for both species is superior compared to the rest of the tested models (A-C). For models A and B, model B using height instead of diameter, is superior for both species yet the values of x for Douglas-fir is closer to the mean (σ = 0). Model D when compared to model C is also superior and especially for Norway spruce, giving no indices not to include soil type and standing volume (the difference between model D and C).

The preferred order of choosing models depending on available variables would therefore be Model D, C, B and A for Norway spruce and Model D, B, C and A for Douglas-fir.

16 Illustration of how the result can be used

The valuation of forestland for the comparison of different land uses, that being choice of species, rotation age or management strategies is often done by calculating the land expectation value (LEV). Incorporating encounters of risks such as windthrow to a stand during every period of the stands life is technically not difficult and intermediate cashflows such as thinnings can be included. Following the example for solving LEV of complex cashflows presented by Bright & Price (2000) gives a function for LEV of:

$$LEV = \frac{NPV_{first}}{\left(1 - \left\{\frac{p_t}{(1+r)^t} + \frac{1-p_t}{(1+r)^T}\right\}\right)}$$

Where NPV_{first} is the net present value of the first rotation p_t is probability of windthrow at time t, and T is the planned end of the rotation. The curly brackets are further called the summed discounted probability of replacement, denoted as A, thus:

$$LEV = \frac{NPV_{first}}{1-A} \qquad (16.1)$$

The individual contribution to A and NPV_{first} are then calculated for all the given entries of thinnings and windthrows to their respective time t (see Table 16.1). Summarising these makes it possible to calculate a risk averse LEV following equation (16.1). This can further be compared to the LEV calculation of a risk-free situation.

16.1 Implementing the risk of windthrow

In a given example, a Douglas-fir stands planned rotation age is 70 years with establishment costs and cashflows from thinnings as specified in Table 16.1. All numbers and values are fictional. For the calculation of windthrow probabilities the stand is planted on coarse sand and is expected to experience maximum windspeeds of 37,5 ms^{-1}. For the given example, model A is used to calculate the windthrow probabilities at ages 20, 30, 40, 50 and 60 years being the midpoint between the thinnings of this thought example. This gives a predicted windthrow probability at 40 years with a diameter of 20,2 cm of:

$$logit\left(\hat{p}\right) = -10{,}0505 - 0{,}3844 + \left(-0{,}2029 \cdot 37{,}5\right) + \left(0{,}00750 \cdot 37{,}5^2\right) + \left(0{,}1616 \cdot 20{,}2\right) + \left(-0{,}00151 \cdot 20{,}2^2\right) = -4{,}8486$$

$$\hat{p} = \frac{e^{(-4{,}8486)}}{1 + e^{(-4{,}8486)}} = 0{,}008$$

The remaining windthrow probabilities using model A for Douglas-fir are listed in Table 16.1. Cashflows if dead is much reduces compared to the anticipated partly because of increased harvest cost, damage to the recoverable timber but mostly because the logs falls short of mature size. Therefore the portfolio change decreasing average m^3 price (Bright & Price 2000).

Table 16.1: Solving LEV of complex cashflows with implementation of windthrow risk (cf. Bright & Price 2000).

Discount rate	0,03	Net present value (first crop) DKK/ha	23.621
Soil type	Coarse sand	Summed discounted probability [A]	0,13187
Maximum windspeed (ms^{-1})	37,5	Land expectation value (LEV) DKK/ha	27.209

Forest valuation

Event	D (cm)	Time (t)	Probability of death or felling	Cumulative probability of survival	Cashflow if dead/ felled (DKK/ha)	Cashflow if alive at t (DKK/ha)	Present value of cashflow (DKK/ha)	Discounted probability of death [A]
Plant	0	0		1,00000		-25000	-25.000	0,00000
Windthrow	9,5	20	0,002	0,99776	3.000		3	0,00124
Windthrow	14,4	30	0,004	0,99363	25.000		43	0,00170
Thin I	16,9	35		0,99363		30000	10.594	0,00000
Windthrow	20,2	40	0,008	0,98590	90.000		213	0,00237
Thin II	22,6	45		0,98590		40000	10.428	0,00000
Windthrow	25,5	50	0,013	0,97343	125.000		355	0,00284
Thin III	27,8	55		0,97343		35.000	6.704	0,00000
Windthrow	30,4	60	0,018	0,95557	130.000		394	0,00303
Thin IV	32,6	65		0,95557		30.000	4.197	0,00000
Fell	35,0	70	1,000	0,00000	130.000		15.689	0,12069
Totals							23.621	0,13187

The LEV under revised expectation of windthrow with a discount rate of 3 % is thus calculated to be DKK/ha 27.209 in the given example compared to DKK/ha 27.397 in the risk-free situation. It is further seen from the cumulative probability of survival that the stand is 95% curtain to survive until planned harvest. More entries could and should be included which would decrease the LEV in the risk averse situation even more.

Chapter V. Discussion of results

17 Main findings

The findings and initial analysis when set against the existing literature as presented in Chapter II are here discussed. The overall aim of this study was to examine correlations between meteorological, stand and geographical conditions for the susceptibility of Douglas-fir to windthrow. Further, it was sought to determine the windthrow stability of Douglas-fir compared to Norway spruce. As noted in the theoretical framework, these correlations and ratios are previously examined for both Douglas-fir and Norway spruce. However, they have not been validated under and in a wider Danish context.

17.1 Correlation between site, stand and meteorology

The results from this thesis show correlation between all three parameters and the predicted windthrow probability which is seen by the included variables of the tested models. The tested models were chosen depending on better fit statistics giving indices that support this claim that both meteorological conditions (windspeed), stand structure (age, height and diameter) and geographical conditions (district and soil classification including mean windspeeds based on topography) all are important for the risk of windthrow. Further, including all three parameters improves the goodness of fit statistics of the models when compared to only using two (see Table 11.3 on page 39, e.g. decrease in AIC for model 8 compared to model 2). Variables describing soil classifications further showed significant relationships between higher content of clay and reduced windthrow probabilities. This consists with previous findings for Germany where Klaus et al. (2011) showed soils with larger grain size to be more sensitive to windthrow. For windspeeds lower than 32 ms^{-1} it was further shown that windthrow was less frequent. This relation has previously been shown to apply for British conditions by Gardiner et al. (2010) with higher damage levels between 30-40 ms^{-1} and huge damages with windspeeds exceeding 40 ms^{-1}.

17.2 Differences between species

In relation to stability across tree species, Douglas-fir shows a lower susceptibility to windthrow than Norway spruce. However, this relation depends vastly on the stand characteristics and geographical location which, as shown in example 6 and in Figure 14.14 on page 57, makes Norway spruce less sensitive to storms than Douglas-fir under some conditions. Across ages however, Douglas-fir is comparatively less susceptible to windthrow than Norway spruce even within a 95 % confidence interval. In relation to climate change and the subsequent predicted droughts in the future, the findings suggest that Douglas-fir could be a substitute to Norway spruce. This under the decision of cultivating sturdier tree species, also in relation to drought.

This further leads to the sub question of whether stability increases by age. For both species a unimodal distribution was found indicated by the best goodness of fit values for the variables Age and Age^2 in the logistic regressions. The risk of windthrow was therefore shown to decrease as the hypothesis suggested but only after the age of 60 years.

18 Validity of data and models

In the methodology section in Chapter III some complications with the dataset for the further analysis is mentioned. Though these complications meant a reduction in valid observations, it is not estimated that it has any significance for the following data processing and results. This is due to the complications not being continuous but sporadic without context. However, it will implicate either higher or lower probabilities, yet this is relative since the dataset could also be larger or smaller which causes the same complications.

As noted in the theoretical framework, Douglas-fir is often planted with an admixture of Norway spruce to reduce the risk of windthrow (Møller 1977; Henriksen 1988). Pure Douglas-fir stands of young age (<20 years) are therefore expected to be few among the dataset which results in most of the Douglas-fir observations to be or previously be mixed stands. There is no correction for this effect in the analysis, despite records of whether the species is the main tree species or an admixture. This is due to complications with verifying whether older stands previously had admixtures and to what extent this was (mixing ratio), since no records of admixture appears due to harvest. Distinguishing between these registrations is therefore not done, though the mixture of coniferous species with both deciduous and other conifers is expected to exist in the dataset and is previously shown to decrease the windthrow probability (Schütz et al. 2006). This additionally implies, that observations of both species could origin from the same stand. However, this feature is not considered to affect the data analysis.

Some variables were further excluded from the analysis such as stem number and basal area due to these not being represented in all inventories. Further, regardless of one of the main research hypothesis being whether stability increases by age, no model with the variable age was chosen for analysis. Compared to other variables describing stand development, age is simply not as good, why diameter and height were favoured. Testing other models in addition to the 12 shown in Table 11.3, along with further testing of better ratios than quadratic and natural logarithm values for the variables, could result in the inclusion of the age variable. This assumption further leads to, that more variations of the dataset variables, as well as the composition of these for different models should be tested to improve probability predictions. The four given models are thus not necessarily the models describing the windthrow probability best based on the given dataset hence further modelling improvements are desired. However, the models do predict realistic estimates of the windthrow probabilities, based on the data material as indicated by the ROC values and decrease in AIC values.

18.1 The tested models

Despite model D being superior to the other models, models A and B might be easier to implement in the management practice of the forest estate. Due to the assumed lack of implementing risk in economic forest stand calculations (Blennow & Sallnäs 2002), models with fewer variables could lead to a higher willingness to do so hence a behavioural change (Fogg 2009). However, the individual models refer to different levels of precision (predictive abilities, lower AIC value), but also motivation for their use (complexity, number of variables) based on their predictive variables obtainability. Some general comments from the model results are discussed below.

18.1.1 Model A

The non-significance of maximum windspeed for Douglas-fir in model A could be an effect of windspeeds less than 32 ms^{-1} not affecting the probability of windthrow much. The division of maximum windspeed into classes going from less and above 30 ms^{-1} could therefore be favourable and possibly increase the significance of this variable in the model's predictive abilities. Windspeeds higher than 32 ms^{-1} are further ranked as hurricanes (Cappelen & Rasmussen 2013) which creates a legal basis for this limit. However, odds ratios showed that increasing the windspeed from 37,5 ms^{-1} to 42,5 ms^{-1} increased the risk of windthrow by 7 times. As also stated by Gardiner et al. (2010) large damages is caused by windspeeds of 30-40 ms^{-1} yet huge damages is expected when windspeeds exceed 40 ms^{-1}. Creating a threshold rather than a continuous variable is therefore not recommended.

18.1.2 Model B

Comparing Norway spruce and Douglas-fir in Figure 14.6 shows Douglas-fir to become more susceptible to windthrow by heights exceeding 30 meters. The two species on the other hand has different height growth and when seen in relation to Figure 13.1 for age development of the two species, Douglas-fir is less susceptible than Norway spruce across all age classes. Due to Douglas-fir outgrowing Norway spruce in height (Bergstedt 2017), which is further harvested around heights of 30 meters, the same relationship could apply for Douglas-fir compared to other species. Growth and yield tables of Sitka spruce and Douglas-fir by Karlberg (1961) shows for instance that on site class II Douglas-fir has reached a height of 25 meters by age 40 years while Sitka spruce (comparable to Norway spruce) has reached 20 meters. The height difference makes the Douglas-fir stand exposed to higher windspeeds and the neighbouring shelter effect is missing. The neighbouring effect however, is not investigated yet this is shown to be significant for the probability of windthrow (Lohmander & Helles 1987). One should therefore be cautious when comparing only by height.

18.1.3 Model C

For model C relationships between taper and predicted windthrow probability is shown in Figure 14.10 and Figure 14.11. Increasing taper was shown to decrease the windthrow probability, which was the case for both species, yet not significant. The highest windthrow probabilities were found to be approximately 25 meters and 22 meters for Norway spruce and Douglas-fir respectively. The results are consistent with previous findings by Rahbek (2003) also showing a decrease in probability. However, he shows stands of 16 meters of Norway spruce to be more susceptible than stands of 20 meters which contradicts with the findings of this study. The decrease nevertheless is small across a wide range of tapers and the variable was not found significant for any of the species. The study by Valinger & Fridman (2011) also did not find taper to be significant and discusses that the reason for this is due to heavy winds in their data and that the stands were overthrew regardless of taper. The same conclusion could be drawn for the present dataset since data origins from stronger storms than on average. On the other hand, more studies found increasing taper to increase the windthrow probability which contradicts with the present findings (Lohmander & Helles 1987; Peltola, Kellomäki, Väisänen, et al. 1999).

18.1.4 Model D

As seen for both model C and D, big differences are seen across districts with e.g. Vadehavet District to be the one with the highest risk of windthrow. An assumption was, that risk aversive forest management practice could be the reason for this difference across districts. For Norway spruce windthrow probability is found to be decreasing with very high mean windspeeds (Table 14.8). For areas e.g. along western faced coastlines windthrow frequencies of Norway spruce are therefore lower. However, this relationship does not apply for Douglas-fir, which shows increasing risk with increasing mean windspeed. Risk aversion is previously shown to reduce rotation age (Brunette et al. 2015; Blennow & Sallnäs 2002). This could be an explanatory factor in the given case, shown by fewer observations of high age classes especially for areas with high mean windspeeds. Based on the results it is further possible to examine whether the decision of planting Douglas-fir and Norway spruce on windthrow prone locations is avoided to reduce risk (e.g. sandy soils and exposed topography shown by *mean windspeed*).

18.2 Limitations of the models

Although the dataset includes observations spread throughout the country (Denmark), some districts and regions are not fully represented regarding, for example, age classes and diameter classes. The entire island of Funen (District Fyn) together with Lolland Falster and southern Zealand (District Storstrøm) and northern Jutland (District Vendsyssel) are represented by few observations. Furthermore, these districts stand observations are relatively young (more than 80 % are less than 50 years old). Usage of the presented models including the variable district (Model C and D) should therefore be done with precaution within these districts (see appendix 6 for districts map).

Further shortcomings of the presented models are the lack of factors such as interaction with neighbouring stands, mixtures and thinning practice (Subramanian et al. 2016). Nevertheless, the models predictions of windthrow probability according to species but also stand characteristics meteorological conditions and geographical location is generally in accordance with previous findings (e.g. Peltola, Kellomäki, Väisänen, et al. 1999; Valinger & Fridman 2011; Albert et al. 2015; Schütz et al. 2006) while some is contradicting (e.g. Albrecht et al. 2012; Lohmander & Helles 1987).

The analysis set out to use two different soil classifications to see if a simplified soil classification were practicable rather than a class variable with more variables. However, the variable SOIL1 was not found significant with two variables and distinguishing between soils containing mostly sand or clay were not possible. This was further seen for the variable SOIL2 which did not show a linear relationship between content of clay and sand for the windthrow stability. More classes however, showed higher significance than two. This further means that when implementing the windthrow models presented here it is recommended to use the soil classifications as used in this thesis hence the soil classification maps compiled by the Institute of agroecology (2016a).

19 General discussions

Determining windthrow probabilities is complex and given the many circumstances that a stand experience and the multiple threats and events it is exposed to together with effects of neighbouring stands and surrounding factors, exact probabilities are hard to determine. Despite of this, the findings, based on a small portion of the many explanatory variables, provides an easy tangible tool for better estimations. In relation to the stated hypotheses, windthrow probability does decrease by age but does so for both species. That Douglas-fir is distinguished by this trait is therefore not seen by the results of the thesis. However, that the species itself is less susceptible to windthrow than Norway spruce is supported by the findings in this thesis. This is shown by all age classes being less susceptible even within a 95 % confidence interval. If the species however is compared by stand structure Norway spruce is superior to Douglas-fir under some circumstances, especially by height.

The implementation of risk in economic calculus by use of the presented models would decrease the expected land value. These calculations nevertheless also rely on fixed prices and market situations. Including risk in the calculus is therefore only one step in getting more precise estimates in a decision-making process yet vital to include when possible.

Though biological benefits of windthrow is not of focus in this thesis, increased focus on biodiversity and elements like deadwood could make use of the findings presented here. The management could aim for increasing the risk of windthrow rather than lower it as proposed by Bormann et al. (1995) which thus leads to partially avoiding the locations and stand structures here said to be of higher windthrow stability.

19.1 Future studies

Determining windthrow probabilities including thinning and harvest volumes and time of such is therefore by the above mentioning's needed in future studies and is seen as crucial for more precise and realistic windthrow probability models.

The intentions with this thesis were further to investigate the assortment of different timber products and qualities in relation to whether the stand had been overthrown by wind or harvested deliberately. It was the hypothesis that due to broken stems and other damages to the tree and stand, the portfolio would change hence a lower timber value (Brunette et al. 2015). Hereby price curves and assortment portfolios could be combined to determine possible loss of timber value due to this timber being windthrown. Data material to support this study however, were not obtainable in a fulfilling quantity and accuracy, yet demand for such knowledge is by the author considered to be desired.

Using models for determining windthrow probabilities of Douglas-fir such as models A, B, C and D in combination with portfolio outcomes for windthrown timber would help in making better economic calculations and risk considerations in forest management.

Based on the existing data material similar models could also be made for other species both coniferous and deciduous. This provides better economic calculations in a decision-making process between species. Further, including risk in LEV calculations only for one species (e.g. Douglas-fir) in a comparison with a risk-free LEV calculation of another species makes a biased assessment in the subsequent choice of which species to cultivate.

20 Conclusions

In this thesis the windthrow risk of Douglas-fir has been assessed by compiling stand characteristics meteorological conditions and site classifications. The same assessment is done for Norway spruce for comparison of the wind stability between species. The results have been discussed in accordance to existing literature supporting the subject, which leads to the following conclusions. Including variables from all categories, improve the predictive abilities of the models. Maximum windspeed was not found to be significant for any of the species. However, windspeeds less than 32 ms^{-1} (windspeeds of less strength than a hurricane) has little effect on windthrow probabilities. Increasing the windspeed from 37,5 to 42,5 ms^{-1} on the other hand increases the windthrow probability by 7 times. This already applies for young and relatively short stands. Mean windspeed was neither found to be significant but showed decreasing probability for Norway spruce on more exposed localities. For Douglas-fir on the other hand, increasing mean windspeed increased windthrow probability.

The probability increased for soils with larger grain size. Higher content of clay was found to be significant for the probability of windthrow. Coarse sand however, was not found to be significant from fine sand and distinguishing between the two is therefore not possible.

For Douglas-fir a unimodal tendency was found in relation to diameter and predicted windthrow probability. However, observations of diameters >50 cm was few. Across all diameters Norway spruce experience higher windthrow probabilities and has an increasing risk by larger diameter. Douglas-fir on the other hand has decreasing risk by large diameters.

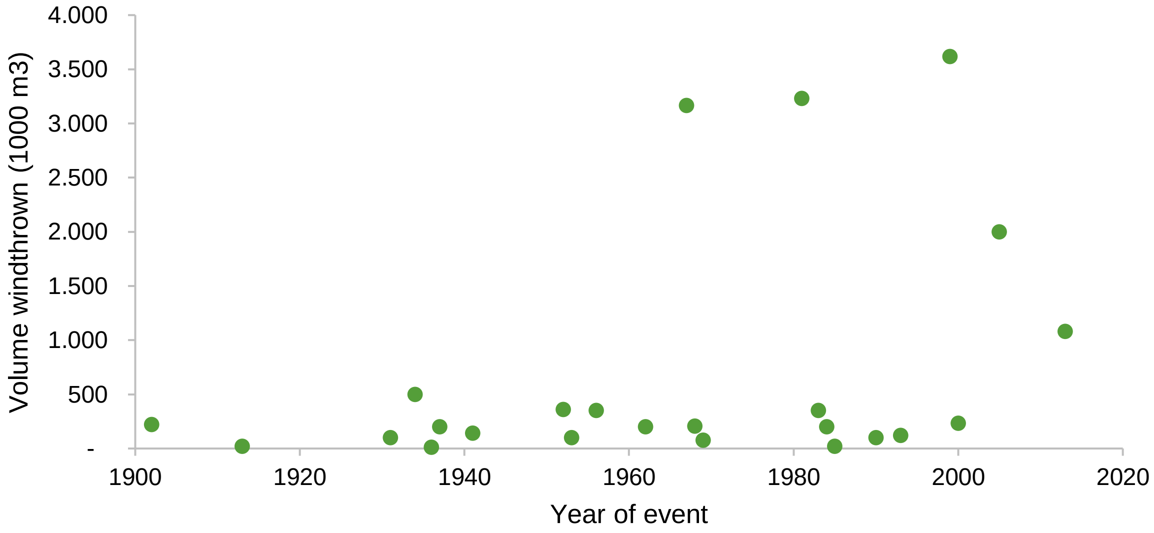
Height is shown to be significant on a 0,1% level for both species and large height classes are therefore shown to be less susceptible. The highest windthrow probabilities were found for stands of 24 and 28 meters for Norway spruce and Douglas-fir respectively. Norway spruce is further less susceptible than Douglas-fir by heights exceeding 30 meters. Taper was shown not to be significant for the windthrow probability. Volume where also not shown to be significant for the windthrow probability though an increasing trend was seen. Some districts have by all storm events been more severely hit than others yielding higher windthrow probabilities in the southern parts of Jutland than any other region, based on the present dataset. In relation to age, windthrow risk is found to decrease for both species by the age of 60 years. That this trend is more profound for Douglas-fir is not implied by the findings. Nevertheless, the hypothesis of whether stability increases by age is found to be plausible.

Model D with variables height, mean windspeed, soil classification, standing volume, taper and district yields the best predictions and is superior when tested against the other models. Compared to model C not including soil classifications and standing volume, Model D predicts lower probabilities of windthrow. Including these variables if possible, is therefore recommended. Models using height instead of Diameter is further superior despite inconvenience with obtaining correct height measurements. The preferred order of choosing models depending on available variables is therefore D, C, B and A for Norway spruce and D, B, C and A for Douglas-fir. The models provide an easy tangible tool for better windthrow risk assessment of both species. However, windthrow is only one risk associated with a forest stands rotation and other factors should be investigated in the future, for better economic calculations and subsequent decision making.

Appendices

Appendix 1. Windthrow severity development in Denmark for the last century

	Years between		1000 m3		
year	**>250.000 m^3**	**all**	**Deciduous**	**Conifer**	**Sum**
1902		-	190	30	220
1913		11,0	-	-	20
1931		18,0	-	-	100
1934	-	3,0	460	40	500
1936		2,0	-	-	10
1937		1,0	-	-	200
1941		4,0	-	-	140
1952	18,0	11,0	356	4	359
1953		1,0	-	-	100
1956	4,0	3,0	333	17	350
1962		6,0	-	-	200
1967	11,0	5,0	1.678	1.489	3.167
1968		1,0	175	32	207
1969		1,0	-	-	75
1981	14,0	12,0	3.100	130	3.230
1983	2,0	2,0	340	10	350
1984		1,0	200	0	200
1985		1,0	-	-	21
1990		5,0	-	-	100
1993		3,0	-	-	120
1999	16,0	6,0	3.285	394	3.619
2000		1,0	234	0	234
2005	6,0	5,0	1.990	10	2.000
2013	8,0	8,0	918	162	1.080
mean	**9,9**	**4,8**			16.602



Appendix 2. Description of terms and variables used in the analysis

Symbol	Description	Units
D	Mean stand diameter at breast height (1.3 m above ground)	cm
H	Mean stand height	m
HD	Taper (height [m] divided by diameter [m])	-
AGE	Age of stand	years
SPECIES	Species DGR (Douglas-fir) and RGR (Norway Spruce)	-
ARE.CL	Land area use of the species class	ha
VHA	Stand volume of the specific species (relative to ARE.CL)	m3/ha
RWIND	Regional windspeed (mean windspeed)	ms-1
MWIND	Maximum windspeed for the individual storm event	ms-1
SOIL1	Soil type classification (2 classes)	-
SOIL2	Soil type classification (8 classes)	-
REGION	Region division (4 classes)	-
DISTRICT	The nature agency’s districts as of 2013 (18 classes)	-
W	Windthrow parameter (0/1 = unharmed/harmed)	-
…2	The individual parameter (D, H, HD… etc.) in the power of 2	-
LN…	The natural logarithm of the parameter (D, H, HD… etc.)	-
SYEAR	Storm specific year	-
DIST.PA.NR.AFD.L	ID variable (district, part, forest, department, letter division)	-
AGE.C	Age classes (10-year intervals)	years
NAME	Name of forest (with the letters æ, ø, å)	-
NAME2	Name of forest (with ? instead of the letters æ, ø, å)	-

Appendix 3. Chosen variables depending on fit statistics

Chosen variables for the analysis are highlighted (bold), p-values not significant on a 5 % level are marked red

		Douglas-fir		Norway spruce	
	Variables	**AIC**	**p-value**	**AIC**	**p-value**
Diameter	D	895.563	<.0001	8822.843	<.0001
	D D2	874.544	0.0004	**8512.871**	**<.0001**
	LND	**873.699**	**<.0001**	8700.237	<.0001
Height	H	885.909	<.0001	8732.053	<.0001
	H H2	**855.396**	**<.0001**	**8527.707**	**<.0001**
	LNH	870.766	<.0001	8646.419	<.0001
Age	AGE	911.565	<.0001	8908.011	<.0001
	AGE AGE2	**889.127**	**0.0002**	**8566.789**	**<.0001**
	LNAGE	892.997	<.0001	8821.254	<.0001
Volume	VHA	915.073	<.0001	8747.194	<.0001
	VHA VHA2	911.993	0.0379	**8566.723**	**<.0001**
	LNVHA	**903.968**	**<.0001**	8612.060	<.0001
Taper	HD	**906.096**	**<.0001**	8934.524	0.3345
	HD HD2	903.233	0.0530	**8907.246**	**<.0001**
	LNHD	909.820	<.0001	8932.089	0.0679
Wind sp. Max	MWIND	**833.293**	**<.0001**	7750.728	<.0001
	MWIND MWIND2	834.931	0.5364	**7515.189**	**<.0001**
	LNMWIND	833.966	<.0001	7807.567	<.0001
Wind sp. mean	RWIND	927.854	0.0566	8771.755	<.0001
	RWIND RWIND2	**903.114**	**0.0006**	8771.399	0.1333
	LNRWIND	926.948	0.0329	**8766.241**	**<.0001**
Soil	SOIL1	930.063	0.2912	8909.280	<.0001
	SOIL2	899.500	<.0001	8503.736	<.0001
Region	REGION	900.456	0.0005	8462.925	<.0001
District	DISTRICT	809.216	0.0002	7310.882	<.0001
Intercept only (L_0)		929.246		8933.451	

Appendix 4. Scripts for different procedures in SAS®

The library is named `thesis` and the three files `DATA`, `RGR` and `DGR` are; all data, Norway spruce only and Douglas-fir only respectively. The windthrow parameter modelled is `W`, taking values of either 0 or 1.

Example 1. Testing different types of the same continuous variable

```
proc logistic DATA= thesis. RGR;
   model W(event='1') = AGE;
run;
proc logistic DATA= thesis. RGR;
   model W(event='1') = AGE AGE2;
run;
proc logistic DATA= thesis. RGR;
   model W(event='1') = LNAGE;
run;
```

Example 2. Testing class variables

```
Title 'DGR DISTRICT';
proc logistic DATA=thesis. DGR;
   class DISTRICT/param=ref;
   model w(event='1') = DISTRICT;
run;
```

Example 3. Correlation

```
proc corr DATA=thesis. RGR;
   var AGE D H HD RWIND MWIND VHA;
run;
```

Models DGR

```
Title 'Model A DGR';
proc logistic DATA=thesis. DGR;
   class SOIL2/param=ref REF=FIRST;
   model w(event='1') = MWIND MWIND2 D D2 SOIL2
   /link=logit lackfit;
   Output out=thesis. DGRA p=p L=L95 U=U95;
run;
Title 'Model B DGR';
proc logistic DATA=thesis. DGR;
   class SOIL2/param=ref REF=FIRST;
   model w(event='1') = MWIND MWIND2 H H2 SOIL2
   /link=logit lackfit;
   Output out=thesis. DGRB p=p L=L95 U=U95;
run;
Title 'Model C DGR';
proc logistic DATA=thesis. DGR;
   class DISTRICT/param=ref REF=FIRST;
   model w(event='1') = DISTRICT LNRWIND H H2 HD HD2
   /link=logit lackfit;
   Output out=thesis. DGRC p=p L=L95 U=U95;
run;
Title 'Model D DGR';
proc logistic DATA=thesis. DGR;
   class SOIL2 DISTRICT/param=ref REF=FIRST;
   model w(event='1') = SOIL2 DISTRICT LNRWIND HD HD2 H H2 VHA VHA2
   /link=logit lackfit;
   Output out=thesis. DGRD p=p L=L95 U=U95;
run;
```

Models RGR

```
Title 'Model An RGR';
proc logistic DATA=thesis. RGR;
   class SOIL2/param=ref REF=FIRST;
   model w(event='1')= MWIND LND SOIL2
   /link=logit lackfit;
   Output out=thesis. RGRA p=p L=L95 U=U95;
run;
Title 'Model B RGR';
proc logistic DATA=thesis. RGR;
   class SOIL2/param=ref REF=FIRST;
   model w(event='1')= MWIND H H2 SOIL2
   /link=logit lackfit;
   Output out=thesis. RGRB p=p L=L95 U=U95;
run;
Title 'Model C RGR';
proc logistic DATA=thesis. RGR;
   class DISTRICT/param=ref REF=FIRST;
   model w(event='1')= DISTRICT RWIND RWIND2 H H2 HD HD2
   /link=logit lackfit;
   Output out=thesis. RGRC p=p L=L95 U=U95;
run;
Title 'Model D RGR';
proc logistic DATA=thesis. RGR;
   class SOIL2 DISTRICT/param=ref REF=FIRST;
   model w(event='1')= SOIL2 DISTRICT RWIND RWIND2 HD HD2 H H2 LNVHA
   /link=logit lackfit;
   Output out=thesis. RGRD p=p L=L95 U=U95;
run;
```

Appendix 5. Soil maps and classification

Variable SOIL1

	Danish name	English name	Percentage by weight
			Clay < 2 mm
🟨	Leret jord	Clay	>15
🟫	Sandet jord	Sand	0-15

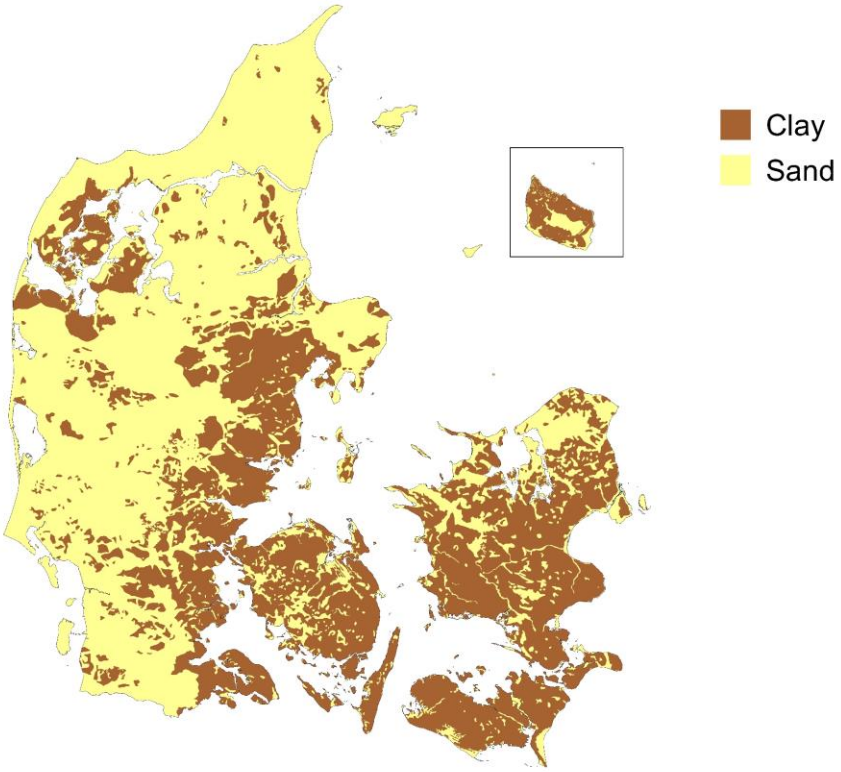
Reference: Institute of agroecology (2016b)

Variable SOIL2

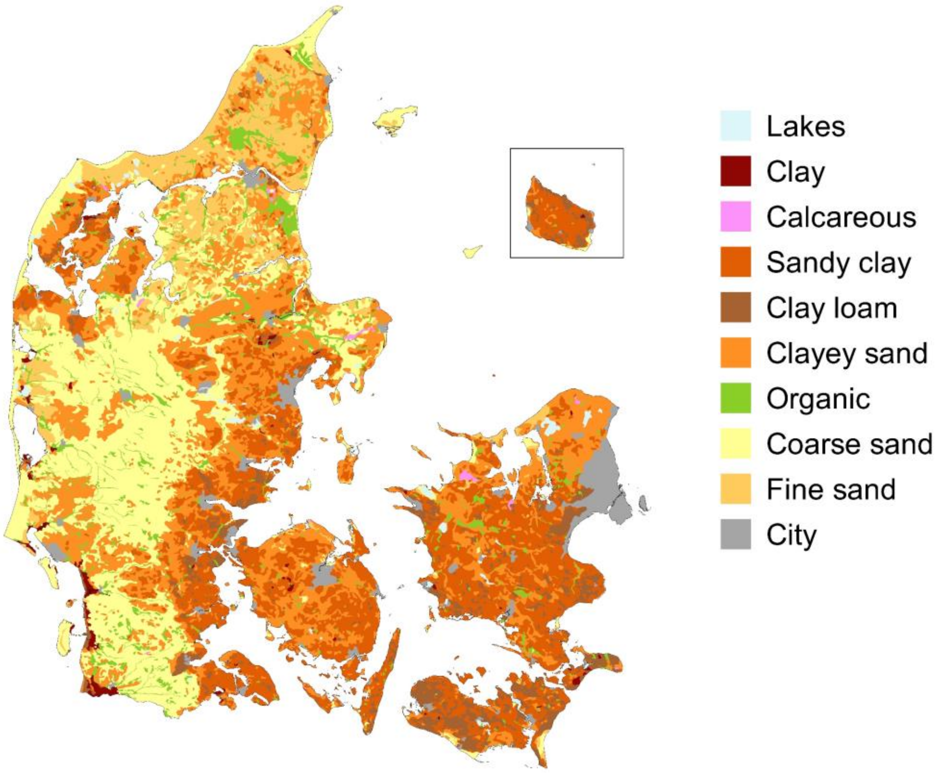
	Danish name	English name	Percentage by weight					
			Clay < 2 mm	Silt 2-20 mm	Fine sand 20-200 mm	Sand tot. 20-2000 mm	Org. 58,7% C	Lime CaCO$_2$
FK1	Grovsandet jord	Coarse sand	0-5	0-20	0-50	75-100	≤10	≤10
FK2	Finsandet jord	Fine sand			50-100			
FK3	Lerblandet sandjord	Clayey sand	5-10	0-25	0-95	65-95		
FK4	Sandblandet lerjord	Sandy clay	10-15	0-30	0-90	55-90		
FK5	Lerjord	Clay loam	15-25	0-35		40-85		
FK6	Svær lerjord	Clay	25-100	0-50		0-75		
FK7	Humusjord	Organic					>10	10-90
FK8	Atypisk	Calcareous					≤10	>10

Reference: Holst (1992)

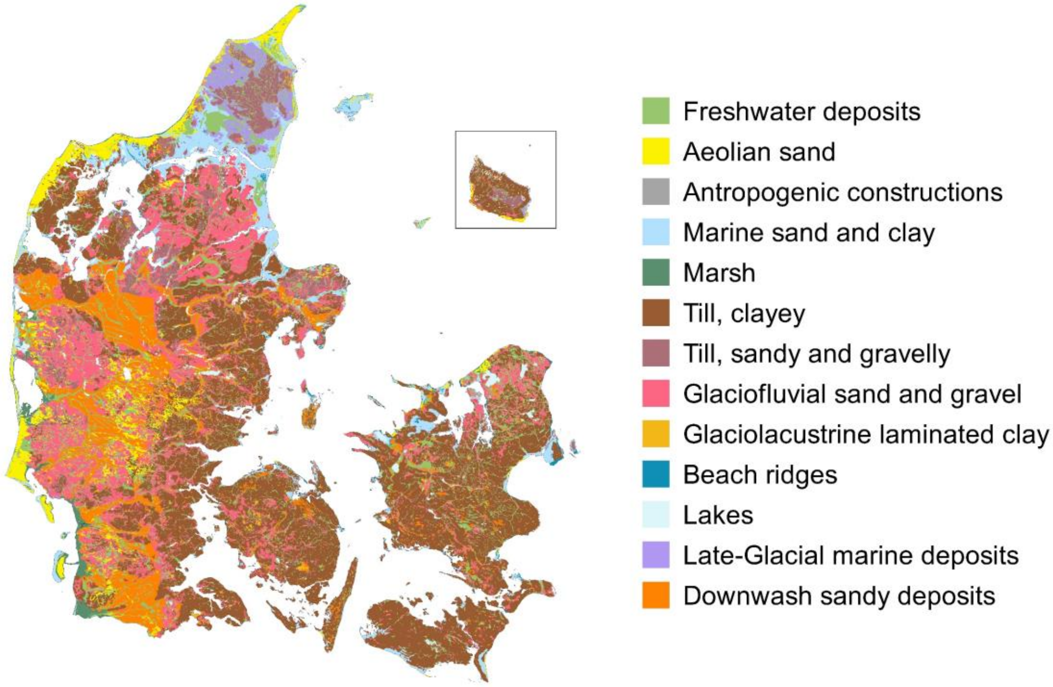
All maps in appendix 5 are compiled in the QGIS software package. Data is gathered from the Institute of agroecology (2016a and 2016b) and Schack Pedersen (2011).



SOIL1 including 2 classes

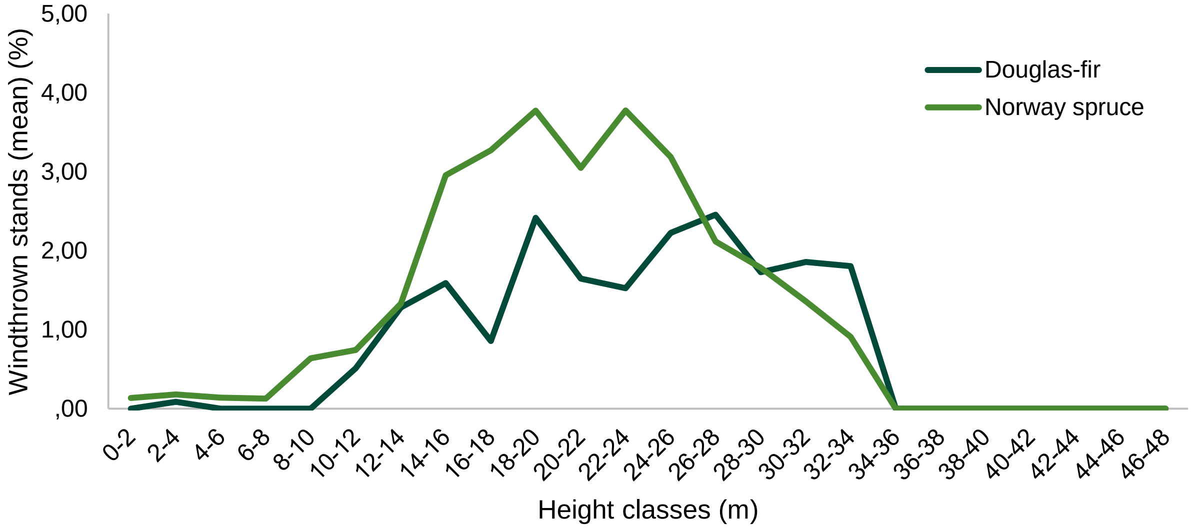


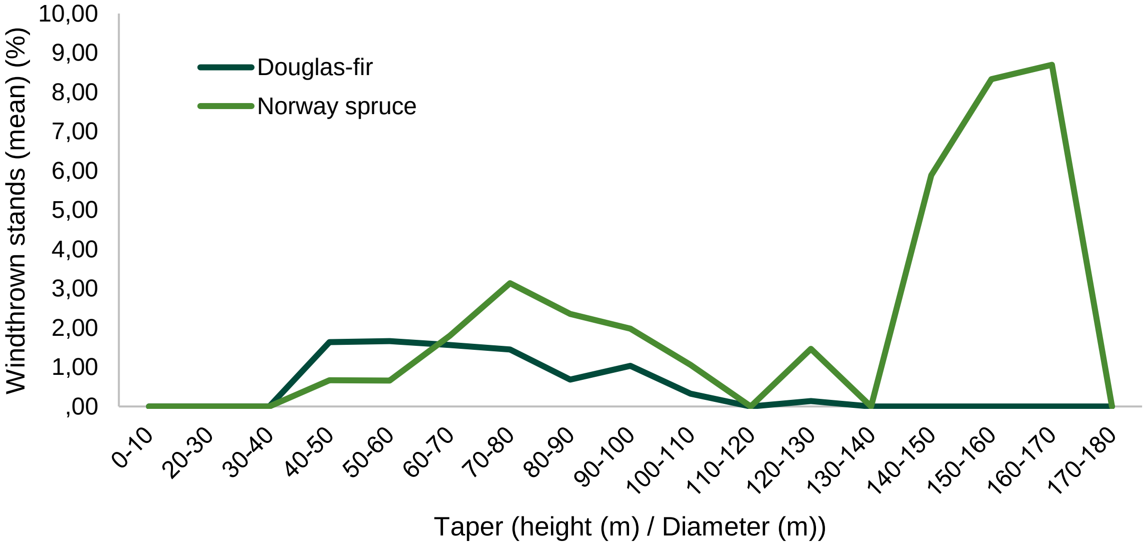
SOIL2 including 8 classes

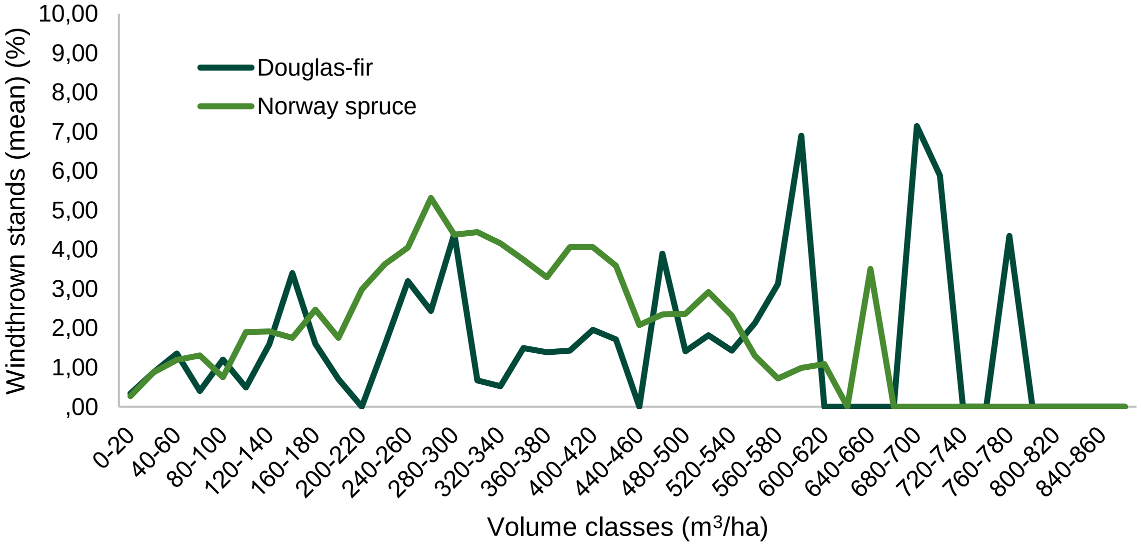


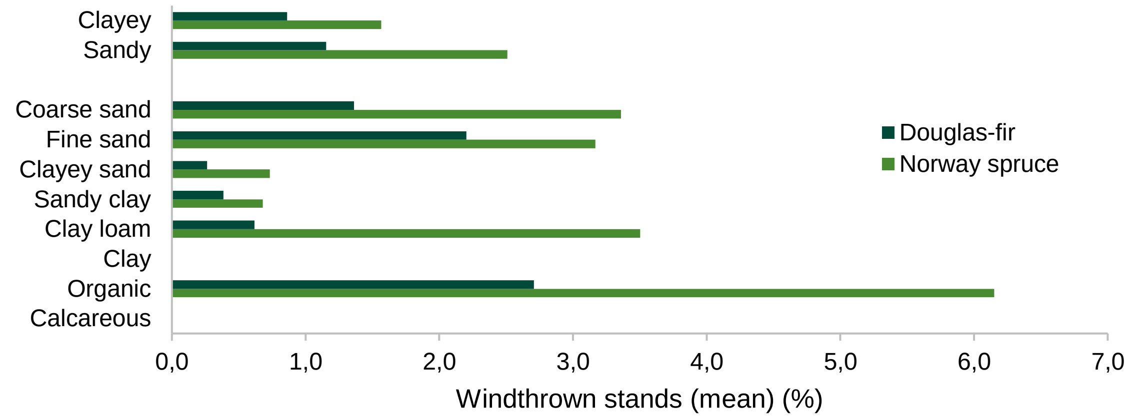
GEUS map used to determine SOIL2 areas within the class “City”

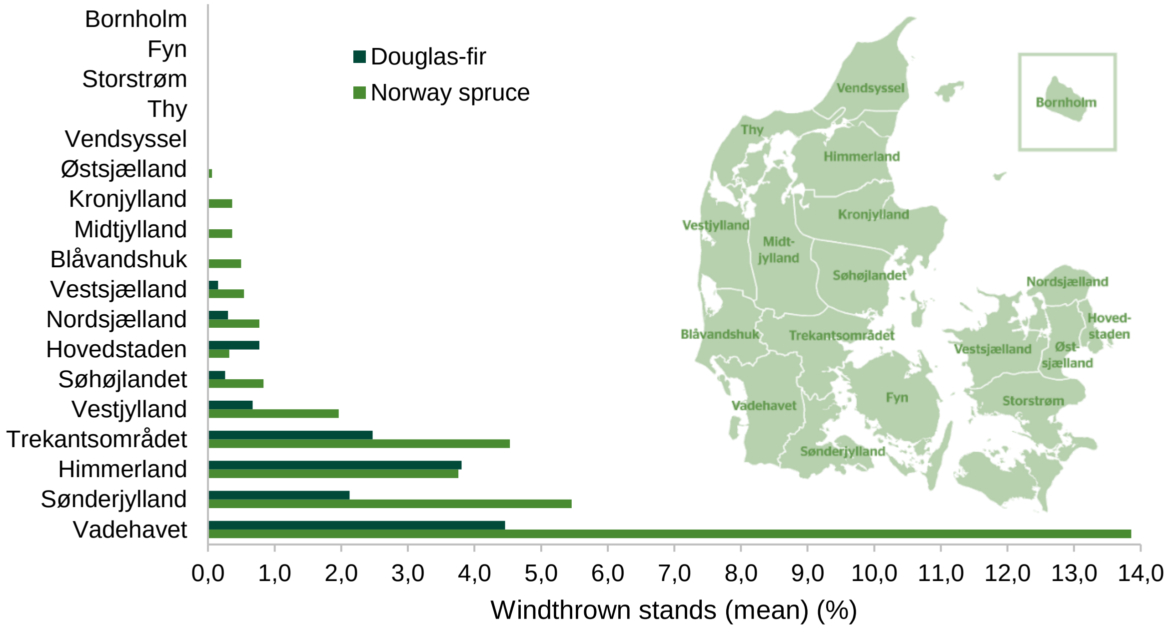
Appendix 6. Graphically presentation of data (mean frequencies of classes)

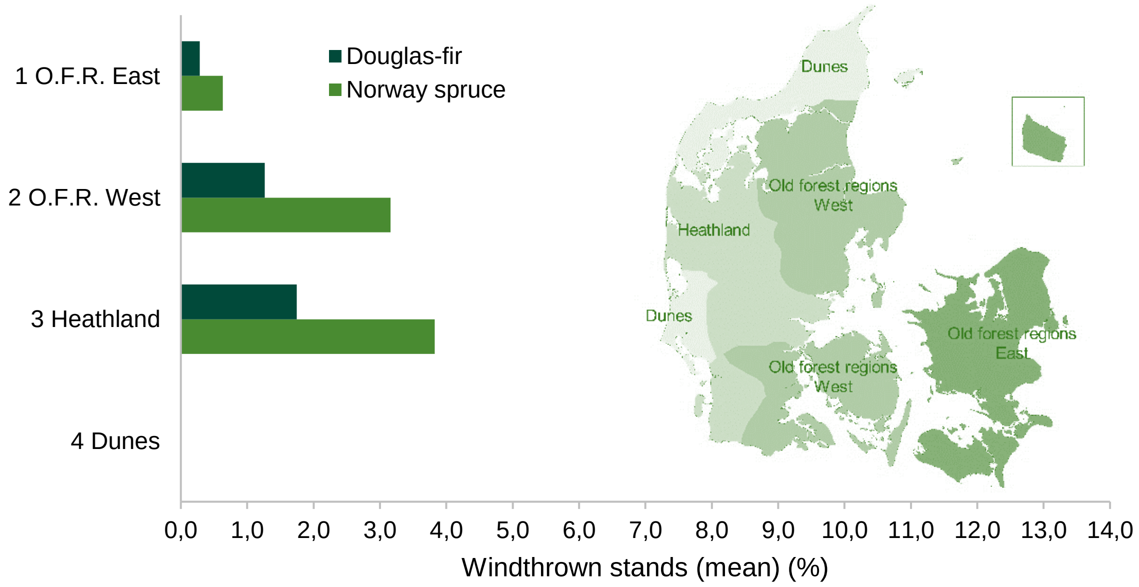












Districts map gathered from Naturstyrelsen (2018), Regions map based on map and tables from Skov og Naturstyrelsen (2005).

Appendix 7. Model outputs

A7 1. Model A DGR

```
                    The LOGISTIC Procedure
                      Model Information

          Data Set                    THESIS.DGR

          Response Variable           W                   W

          Number of Response Levels   2

          Model                       binary logit

          Optimization Technique      Fisher's scoring


              Number of Observations Read   7751

              Number of Observations Used   7751


                      Response Profile

                   Ordered   W         Total
                     Value         Frequency

                         1   0          7667

                         2   1            84


              Probability modelled is W=1.


                  Class Level Information

           Class   Value                Design Variables

           SOIL2   Finsandet jord        0    0    0    0    0

                   Grovsandet jord       1    0    0    0    0

                   Humusjord             0    1    0    0    0

                   Lerblandet sandjord   0    0    1    0    0

                   Lerjord               0    0    0    1    0

                   Sandblandet lerjord   0    0    0    0    1


                 Model Convergence Status

           Convergence criterion (GCONV=1E-8) satisfied.


                   Model Fit Statistics

              Criterion   Intercept Only   Intercept and
                                              Covariates

              AIC                929.246         708.316

              SC                 936.202         777.871

              -2 Log L           927.246         688.316


            Testing Global Null Hypothesis: BETA=0

           Test               Chi-Square   DF   Pr > ChiSq

           Likelihood Ratio     238.9304    9       <.0001
```

```
                 Testing Global Null Hypothesis: BETA=0

           Test          Chi-Square    DF    Pr > ChiSq

           Score           258.5182     9        <.0001

           Wald            183.9887     9        <.0001


                    Type 3 Analysis of Effects

              Effect        DF          Wald    Pr > ChiSq
                                  Chi-Square

              MWIND          1        0.0748        0.7844

              MWIND2         1        0.6060        0.4363

              D              1       32.9266        <.0001

              D2             1       13.3162        0.0003

              SOIL2          5       37.5099        <.0001


              Analysis of Maximum Likelihood Estimates

Parameter                           DF    Estimate    Standard          Wald    Pr > ChiSq
                                                         Error    Chi-Square

Intercept                            1    -10.0505     14.2238        0.4993        0.4798

MWIND                                1     -0.2029      0.7415        0.0748        0.7844

MWIND2                               1     0.00750     0.00963        0.6060        0.4363

D                                    1      0.1616      0.0282       32.9266        <.0001

D2                                   1    -0.00151    0.000415       13.3162        0.0003

SOIL2     Grovsandet jord            1     -0.3844      0.3421        1.2628        0.2611

SOIL2     Humusjord                  1     0.00480      0.4285        0.0001        0.9911

SOIL2     Lerblandet sandjord        1     -2.2266      0.5902       14.2337        0.0002

SOIL2     Lerjord                    1     -2.6466      1.0646        6.1802        0.0129

SOIL2     Sandblandet lerjord        1     -2.1665      0.5211       17.2857        <.0001


                          Odds Ratio Estimates

  Effect                                          Point Estimate        95% Wald
                                                                   Confidence Limits

  MWIND                                                    0.816      0.191     3.492

  MWIND2                                                   1.008      0.989     1.027

  D                                                        1.175      1.112     1.242

  D2                                                       0.998      0.998     0.999

  SOIL2 Grovsandet jord vs Finsandet jord                  0.681      0.348     1.331

  SOIL2 Humusjord vs Finsandet jord                        1.005      0.434     2.327

  SOIL2 Lerblandet sandjord vs Finsandet jord              0.108      0.034     0.343

  SOIL2 Lerjord vs Finsandet jord                          0.071      0.009     0.571

  SOIL2 Sandblandet lerjord vs Finsandet jord              0.115      0.041     0.318
```

```
     Association of Predicted Probabilities and
                 Observed Responses

Percent Concordant        90.1  Somers' D  0.802
Percent Discordant         9.9  Gamma      0.802
Percent Tied               0.0  Tau-a      0.017
Pairs                   644028  c          0.901

        Partition for the Hosmer and Lemeshow Test

Group  Total        W = 1                 W = 0
               Observed  Expected  Observed  Expected
    1    781          0      0.08       781    780.92
    2    773          0      0.24       773    772.76
    3    775          1      0.63       774    774.37
    4    775          0      0.86       775    774.14
    5    776          2      1.11       774    774.89
    6    776          1      2.17       775    773.83
    7    775          4      3.93       771    771.07
    8    777          6      5.81       771    771.19
    9    773         14     13.70       759    759.30
   10    770         56     55.47       714    714.53

          Hosmer and Lemeshow Goodness-of-Fit
                         Test

           Chi-Square    DF     Pr > ChiSq
               2.7767     8         0.9476
```

A7 2. Model B DGR

```
                    The LOGISTIC Procedure
                      Model Information

      Data Set                      THESIS.DGR

      Response Variable             W                W

      Number of Response Levels     2

      Model                         binary logit

      Optimization Technique        Fisher's scoring


           Number of Observations Read   7751

           Number of Observations Used   7751


                      Response Profile

                  Ordered   W       Total
                    Value       Frequency

                        1   0        7667

                        2   1          84


                Probability modelled is W=1.


                   Class Level Information

        Class   Value                 Design Variables

        SOIL2   Finsandet jord         0   0   0   0   0

                Grovsandet jord        1   0   0   0   0

                Humusjord              0   1   0   0   0

                Lerblandet sandjord    0   0   1   0   0

                Lerjord                0   0   0   1   0

                Sandblandet lerjord    0   0   0   0   1


                 Model Convergence Status

        Convergence criterion (GCONV=1E-8) satisfied.


                   Model Fit Statistics

           Criterion   Intercept Only   Intercept and
                                           Covariates

           AIC                929.246         688.008

           SC                 936.202         757.564

           -2 Log L           927.246         668.008


          Testing Global Null Hypothesis: BETA=0

        Test               Chi-Square   DF   Pr > ChiSq

        Likelihood Ratio     259.2379    9       <.0001
```

```
               Testing Global Null Hypothesis: BETA=0

               Test             Chi-Square   DF   Pr > ChiSq

               Score              259.4594    9       <.0001

               Wald               174.5596    9       <.0001


                     Type 3 Analysis of Effects

                  Effect      DF         Wald   Pr > ChiSq
                                   Chi-Square

                  MWIND        1       0.1431       0.7052

                  MWIND2       1       0.8336       0.3612

                  H            1      23.9080       <.0001

                  H2           1      14.3606       0.0002

                  SOIL2        5      36.8678       <.0001


              Analysis of Maximum Likelihood Estimates

Parameter                     DF   Estimate   Standard         Wald   Pr > ChiSq
                                                 Error   Chi-Square

Intercept                      1   -11.5943    13.8964       0.6961       0.4041

MWIND                          1    -0.2737     0.7235       0.1431       0.7052

MWIND2                         1    0.00859    0.00941       0.8336       0.3612

H                              1     0.4764     0.0974      23.9080       <.0001

H2                             1   -0.00848    0.00224      14.3606       0.0002

SOIL2     Grovsandet jord      1    -0.3106     0.3436       0.8173       0.3660

SOIL2     Humusjord            1     0.0726     0.4287       0.0287       0.8655

SOIL2     Lerblandet sandjord  1    -2.1835     0.5895      13.7185       0.0002

SOIL2     Lerjord              1    -2.6601     1.0650       6.2380       0.0125

SOIL2     Sandblandet lerjord  1    -2.0451     0.5183      15.5671       <.0001


                        Odds Ratio Estimates

 Effect                                        Point Estimate      95% Wald
                                                              Confidence Limits

 MWIND                                                  0.761     0.184     3.140

 MWIND2                                                 1.009     0.990     1.027

 H                                                      1.610     1.330     1.949

 H2                                                     0.992     0.987     0.996

 SOIL2 Grovsandet jord vs Finsandet jord                0.733     0.374     1.437

 SOIL2 Humusjord vs Finsandet jord                      1.075     0.464     2.491

 SOIL2 Lerblandet sandjord vs Finsandet jord            0.113     0.035     0.358

 SOIL2 Lerjord vs Finsandet jord                        0.070     0.009     0.564

 SOIL2 Sandblandet lerjord vs Finsandet jord            0.129     0.047     0.357
```

Association of Predicted Probabilities and Observed Responses

Percent Concordant	91.2	Somers' D	0.824
Percent Discordant	8.8	Gamma	0.824
Percent Tied	0.0	Tau-a	0.018
Pairs	644028	c	0.912

Partition for the Hosmer and Lemeshow Test

Group	Total	W = 1		W = 0	
		Observed	Expected	Observed	Expected
1	780	0	0.02	780	779.98
2	767	0	0.07	767	766.93
3	776	0	0.21	776	775.79
4	771	0	0.56	771	770.44
5	782	4	0.82	778	781.18
6	777	0	1.73	777	775.27
7	776	2	3.53	774	772.47
8	776	5	4.98	771	771.02
9	777	17	15.35	760	761.65
10	769	56	56.74	713	712.26

Hosmer and Lemeshow Goodness-of-Fit Test

Chi-Square	DF	Pr > ChiSq
15.9014	8	0.0438

A7 3. Model C DGR

```
                         The LOGISTIC Procedure
                           Model Information

            Data Set                      THESIS.DGR

            Response Variable             W                W

            Number of Response Levels     2

            Model                         binary logit

            Optimization Technique        Fisher's scoring

                Number of Observations Read   7751

                Number of Observations Used   7751

                            Response Profile

                          Ordered  W        Total
                            Value       Frequency

                                1  0         7667

                                2  1           84

                     Probability modelled is W=1.

                        Class Level Information

Class       Value                           Design Variables

DISTRICT    Aalborg          0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0

            Blåvandshuk      1  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0

            Bornholm         0  1  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0

            Fyn              0  0  1  0  0  0  0  0  0  0  0  0  0  0  0  0  0

            Hovedstaden      0  0  0  1  0  0  0  0  0  0  0  0  0  0  0  0  0

            Kronjylland      0  0  0  0  1  0  0  0  0  0  0  0  0  0  0  0  0

            Midtjylland      0  0  0  0  0  1  0  0  0  0  0  0  0  0  0  0  0

            Nordsjælland     0  0  0  0  0  0  1  0  0  0  0  0  0  0  0  0  0

            Ribe             0  0  0  0  0  0  0  1  0  0  0  0  0  0  0  0  0

            Storstrøm        0  0  0  0  0  0  0  0  1  0  0  0  0  0  0  0  0

            Søhøjlandet      0  0  0  0  0  0  0  0  0  1  0  0  0  0  0  0  0

            Sønderjylland    0  0  0  0  0  0  0  0  0  0  1  0  0  0  0  0  0

            Thy              0  0  0  0  0  0  0  0  0  0  0  1  0  0  0  0  0

            Trekantsområdet  0  0  0  0  0  0  0  0  0  0  0  0  1  0  0  0  0

            Vendsyssel       0  0  0  0  0  0  0  0  0  0  0  0  0  1  0  0  0

            Vestjylland      0  0  0  0  0  0  0  0  0  0  0  0  0  0  1  0  0

            Vestsjælland     0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  1  0

            Østsjælland      0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  1
```

```
                              Model Convergence Status

                    Quasi-complete separation of data points detected.


                   Warning: The maximum likelihood estimate may not exist.


Warning: The LOGISTIC procedure continues in spite of the above warning. Results shown are based on the last
         maximum likelihood iteration. Validity of the model fit is questionable.
                                Model Fit Statistics

                        Criterion  Intercept Only  Intercept and
                                                     Covariates

                        AIC               929.246        690.845

                        SC                936.202        850.823

                        -2 Log L          927.246        644.845


                      Testing Global Null Hypothesis: BETA=0

                     Test              Chi-Square   DF   Pr > ChiSq

                     Likelihood Ratio    282.4011   22       <.0001

                     Score               289.8534   22       <.0001

                     Wald                113.2245   22       <.0001


                            Type 3 Analysis of Effects

                        Effect       DF         Wald   Pr > ChiSq
                                          Chi-Square

                        DISTRICT     17      66.6685       <.0001

                        LNRWIND       1       1.2854       0.2569

                        H             1      26.8272       <.0001

                        H2            1      22.5952       <.0001

                        HD            1       1.8854       0.1697

                        HD2           1       1.6689       0.1964


                      Analysis of Maximum Likelihood Estimates

    Parameter                    DF   Estimate   Standard         Wald   Pr > ChiSq
                                                    Error   Chi-Square

    Intercept                     1    -1.4722     4.8901       0.0906       0.7634

    DISTRICT   Blåvandshuk        1   -14.4437      929.8       0.0002       0.9876

    DISTRICT   Bornholm           1   -15.1524      568.6       0.0007       0.9787

    DISTRICT   Fyn                1   -14.6942     1011.8       0.0002       0.9884

    DISTRICT   Hovedstaden        1    -1.9744     1.0694       3.4087       0.0649

    DISTRICT   Kronjylland        1   -14.6954      328.0       0.0020       0.9643

    DISTRICT   Midtjylland        1   -14.5904      227.5       0.0041       0.9489

    DISTRICT   Nordsjælland       1    -2.8794     0.7864      13.4079       0.0003

    DISTRICT   Ribe               1     1.1094     0.3937       7.9397       0.0048

    DISTRICT   Storstrøm          1   -14.7346     1564.6       0.0001       0.9925
```

Analysis of Maximum Likelihood Estimates

Parameter		DF	Estimate	Standard Error	Wald Chi-Square	Pr > ChiSq
DISTRICT	Søhøjlandet	1	-2.7689	0.7831	12.5032	0.0004
DISTRICT	Sønderjylland	1	-0.0827	0.4065	0.0414	0.8388
DISTRICT	Thy	1	-13.8296	564.3	0.0006	0.9804
DISTRICT	Trekantsområdet	1	0.0654	0.4351	0.0226	0.8805
DISTRICT	Vendsyssel	1	-13.3116	934.6	0.0002	0.9886
DISTRICT	Vestjylland	1	-0.5203	0.8244	0.3983	0.5280
DISTRICT	Vestsjælland	1	-3.2767	1.0525	9.6925	0.0019
DISTRICT	Østsjælland	1	-14.5904	479.2	0.0009	0.9757
LNRWIND		1	-2.9416	2.5946	1.2854	0.2569
H		1	0.5789	0.1118	26.8272	<.0001
H2		1	-0.0120	0.00253	22.5952	<.0001
HD		1	-0.0753	0.0549	1.8854	0.1697
HD2		1	0.000466	0.000360	1.6689	0.1964

Odds Ratio Estimates

Effect	Point Estimate	95% Wald Confidence Limits	
DISTRICT Blåvandshuk vs Aalborg	<0.001	<0.001	>999.999
DISTRICT Bornholm vs Aalborg	<0.001	<0.001	>999.999
DISTRICT Fyn vs Aalborg	<0.001	<0.001	>999.999
DISTRICT Hovedstaden vs Aalborg	0.139	0.017	1.129
DISTRICT Kronjylland vs Aalborg	<0.001	<0.001	>999.999
DISTRICT Midtjylland vs Aalborg	<0.001	<0.001	>999.999
DISTRICT Nordsjælland vs Aalborg	0.056	0.012	0.262
DISTRICT Ribe vs Aalborg	3.033	1.402	6.560
DISTRICT Storstrøm vs Aalborg	<0.001	<0.001	>999.999
DISTRICT Søhøjlandet vs Aalborg	0.063	0.014	0.291
DISTRICT Sønderjylland vs Aalborg	0.921	0.415	2.042
DISTRICT Thy vs Aalborg	<0.001	<0.001	>999.999
DISTRICT Trekantsområdet vs Aalborg	1.068	0.455	2.505
DISTRICT Vendsyssel vs Aalborg	<0.001	<0.001	>999.999
DISTRICT Vestjylland vs Aalborg	0.594	0.118	2.991
DISTRICT Vestsjælland vs Aalborg	0.038	0.005	0.297
DISTRICT Østsjælland vs Aalborg	<0.001	<0.001	>999.999
LNRWIND	0.053	<0.001	8.531
H	1.784	1.433	2.221
H2	0.988	0.983	0.993

```
                          Odds Ratio Estimates

Effect                                Point Estimate       95% Wald
                                                       Confidence Limits

HD                                             0.927     0.833      1.033

HD2                                            1.000     1.000      1.001


                 Association of Predicted Probabilities and
                             Observed Responses

            Percent Concordant       93.4   Somers' D   0.868

            Percent Discordant        6.6   Gamma       0.868

            Percent Tied              0.0   Tau-a       0.019

            Pairs                  644028   c           0.934


                 Partition for the Hosmer and Lemeshow Test

          Group   Total          W = 1                  W = 0

                          Observed   Expected   Observed   Expected

              1    2812          0       0.00       2812    2812.00

              2     780          1       0.19        779     779.81

              3     780          1       0.69        779     779.31

              4     776          0       1.56        776     774.44

              5     777          2       2.51        775     774.49

              6     775          7       5.94        768     769.06

              7    1051         73      73.10        978     977.90


                 Hosmer and Lemeshow Goodness-of-Fit
                                 Test

                    Chi-Square     DF        Pr > ChiSq

                        5.4640      5            0.3619
```

Note: In calculating the Expected values, predicted probabilities less than 1E-6 and greater than 0.999999 were changed to 1E-6 and 0.999999 respectively.

A7 4. Model D DGR

The LOGISTIC Procedure

Model Information

Data Set	THESIS.DGR	
Response Variable	W	W
Number of Response Levels	2	
Model	binary logit	
Optimization Technique	Fisher's scoring	

Number of Observations Read	7751
Number of Observations Used	7751

Response Profile

Ordered Value	W	Total Frequency
1	0	7667
2	1	84

Probability modelled is W=1.

Class Level Information

Class	Value	Design Variables																
DISTRICT	Aalborg	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Blåvandshuk	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Bornholm	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Fyn	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Hovedstaden	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
	Kronjylland	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
	Midtjylland	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
	Nordsjælland	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
	Ribe	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
	Storstrøm	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
	Søhøjlandet	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
	Sønderjylland	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
	Thy	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
	Trekantsområdet	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
	Vendsyssel	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
	Vestjylland	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
	Vestsjælland	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
	Østsjælland	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
SOIL2	Finsandet jord	0	0	0	0	0												

```
                              Class Level Information

   Class      Value                                     Design Variables

              Grovsandet jord       1  0  0  0  0

              Humusjord             0  1  0  0  0

              Lerblandet sandjord   0  0  1  0  0

              Lerjord               0  0  0  1  0

              Sandblandet lerjord   0  0  0  0  1

                              Model Convergence Status

                  Quasi-complete separation of data points detected.

              Warning: The maximum likelihood estimate may not exist.

Warning: The LOGISTIC procedure continues despite the above warning. Results shown are based on the last
         maximum likelihood iteration. Validity of the model fit is questionable.
                                Model Fit Statistics

                         Criterion  Intercept Only  Intercept and
                                                       Covariates

                         AIC               929.246        649.169

                         SC                936.202        857.836

                         -2 Log L          927.246        589.169

                        Testing Global Null Hypothesis: BETA=0

                      Test              Chi-Square  DF   Pr > ChiSq

                      Likelihood Ratio    338.0771  29       <.0001

                      Score               343.5554  29       <.0001

                      Wald                140.5620  29       <.0001

                              Type 3 Analysis of Effects

                        Effect      DF        Wald  Pr > ChiSq
                                        Chi-Square

                        SOIL2        5     39.3904      <.0001

                        DISTRICT    17     54.1600      <.0001

                        LNRWIND      1      2.6097      0.1062

                        HD           1      9.5042      0.0020

                        HD2          1      8.9654      0.0028

                        H            1     29.8037      <.0001

                        H2           1     23.7151      <.0001

                        VHA          1      0.0337      0.8544

                        VHA2         1      1.0310      0.3099
```

Analysis of Maximum Likelihood Estimates

Parameter		DF	Estimate	Standard Error	Wald Chi-Square	Pr > ChiSq
Intercept		1	8.9512	8.4180	1.1307	0.2876
SOIL2	Grovsandet jord	1	-1.3353	1.4519	0.8459	0.3577
SOIL2	Humusjord	1	-2.7394	1.4706	3.4699	0.0625
SOIL2	Lerblandet sandjord	1	-4.2302	1.5776	7.1904	0.0073
SOIL2	Lerjord	1	-3.0418	1.6924	3.2304	0.0723
SOIL2	Sandblandet lerjord	1	-2.9130	1.4314	4.1414	0.0418
DISTRICT	Blåvandshuk	1	-13.5740	743.7	0.0003	0.9854
DISTRICT	Bornholm	1	-12.0431	560.6	0.0005	0.9829
DISTRICT	Fyn	1	-10.3652	971.1	0.0001	0.9915
DISTRICT	Hovedstaden	1	1.0252	1.6770	0.3737	0.5410
DISTRICT	Kronjylland	1	-12.8001	274.7	0.0022	0.9628
DISTRICT	Midtjylland	1	-13.3043	199.7	0.0044	0.9469
DISTRICT	Nordsjælland	1	0.4688	1.3359	0.1232	0.7256
DISTRICT	Ribe	1	3.9142	1.6740	5.4671	0.0194
DISTRICT	Storstrøm	1	-11.5645	1590.3	0.0001	0.9942
DISTRICT	Søhøjlandet	1	-1.2154	1.5703	0.5991	0.4389
DISTRICT	Sønderjylland	1	2.0274	1.5017	1.8227	0.1770
DISTRICT	Thy	1	-12.6339	461.0	0.0008	0.9781
DISTRICT	Trekantsområdet	1	2.1560	1.5301	1.9855	0.1588
DISTRICT	Vendsyssel	1	-12.0292	809.7	0.0002	0.9881
DISTRICT	Vestjylland	1	1.2052	1.8475	0.4256	0.5142
DISTRICT	Vestsjælland	1	-0.9625	1.6282	0.3495	0.5544
DISTRICT	Østsjælland	1	-11.2984	512.1	0.0005	0.9824
LNRWIND		1	-7.5446	4.6702	2.6097	0.1062
HD		1	-0.1477	0.0479	9.5042	0.0020
HD2		1	0.000883	0.000295	8.9654	0.0028
H		1	0.6040	0.1106	29.8037	<.0001
H2		1	-0.0124	0.00254	23.7151	<.0001
VHA		1	-0.00036	0.00195	0.0337	0.8544
VHA2		1	3.533E-6	3.48E-6	1.0310	0.3099

Odds Ratio Estimates

Effect	Point Estimate	95% Wald Confidence Limits	
SOIL2 Grovsandet jord vs Finsandet jord	0.263	0.015	4.528

Odds Ratio Estimates

Effect	Point Estimate	95% Wald Confidence Limits	
SOIL2 Humusjord vs Finsandet jord	0.065	0.004	1.154
SOIL2 Lerblandet sandjord vs Finsandet jord	0.015	<0.001	0.320
SOIL2 Lerjord vs Finsandet jord	0.048	0.002	1.317
SOIL2 Sandblandet lerjord vs Finsandet jord	0.054	0.003	0.898
DISTRICT Blåvandshuk vs Aalborg	<0.001	<0.001	>999.999
DISTRICT Bornholm vs Aalborg	<0.001	<0.001	>999.999
DISTRICT Fyn vs Aalborg	<0.001	<0.001	>999.999
DISTRICT Hovedstaden vs Aalborg	2.788	0.104	74.592
DISTRICT Kronjylland vs Aalborg	<0.001	<0.001	>999.999
DISTRICT Midtjylland vs Aalborg	<0.001	<0.001	>999.999
DISTRICT Nordsjælland vs Aalborg	1.598	0.117	21.913
DISTRICT Ribe vs Aalborg	50.108	1.884	>999.999
DISTRICT Storstrøm vs Aalborg	<0.001	<0.001	>999.999
DISTRICT Søhøjlandet vs Aalborg	0.297	0.014	6.438
DISTRICT Sønderjylland vs Aalborg	7.594	0.400	144.128
DISTRICT Thy vs Aalborg	<0.001	<0.001	>999.999
DISTRICT Trekantsområdet vs Aalborg	8.637	0.430	173.286
DISTRICT Vendsyssel vs Aalborg	<0.001	<0.001	>999.999
DISTRICT Vestjylland vs Aalborg	3.338	0.089	124.735
DISTRICT Vestsjælland vs Aalborg	0.382	0.016	9.287
DISTRICT Østsjælland vs Aalborg	<0.001	<0.001	>999.999
LNRWIND	<0.001	<0.001	4.998
HD	0.863	0.785	0.948
HD2	1.001	1.000	1.001
H	1.829	1.473	2.272
H2	0.988	0.983	0.993
VHA	1.000	0.996	1.003
VHA2	1.000	1.000	1.000

Association of Predicted Probabilities and Observed Responses

Percent Concordant	94.6	Somers' D	0.892
Percent Discordant	5.4	Gamma	0.892
Percent Tied	0.0	Tau-a	0.019
Pairs	644028	c	0.946

Partition for the Hosmer and Lemeshow Test

Group	Total	W = 1		W = 0	
		Observed	Expected	Observed	Expected
1	2829	0	0.00	2829	2829.00
2	775	0	0.07	775	774.93
3	759	1	0.33	758	758.67
4	776	0	0.75	776	775.25
5	775	0	1.64	775	773.36
6	777	11	5.05	766	771.95
7	1060	72	76.15	988	983.85

Hosmer and Lemeshow Goodness-of-Fit Test

Chi-Square	DF	Pr > ChiSq
11.1302	5	0.0489

Note: In calculating the Expected values, predicted probabilities less than 1E-6 and greater than 0.999999 were changed to 1E-6 and 0.999999 respectively.

A7 5. Model A RGR

```
                    The LOGISTIC Procedure
                      Model Information

          Data Set                     THESIS.RGR
          Response Variable            W                W
          Number of Response Levels    2
          Model                        binary logit
          Optimization Technique       Fisher's scoring

              Number of Observations Read   40313
              Number of Observations Used   40313

                      Response Profile

                    Ordered  W       Total
                      Value      Frequency

                          1  0       39372
                          2  1         941

                Probability modelled is W=1.

                   Class Level Information

       Class   Value                          Design Variables

       SOIL2   Finsandet jord                 0  0  0  0  0  0  0
               Grovsandet jord                1  0  0  0  0  0  0
               Humusjord                      0  1  0  0  0  0  0
               Lerblandet sandjord            0  0  1  0  0  0  0
               Lerjord                        0  0  0  1  0  0  0
               Sandblandet lerjord            0  0  0  0  1  0  0
               Speciel jordtype/kalkrig jord  0  0  0  0  0  1  0
               Svær lerjord                   0  0  0  0  0  0  1

                  Model Convergence Status

          Convergence criterion (GCONV=1E-8) satisfied.

                    Model Fit Statistics

            Criterion  Intercept Only  Intercept and
                                          Covariates

            AIC              8933.451       7166.914
            SC               8942.055       7252.958
            -2 Log L         8931.451       7146.914
```

Testing Global Null Hypothesis: BETA=0

Test	Chi-Square	DF	Pr > ChiSq
Likelihood Ratio	1784.5373	9	<.0001
Score	1694.9783	9	<.0001
Wald	1320.2113	9	<.0001

Type 3 Analysis of Effects

Effect	DF	Wald Chi-Square	Pr > ChiSq
MWIND	1	779.7667	<.0001
LND	1	281.4689	<.0001
SOIL2	7	211.2447	<.0001

Analysis of Maximum Likelihood Estimates

Parameter		DF	Estimate	Standard Error	Wald Chi-Square	Pr > ChiSq
Intercept		1	-20.0694	0.5571	1297.6735	<.0001
MWIND		1	0.3259	0.0117	779.7667	<.0001
LND		1	1.5087	0.0899	281.4689	<.0001
SOIL2	Grovsandet jord	1	-0.3493	0.1358	6.6189	0.0101
SOIL2	Humusjord	1	0.0356	0.1656	0.0462	0.8298
SOIL2	Lerblandet sandjord	1	-1.4167	0.1729	67.1336	<.0001
SOIL2	Lerjord	1	-1.2668	0.2795	20.5491	<.0001
SOIL2	Sandblandet lerjord	1	-1.9123	0.1945	96.6405	<.0001
SOIL2	Speciel jordtype/kalkrig jord	1	-10.7474	691.2	0.0002	0.9876
SOIL2	Svær lerjord	1	-11.7778	211.1	0.0031	0.9555

Odds Ratio Estimates

Effect	Point Estimate	95% Wald Confidence Limits	
MWIND	1.385	1.354	1.417
LND	4.521	3.790	5.392
SOIL2 Grovsandet jord vs Finsandet jord	0.705	0.540	0.920
SOIL2 Humusjord vs Finsandet jord	1.036	0.749	1.433
SOIL2 Lerblandet sandjord vs Finsandet jord	0.243	0.173	0.340
SOIL2 Lerjord vs Finsandet jord	0.282	0.163	0.487
SOIL2 Sandblandet lerjord vs Finsandet jord	0.148	0.101	0.216
SOIL2 Speciel jordtype/kalkrig jord vs Finsandet jord	<0.001	<0.001	>999.999
SOIL2 Svær lerjord vs Finsandet jord	<0.001	<0.001	>999.999

```
Association of Predicted Probabilities and Observed
                    Responses

Percent Concordant         84.5   Somers' D   0.690

Percent Discordant         15.5   Gamma       0.691

Percent Tied                0.0   Tau-a       0.031

Pairs                  37049052   c           0.845

        Partition for the Hosmer and Lemeshow Test

Group   Total          W = 1                  W = 0

               Observed   Expected   Observed   Expected

    1   4034          1       1.98       4033    4032.02

    2   4027         27       5.65       4000    4021.35

    3   4027         15      10.16       4012    4016.84

    4   4025         40      15.68       3985    4009.32

    5   4030         25      24.55       4005    4005.45

    6   4028         21      40.31       4007    3987.69

    7   4020         33      64.05       3987    3955.95

    8   4025         63     101.96       3962    3923.04

    9   4030        144     164.14       3886    3865.86

   10   4067        572     512.54       3495    3554.46

         Hosmer and Lemeshow Goodness-of-Fit
                        Test

            Chi-Square     DF       Pr > ChiSq

              171.8797      8           <.0001
```

A7 6. Model B RGR

The LOGISTIC Procedure

Model Information

Data Set	THESIS.RGR	
Response Variable	W	W
Number of Response Levels	2	
Model	binary logit	
Optimization Technique	Fisher's scoring	

Number of Observations Read	40313
Number of Observations Used	40313

Response Profile

Ordered Value	W	Total Frequency
1	0	39372
2	1	941

Probability modelled is W=1.

Class Level Information

Class	Value	Design Variables						
SOIL2	Finsandet jord	0	0	0	0	0	0	0
	Grovsandet jord	1	0	0	0	0	0	0
	Humusjord	0	1	0	0	0	0	0
	Lerblandet sandjord	0	0	1	0	0	0	0
	Lerjord	0	0	0	1	0	0	0
	Sandblandet lerjord	0	0	0	0	1	0	0
	Speciel jordtype/kalkrig jord	0	0	0	0	0	1	0
	Svær lerjord	0	0	0	0	0	0	1

Model Convergence Status

Convergence criterion (GCONV=1E-8) satisfied.

Model Fit Statistics

Criterion	Intercept Only	Intercept and Covariates
AIC	8933.451	7087.842
SC	8942.055	7182.491
-2 Log L	8931.451	7065.842

```
               Testing Global Null Hypothesis: BETA=0

               Test              Chi-Square    DF    Pr > ChiSq

               Likelihood Ratio   1865.6085    10        <.0001

               Score              1735.1420    10        <.0001

               Wald               1285.4039    10        <.0001

                     Type 3 Analysis of Effects

                  Effect      DF          Wald   Pr > ChiSq
                                    Chi-Square

                  MWIND        1      779.6322       <.0001

                  H            1      112.6737       <.0001

                  H2           1       69.8004       <.0001

                  SOIL2        7      180.6350       <.0001

               Analysis of Maximum Likelihood Estimates

Parameter                              DF   Estimate   Standard         Wald   Pr > ChiSq
                                                          Error   Chi-Square

Intercept                               1   -20.5194     0.6140    1116.9184       <.0001

MWIND                                   1     0.3303     0.0118     779.6322       <.0001

H                                       1     0.4533     0.0427     112.6737       <.0001

H2                                      1   -0.00952    0.00114      69.8004       <.0001

SOIL2   Grovsandet jord                 1    -0.2966     0.1368       4.7021       0.0301

SOIL2   Humusjord                       1     0.0894     0.1663       0.2890       0.5909

SOIL2   Lerblandet sandjord             1    -1.2319     0.1727      50.8875       <.0001

SOIL2   Lerjord                         1    -1.1450     0.2789      16.8597       <.0001

SOIL2   Sandblandet lerjord             1    -1.7615     0.1944      82.0969       <.0001

SOIL2   Speciel jordtype/kalkrig jord   1   -10.9512      691.6       0.0003       0.9874

SOIL2   Svær lerjord                    1   -11.8586      211.0       0.0032       0.9552

                          Odds Ratio Estimates

 Effect                                                Point Estimate        95% Wald
                                                                         Confidence Limits

 MWIND                                                          1.391     1.359      1.424

 H                                                              1.574     1.447      1.711

 H2                                                             0.991     0.988      0.993

 SOIL2 Grovsandet jord vs Finsandet jord                        0.743     0.569      0.972

 SOIL2 Humusjord vs Finsandet jord                              1.094     0.789      1.515

 SOIL2 Lerblandet sandjord vs Finsandet jord                    0.292     0.208      0.409

 SOIL2 Lerjord vs Finsandet jord                                0.318     0.184      0.550

 SOIL2 Sandblandet lerjord vs Finsandet jord                    0.172     0.117      0.251

 SOIL2 Speciel jordtype/kalkrig jord vs Finsandet jord         <0.001    <0.001   >999.999

 SOIL2 Svær lerjord vs Finsandet jord                          <0.001    <0.001   >999.999
```

Association of Predicted Probabilities and Observed Responses

Percent Concordant	85.0	Somers' D	0.700
Percent Discordant	15.0	Gamma	0.701
Percent Tied	0.0	Tau-a	0.032
Pairs	37049052	c	0.850

Partition for the Hosmer and Lemeshow Test

Group	Total	W = 1		W = 0	
		Observed	Expected	Observed	Expected
1	4037	0	1.04	4037	4035.96
2	4016	13	4.32	4003	4011.68
3	4030	30	8.35	4000	4021.65
4	4025	46	13.29	3979	4011.71
5	4026	19	20.89	4007	4005.11
6	4030	23	35.75	4007	3994.25
7	4036	28	59.73	4008	3976.27
8	4032	55	111.74	3977	3920.26
9	4029	131	174.43	3898	3854.57
10	4052	596	511.46	3456	3540.54

Hosmer and Lemeshow Goodness-of-Fit Test

Chi-Square	DF	Pr > ChiSq
234.2915	8	<.0001

A7 7. Model C RGR

```
                        The LOGISTIC Procedure
                          Model Information

          Data Set                       THESIS.RGR
          Response Variable              W                  W
          Number of Response Levels      2
          Model                          binary logit
          Optimization Technique         Fisher's scoring

              Number of Observations Read    40313
              Number of Observations Used    40313

                          Response Profile

                       Ordered   W         Total
                         Value        Frequency
                             1   0        39372
                             2   1          941

                   Probability modelled is W=1.

                       Class Level Information

Class      Value                         Design Variables
DISTRICT   Aalborg           0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
           Blåvandshuk       1  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
           Bornholm          0  1  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
           Fyn               0  0  1  0  0  0  0  0  0  0  0  0  0  0  0  0  0
           Hovedstaden       0  0  0  1  0  0  0  0  0  0  0  0  0  0  0  0  0
           Kronjylland       0  0  0  0  1  0  0  0  0  0  0  0  0  0  0  0  0
           Midtjylland       0  0  0  0  0  1  0  0  0  0  0  0  0  0  0  0  0
           Nordsjælland      0  0  0  0  0  0  1  0  0  0  0  0  0  0  0  0  0
           Ribe              0  0  0  0  0  0  0  1  0  0  0  0  0  0  0  0  0
           Storstrøm         0  0  0  0  0  0  0  0  1  0  0  0  0  0  0  0  0
           Søhøjlandet       0  0  0  0  0  0  0  0  0  1  0  0  0  0  0  0  0
           Sønderjylland     0  0  0  0  0  0  0  0  0  0  1  0  0  0  0  0  0
           Thy               0  0  0  0  0  0  0  0  0  0  0  1  0  0  0  0  0
           Trekantsområdet   0  0  0  0  0  0  0  0  0  0  0  0  1  0  0  0  0
           Vendsyssel        0  0  0  0  0  0  0  0  0  0  0  0  0  1  0  0  0
           Vestjylland       0  0  0  0  0  0  0  0  0  0  0  0  0  0  1  0  0
           Vestsjælland      0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  1  0
           Østsjælland       0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  1
```

```
                       Model Convergence Status

             Convergence criterion (GCONV=1E-8) satisfied.


                         Model Fit Statistics

              Criterion    Intercept Only    Intercept and
                                                Covariates

              AIC               8933.451          6630.060

              SC                8942.055          6836.566

              -2 Log L          8931.451          6582.060


                Testing Global Null Hypothesis: BETA=0

           Test                Chi-Square    DF    Pr > ChiSq

           Likelihood Ratio     2349.3906    23        <.0001

           Score                2994.3621    23        <.0001

           Wald                 1508.7218    23        <.0001


                      Type 3 Analysis of Effects

              Effect        DF          Wald    Pr > ChiSq
                                  Chi-Square

              DISTRICT      17     1145.9601        <.0001

              RWIND          1       44.7429        <.0001

              RWIND2         1       47.2376        <.0001

              H              1      175.8557        <.0001

              H2             1      128.7344        <.0001

              HD             1        1.2177        0.2698

              HD2            1        0.5651        0.4522


                 Analysis of Maximum Likelihood Estimates

Parameter                   DF    Estimate    Standard          Wald    Pr > ChiSq
                                                 Error    Chi-Square

Intercept                    1     10.8023      3.0435       12.5972        0.0004

DISTRICT   Blåvandshuk       1     -1.7576      0.7331        5.7483        0.0165

DISTRICT   Bornholm          1    -15.0538       252.2        0.0036        0.9524

DISTRICT   Fyn               1    -15.0741       716.2        0.0004        0.9832

DISTRICT   Hovedstaden       1     -2.9444      0.7332       16.1244        <.0001

DISTRICT   Kronjylland       1     -2.5005      0.4430       31.8670        <.0001

DISTRICT   Midtjylland       1     -2.3544      0.2589       82.7136        <.0001

DISTRICT   Nordsjælland      1     -1.9389      0.2153       81.0930        <.0001

DISTRICT   Ribe              1      1.9810      0.1837      116.2632        <.0001

DISTRICT   Storstrøm         1    -15.1378      1095.1        0.0002        0.9890

DISTRICT   Søhøjlandet       1     -1.7499      0.3109       31.6809        <.0001

DISTRICT   Sønderjylland     1      0.5583      0.1841        9.1987        0.0024
```

Analysis of Maximum Likelihood Estimates

Parameter		DF	Estimate	Standard Error	Wald Chi-Square	Pr > ChiSq
DISTRICT	Thy	1	-14.5323	313.1	0.0022	0.9630
DISTRICT	Trekantsområdet	1	0.4215	0.2014	4.3793	0.0364
DISTRICT	Vendsyssel	1	-14.8464	623.3	0.0006	0.9810
DISTRICT	Vestjylland	1	-0.2606	0.2320	1.2616	0.2613
DISTRICT	Vestsjælland	1	-1.9370	0.3944	24.1150	<.0001
DISTRICT	Østsjælland	1	-4.3278	1.0159	18.1475	<.0001
RWIND		1	-5.8301	0.8716	44.7429	<.0001
RWIND2		1	0.4377	0.0637	47.2376	<.0001
H		1	0.6140	0.0463	175.8557	<.0001
H2		1	-0.0139	0.00123	128.7344	<.0001
HD		1	-0.0244	0.0221	1.2177	0.2698
HD2		1	0.000101	0.000134	0.5651	0.4522

Odds Ratio Estimates

Effect	Point Estimate	95% Wald Confidence Limits	
DISTRICT Blåvandshuk vs Aalborg	0.172	0.041	0.726
DISTRICT Bornholm vs Aalborg	<0.001	<0.001	>999.999
DISTRICT Fyn vs Aalborg	<0.001	<0.001	>999.999
DISTRICT Hovedstaden vs Aalborg	0.053	0.013	0.222
DISTRICT Kronjylland vs Aalborg	0.082	0.034	0.195
DISTRICT Midtjylland vs Aalborg	0.095	0.057	0.158
DISTRICT Nordsjælland vs Aalborg	0.144	0.094	0.219
DISTRICT Ribe vs Aalborg	7.250	5.058	10.392
DISTRICT Storstrøm vs Aalborg	<0.001	<0.001	>999.999
DISTRICT Søhøjlandet vs Aalborg	0.174	0.094	0.320
DISTRICT Sønderjylland vs Aalborg	1.748	1.218	2.507
DISTRICT Thy vs Aalborg	<0.001	<0.001	>999.999
DISTRICT Trekantsområdet vs Aalborg	1.524	1.027	2.262
DISTRICT Vendsyssel vs Aalborg	<0.001	<0.001	>999.999
DISTRICT Vestjylland vs Aalborg	0.771	0.489	1.214
DISTRICT Vestsjælland vs Aalborg	0.144	0.067	0.312
DISTRICT Østsjælland vs Aalborg	0.013	0.002	0.097
RWIND	0.003	<0.001	0.016
RWIND2	1.549	1.367	1.755
H	1.848	1.687	2.023
H2	0.986	0.984	0.989

Odds Ratio Estimates

Effect	Point Estimate	95% Wald Confidence Limits	
HD	0.976	0.935	1.019
HD2	1.000	1.000	1.000

Association of Predicted Probabilities and Observed Responses

Percent Concordant	88.6	Somers' D	0.772
Percent Discordant	11.4	Gamma	0.773
Percent Tied	0.0	Tau-a	0.035
Pairs	37049052	c	0.886

Partition for the Hosmer and Lemeshow Test

Group	Total	W = 1		W = 0	
		Observed	Expected	Observed	Expected
1	4022	0	0.03	4022	4021.97
2	4031	2	1.06	4029	4029.94
3	4033	10	5.06	4023	4027.94
4	4028	13	13.64	4015	4014.36
5	4031	19	20.88	4012	4010.12
6	4030	34	28.71	3996	4001.29
7	4030	36	38.98	3994	3991.02
8	4032	47	66.00	3985	3966.00
9	4031	174	180.66	3857	3850.34
10	4045	606	585.95	3439	3459.05

Hosmer and Lemeshow Goodness-of-Fit Test

Chi-Square	DF	Pr > ChiSq
13.7115	8	0.0896

A7 8. Model D RGR

```
                              The LOGISTIC Procedure
                                Model Information

              Data Set                     THESIS.RGR
              Response Variable            W                 W
              Number of Response Levels    2
              Model                        binary logit
              Optimization Technique       Fisher's scoring

                    Number of Observations Read   40313
                    Number of Observations Used   40313

                                Response Profile

                           Ordered   W        Total
                             Value        Frequency

                                 1   0        39372
                                 2   1          941

                          Probability modelled is W=1.

                             Class Level Information

Class      Value                                  Design Variables
SOIL2      Finsandet jord                 0  0  0  0  0  0  0
           Grovsandet jord                1  0  0  0  0  0  0
           Humusjord                      0  1  0  0  0  0  0
           Lerblandet sandjord            0  0  1  0  0  0  0
           Lerjord                        0  0  0  1  0  0  0
           Sandblandet lerjord            0  0  0  0  1  0  0
           Speciel jordtype/kalkrig jord  0  0  0  0  0  1  0
           Svær lerjord                   0  0  0  0  0  0  1
DISTRICT   Aalborg                        0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
           Blåvandshuk                    1  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
           Bornholm                       0  1  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
           Fyn                            0  0  1  0  0  0  0  0  0  0  0  0  0  0  0  0  0
           Hovedstaden                    0  0  0  1  0  0  0  0  0  0  0  0  0  0  0  0  0
           Kronjylland                    0  0  0  0  1  0  0  0  0  0  0  0  0  0  0  0  0
           Midtjylland                    0  0  0  0  0  1  0  0  0  0  0  0  0  0  0  0  0
           Nordsjælland                   0  0  0  0  0  0  1  0  0  0  0  0  0  0  0  0  0
           Ribe                           0  0  0  0  0  0  0  1  0  0  0  0  0  0  0  0  0
           Storstrøm                      0  0  0  0  0  0  0  0  1  0  0  0  0  0  0  0  0
           Søhøjlandet                    0  0  0  0  0  0  0  0  0  1  0  0  0  0  0  0  0
```

```
                              Class Level Information

Class      Value                          Design Variables

           Sønderjylland      0  0  0  0  0  0  0  0  0  0  1  0  0  0  0  0  0

           Thy                0  0  0  0  0  0  0  0  0  0  0  1  0  0  0  0  0

           Trekantsområdet    0  0  0  0  0  0  0  0  0  0  0  0  1  0  0  0  0

           Vendsyssel         0  0  0  0  0  0  0  0  0  0  0  0  0  1  0  0  0

           Vestjylland        0  0  0  0  0  0  0  0  0  0  0  0  0  0  1  0  0

           Vestsjælland       0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  1  0

           Østsjælland        0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  1

                              Model Convergence Status

                   Convergence criterion (GCONV=1E-8) satisfied.

                               Model Fit Statistics

                    Criterion   Intercept Only   Intercept and
                                                    Covariates

                    AIC              8933.451        6234.398

                    SC               8942.055        6509.740

                    -2 Log L         8931.451        6170.398

                     Testing Global Null Hypothesis: BETA=0

                 Test               Chi-Square   DF   Pr > ChiSq

                 Likelihood Ratio    2761.0530   31       <.0001

                 Score               3436.4311   31       <.0001

                 Wald                1722.5411   31       <.0001

                           Type 3 Analysis of Effects

                   Effect       DF         Wald   Pr > ChiSq
                                     Chi-Square

                   SOIL2         7     172.7594       <.0001

                   DISTRICT     17    1020.2656       <.0001

                   RWIND         1      22.9172       <.0001

                   RWIND2        1      23.8056       <.0001

                   HD            1       4.2386       0.0395

                   HD2           1       2.2200       0.1362

                   H             1     127.9611       <.0001

                   H2            1      85.3462       <.0001

                   LNVHA         1     116.0179       <.0001
```

```
                         Analysis of Maximum Likelihood Estimates

Parameter                                    DF   Estimate   Standard        Wald   Pr > ChiSq
                                                                Error  Chi-Square

Intercept                                     1     6.7344     3.4789      3.7474       0.0529

SOIL2      Grovsandet jord                    1     0.1745     0.3749      0.2167       0.6416

SOIL2      Humusjord                          1    -0.8221     0.3836      4.5915       0.0321

SOIL2      Lerblandet sandjord                1    -1.8386     0.3882     22.4271       <.0001

SOIL2      Lerjord                            1    -0.3642     0.4376      0.6925       0.4053

SOIL2      Sandblandet lerjord                1    -1.2161     0.3855      9.9527       0.0016

SOIL2      Speciel jordtype/kalkrig jord      1    -1.4318    12319.5      0.0000       0.9999

SOIL2      Svær lerjord                       1   -16.6290     3357.0      0.0000       0.9960

DISTRICT   Blåvandshuk                        1    -1.7282     0.7892      4.7947       0.0285

DISTRICT   Bornholm                           1   -14.8685      432.4      0.0012       0.9726

DISTRICT   Fyn                                1   -14.8222     1225.5      0.0001       0.9903

DISTRICT   Hovedstaden                        1    -1.6739     0.8200      4.1668       0.0412

DISTRICT   Kronjylland                        1    -2.4030     0.5768     17.3544       <.0001

DISTRICT   Midtjylland                        1    -2.2048     0.4392     25.1994       <.0001

DISTRICT   Nordsjælland                       1    -0.2282     0.4062      0.3155       0.5743

DISTRICT   Ribe                               1     2.5267     0.4128     37.4649       <.0001

DISTRICT   Storstrøm                          1   -14.9736     1915.2      0.0001       0.9938

DISTRICT   Søhøjlandet                        1    -1.5386     0.4584     11.2671       0.0008

DISTRICT   Sønderjylland                      1     0.9633     0.4057      5.6376       0.0176

DISTRICT   Thy                                1   -15.4417      482.5      0.0010       0.9745

DISTRICT   Trekantsområdet                    1     0.6729     0.4156      2.6209       0.1055

DISTRICT   Vendsyssel                         1   -15.5042      963.5      0.0003       0.9872

DISTRICT   Vestjylland                        1    -0.3796     0.4466      0.7226       0.3953

DISTRICT   Vestsjælland                       1    -1.0739     0.4997      4.6182       0.0316

DISTRICT   Østsjælland                        1    -2.6818     1.0764      6.2067       0.0127

RWIND                                         1    -4.8377     1.0106     22.9172       <.0001

RWIND2                                        1     0.3662     0.0751     23.8056       <.0001

HD                                            1    -0.0462     0.0224      4.2386       0.0395

HD2                                           1   0.000200   0.000134      2.2200       0.1362

H                                             1     0.5411     0.0478    127.9611       <.0001

H2                                            1    -0.0116    0.00126     85.3462       <.0001

LNVHA                                         1     0.4234     0.0393    116.0179       <.0001


                                  Odds Ratio Estimates

  Effect                                             Point Estimate       95% Wald
                                                                      Confidence Limits

  SOIL2 Grovsandet jord vs Finsandet jord                     1.191     0.571       2.483
```

Odds Ratio Estimates

Effect	Point Estimate	95% Wald Confidence Limits	
SOIL2 Humusjord vs Finsandet jord	0.440	0.207	0.932
SOIL2 Lerblandet sandjord vs Finsandet jord	0.159	0.074	0.340
SOIL2 Lerjord vs Finsandet jord	0.695	0.295	1.638
SOIL2 Sandblandet lerjord vs Finsandet jord	0.296	0.139	0.631
SOIL2 Speciel jordtype/kalkrig jord vs Finsandet jord	0.239	<0.001	>999.999
SOIL2 Svær lerjord vs Finsandet jord	<0.001	<0.001	>999.999
DISTRICT Blåvandshuk vs Aalborg	0.178	0.038	0.834
DISTRICT Bornholm vs Aalborg	<0.001	<0.001	>999.999
DISTRICT Fyn vs Aalborg	<0.001	<0.001	>999.999
DISTRICT Hovedstaden vs Aalborg	0.188	0.038	0.935
DISTRICT Kronjylland vs Aalborg	0.090	0.029	0.280
DISTRICT Midtjylland vs Aalborg	0.110	0.047	0.261
DISTRICT Nordsjælland vs Aalborg	0.796	0.359	1.765
DISTRICT Ribe vs Aalborg	12.512	5.571	28.100
DISTRICT Storstrøm vs Aalborg	<0.001	<0.001	>999.999
DISTRICT Søhøjlandet vs Aalborg	0.215	0.087	0.527
DISTRICT Sønderjylland vs Aalborg	2.620	1.183	5.804
DISTRICT Thy vs Aalborg	<0.001	<0.001	>999.999
DISTRICT Trekantsområdet vs Aalborg	1.960	0.868	4.426
DISTRICT Vendsyssel vs Aalborg	<0.001	<0.001	>999.999
DISTRICT Vestjylland vs Aalborg	0.684	0.285	1.642
DISTRICT Vestsjælland vs Aalborg	0.342	0.128	0.910
DISTRICT Østsjælland vs Aalborg	0.068	0.008	0.564
RWIND	0.008	0.001	0.057
RWIND2	1.442	1.245	1.671
HD	0.955	0.914	0.998
HD2	1.000	1.000	1.000
H	1.718	1.564	1.887
H2	0.988	0.986	0.991
LNVHA	1.527	1.414	1.649

Association of Predicted Probabilities and Observed Responses

Percent Concordant	90.2	Somers' D	0.804
Percent Discordant	9.8	Gamma	0.804

Association of Predicted Probabilities and Observed Responses

Percent Tied	0.0	Tau-a	0.037
Pairs	37049052	c	0.902

Partition for the Hosmer and Lemeshow Test

Group	Total	W = 1		W = 0	
		Observed	Expected	Observed	Expected
1	4024	0	0.01	4024	4023.99
2	4036	2	0.56	4034	4035.44
3	4032	7	2.80	4025	4029.20
4	4031	10	7.25	4021	4023.75
5	4032	15	15.07	4017	4016.93
6	4031	19	25.33	4012	4005.67
7	4030	44	38.13	3986	3991.87
8	4033	70	61.37	3963	3971.63
9	4031	142	138.49	3889	3892.51
10	4033	632	651.97	3401	3381.03

Hosmer and Lemeshow Goodness-of-Fit Test

Chi-Square	DF	Pr > ChiSq
15.5847	8	0.0487

References

Akaike, H., 1974. A new look at the statistical model identification. *IEEE transactions on automatic control*, 19(6), pp.716–723.

Albert, M. et al., 2015. Assessing risks and uncertainties in forest dynamics under different management scenarios and climate change. *Forest Ecosystems*, 2(1), p.14.

Albrecht, A. et al., 2012. How does silviculture affect storm damage in forests of south-western Germany? Results from empirical modeling based on long-term observations. *European Journal of Forest Research*, 131(1), pp.229–247.

Albrecht, A. et al., 2013. Storm damage of Douglas-fir unexpectedly high compared to Norway spruce. *Official journal of the Institut National de la Recherche Agronomique (INRA)*, 70(2), pp.195–207.

Andersson, M. et al., 2006. Miljökonsekvenser för biologisk mångfald. *Underlagsrapport inom project stormanalys. Skogsstyrelsen Rapport*, 11, p.2006.

Augusto, L., Bonnaud, P. & Ranger, J., 1998. Impact of tree species on forest soil acidification. *Forest Ecology and Management*, 105(1), pp.67–78.

Aven, T. & Renn, O., 2009. On risk defined as an event where the outcome is uncertain. *Journal of Risk Research*, 12(1), pp.1–11.

Battisti, C., 2016. An introduction to disturbance ecology, a road map for wildlife management and conservation. In C. Battisti, G. Poeta, & G. Fanelli, eds. Switzerland: Springer, p. 7–12 (Chapter 2).

Ben-Akiva, M. & Swait, J., 1986. The Akaike likelihood ratio index. *Transportation Science*, 20(2), pp.133–136.

Bergstedt, A., 2017. *Skovdyrkning i praksis*, Institut for Geovidenskab og Naturforvaltning Københavns Universitet.

Blennow, K. et al., 2013. Understanding risk in forest ecosystem services: implications for effective risk management, communication and planning. *Forestry*, 87(2), pp.219–228.

Blennow, K. & Sallnäs, O., 2002. Risk Perception Among Non-industrial Private Forest Owners. *Scandinavian Journal of Forest Research*, 17(5), pp.472–479. Available at: https://doi.org/10.1080/028275802320435487.

Bonnesoeur, V. et al., 2016. Forest trees filter chronic wind-signals to acclimate to high winds. *New Phytologist*, 210(3), pp.850–860.

Bormann, B.T. et al., 1995. Rapid soil development after windthrow disturbance in pristine forests. *Journal of Ecology*, pp.747–757.

Bouget, C. & Duelli, P., 2004. The effects of windthrow on forest insect communities: a literature review. *Biological Conservation*, 118(3), pp.281–299.

Bright, G. & Price, C., 2000. Valuing forest land under hazards to crop survival. *Forestry*, 73(4), pp.361–370.

Broadmeadow, M.S.J., 2002. *Climate change: Impacts on UK forests*, Forestry Commission.

Brunette, M., Couture, S. & Laye, J., 2015. Optimising forest management under storm risk with a Markov decision process model. *Journal of Environmental Economics and Policy*, 4(2), pp.141–163. Available at: https://doi.org/10.1080/21606544.2014.982712.

Buongiorno, J., Zhou, M. & Johnston, C., 2017. Risk aversion and risk seeking in multicriteria forest management: a Markov decision process approach. *Canadian Journal of Forest Research*, 47(6), pp.800–807.

Cappelen, J., 2013. Danmarks klima 2013-with English summary. DMI Teknisk Rapport No. 14-01.

Cappelen, J., 2017. DMI rapport 16-07 Storm og ekstrem vind i Danmark-opgørelser og analyser til og med 2015.

Cappelen, J. & Jørgensen, B., 1999. *Observed wind speed and direction in Denmark-with climatological standard normals, 1961-90*, Danmarks Meteorologiske Institut.

Cappelen, J. & Rasmussen, M., 2013. Beaufort-skalaen. *Danish meteorological institute*. Available at: https://www.dmi.dk/laer-om/temaer/vejr/vejrgudernes-hvirvlende-dans/beaufort-skalaen/ [Accessed March 26, 2018].

Carpenter, G., 2005. Windstorm Erwin/Gudrun—January 2005. *New York: Guy Carpenter & Company, Specialty Practice Briefing*, 2, p.14.

Caudullo, G., Tinner, W. & de Rigo, D., 2016. *Picea abies in Europe: distribution, habitat, usage and threats* J. San-Miguel-Ayanz et al., eds., Luxembourg: Publication Office of the European Union.

Chorus, C.G., 2012. *Random Regret-based discrete choice modeling: A tutorial*, Springer Science & Business Media.

Christensen, O.B. & Hess, M.S., 2013. Klimamodeller varsler flere storme i fremtiden. *Danish meteorological institute*. Available at: http://www.dmi.dk/nyheder/arkiv/nyheder-2013/12/klimamodeller-varsler-flere-storme-i-fremtiden/ [Accessed May 8, 2018].

Dansk Skovforening, 2014. Stormene væltede over 1 million m3 træ i private og kommunale skove i 2013. Available at: http://www.skovforeningen.dk/site/nyheder/2086/ [Accessed April 13, 2018].

Deutschländer, T. et al., 2013. Severe storm XAVER across northern Europe from 5 to 7 December 2013. *Deutscher Wetterdienst*.

Díaz-Yáñez, O. et al., 2017. How does forest composition and structure affect the stability against wind and snow? *Forest Ecology and Management*, 401, pp.215–222.

Dow, J. & Werlang, S.R. da C., 1992. Uncertainty Aversion, Risk Aversion, and the Optimal Choice of Portfolio. *Econometrica*, 60(1), pp.197–204.

Ejlersen, B.O., 2018. The nature agency's Forest inventories from 1999, 2002, 2004, 2013 and 2017. *Naturstyrelsen Gjøddinggård Førstballevej 2 7183 Randbøl*.

EMD, 2001. *Danish Wind Resource Map with data export to GIS-format*, Aalborg.

Eriksen, J., 2014. Rekordvandstande i Isefjorden og Roskilde Fjord. *Vejret*, 138(1), pp.40–48.

EUFORGEN, 2013. Distribution map of norway spruce (Picea abies). Available at: www.euforgen.org.

Everham, E.M. & Brokaw, N.V.L., 1996. Forest damage and recovery from catastrophic wind. *The botanical review*, 62(2), pp.113–185.

Fogg, B.J., 2009. A Behavior Model for Persuasive Design. In *Proceedings of the 4th International Conference on Persuasive Technology*. Persuasive '09. New York, NY, USA: ACM, p. 40:1--40:7. Available at: http://doi.acm.org/10.1145/1541948.1541999.

Frame, T. et al., 2017. Meteorological risk: extra-tropical cyclones, tropical cyclones and convective storms.

Gardiner, B. et al., 2008. A review of mechanistic modelling of wind damage risk to forests. *Forestry: An International Journal of Forest Research*, 81(3), pp.447–463.

Gardiner, B. et al., 2010. Destructive storms in European forests: past and forthcoming impacts. *Destructive storms in European forests: past and forthcoming impacts.*

Gardiner, B.A. & Quine, C.P., 2000. Management of forests to reduce the risk of abiotic damage—a review with particular reference to the effects of strong winds. *Forest Ecology and Management*, 135(1–3), pp.261–277.

Givnish, T.J., 1995. Plant stems: biomechanical adaptation for energy capture and influence on species distributions. In *Plant stems*. Elsevier, pp. 3–49.

Haanpää, S. et al., 2006. Impacts of winter storm Gudrun of 7th–9th January 2005 and measures taken in Baltic Sea Region. *ASTRA Winterstorm study*.

Haeseler, S. & Lefebvre, C., 2013. Heavy storm CHRISTIAN on 28 October 2013. *Deutscher Wetterdienst*.

Hale, S.E. et al., 2015. Comparison and validation of three versions of a forest wind risk model. *Environmental Modelling and Software*, 68, p.27.

Hanewinkel, M., Hummel, S. & Albrecht, A., 2011. Assessing natural hazards in forestry for risk management: a review. *European Journal of Forest Research*, 130(3), pp.329–351.

Hanewinkel, M., Zhou, W. & Schill, C., 2004. A neural network approach to identify forest stands susceptible to wind damage. *Forest Ecology and Management*, 196(2), pp.227–243. Available at: http://www.sciencedirect.com/science/article/pii/S0378112704002154.

Hansen, E.K., 2013. *Single tree stability, root architecture and basal sweep of young conifers A comparison study on containerized (Jiffy7) vs. bare rooted plants*. University of Copenhagen.

Hansen, N., 2013a. Fem storme i stødet. *DMI*. Available at: https://www.dmi.dk/nyheder/arkiv/nyheder-2013/12/fem-storme-i-stoedet/ [Accessed June 5, 2018].

Hansen, N., 2013b. Fire storme mødes - stød udveksles. *Danish meteorological institute*. Available at: https://www.dmi.dk/nyheder/arkiv/nyheder-2013/10/fire-storme-moedes-stoed-udveksles/ [Accessed March 29, 2018].

Henriksen, H.A., 1988. *Skoven og dens dyrkning* H. A. Henriksen & D. Skovforening, eds., Kbh: Dansk Skovforening : Nyt Nordisk Forlag.

Herman, R.K. & Lavender, D.P., 1990. Pseudotsuga menziesii (Mirb.) Franco. *Silvics of North America*, 1, pp.527–554.

Hermann, R.K. & Lavender, D.P., 1999. Douglas-fir planted forests. *New Forests*, 17(1), pp.53–70.

Hewson, T.D. & Neu, U., 2015. Cyclones, windstorms and the IMILAST project. *Tellus A: Dynamic Meteorology and Oceanography*, 67(1), p.27128.

Hildebrandt, P. & Knoke, T., 2011. Investment decisions under uncertainty—a methodological review on forest science studies. *Forest Policy and Economics*, 13(1), pp.1–15.

Hintz, D. & Dahl, J.C., 2017. Ekskursionsfører til Dansk Skovforenings ekskursion på Løvenholm 24. maj 2017.

Holst, K.A., 1992. *Den danske jordklassificering*, København: Det Kongelige Danske Geografiske Selskab.

Hosmer, D.W., 2013. *Applied Logistic Regression* 3. ed. D. W. Hosmer, S. Lemeshow, & R. X. Sturdivant, eds., New York: John Wiley & Sons, Incorporated.

Institute of agroecology, 2016a. *Den Danske Jordklassificering 1:50.000 og 1:200.000*, University of Aarhus. Available at: http://dca.au.dk/forskning/den-danske-jordklassificering/.

Institute of agroecology, 2016b. *Leret-sandet underjord*, University of Aarhus. Available at: http://dca.au.dk/forskning/den-danske-jordklassificering/.

Jones, S.C. et al., 2003. The extratropical transition of tropical cyclones: Forecast challenges, current understanding, and future directions. *Weather Forecast.*, 18(6), pp.1052–1092.

Jørgensen, B.B. & Nielsen, C.N., 2001. Skovdyrkningens indflydelse på stormstabilitet. In *Skov & Landskabskonferencen 2001*. Center for Skov, Landskab og Planlægning/Københavns Universitet, pp. 43–54.

Kaplan, S. & Garrick, B.J., 1981. On the quantitative definition of risk. *Risk analysis*, 1(1), pp.11–27.

Karlberg, S., 1961. *Development and yield of Douglas fir (Pseudotsuga taxifolia (Poir.) Britt.) and Sitka spruce (Picea sitchensis (Bong.) Carr.) in southern Scandinavia and on the Pacific Coast*,

Kellomäki, S. et al., 2005. Adaptation of forest ecosystems, forests and forestry to climate change. FINADAPT Working Paper 4.

Keskitalo, E.C.H. et al., 2016. Adaptation to Climate Change in Swedish Forestry. *Forests*, 7(2), p.28.

Klaus, M. et al., 2011. Integrated methodology to assess windthrow impacts on forest stands under climate change. *Forest Ecology and Management*, 261(11), pp.1799–1810.

Klinka, K. et al., 1999. The distribution and synopsis of ecological and silvical characteristics of tree species of British Columbia's forests.

Kooch, Y., Darabi, S.M. & Hosseini, S.M., 2015. Effects of Pits and Mounds Following Windthrow Events on Soil Features and Greenhouse Gas Fluxes in a Temperate Forest. *Pedosphere*, 25(6), pp.853–867.

Kortforsyningen, 2018. Danmarks Administrative Geografiske Inddeling (DAGI) 1:10.000. *Styrelsen for dataforsyning og effektivisering*. Available at: https://download.kortforsyningen.dk/content/danmarks-administrative-geografiske-inddeling-110000 [Accessed June 5, 2018].

Van Laar, A. & Akça, A., 2007. Forest mensuration. Managing forest ecosystems, Vol. 13.

Larsen, J.B., 2005. *Naturnær skovdrift*, København: Dansk Skovforening.

Little, E.L., 1999. Digital representation of the atlas of United States trees. *US Geological Survey, Reston, VA.* Available at: https://catalog.data.gov/dataset/digital-representation-of-atlas-of-united-states-trees-by-elbert-l-little-jr.

Lohmander, P. & Helles, F., 1987. Windthrow probability as a function of stand characteristics and shelter. *Scandinavian Journal of Forest Research*, 2(1–4), pp.227–238.

Loisel, P., 2011. Faustmann rotation and population dynamics in the presence of a risk of destructive events. *Journal of forest economics*, 17(3), pp.235–247.

Long, J.N., Dean, T.J. & Roberts, S.D., 2004. Linkages between silviculture and ecology: examination of several important conceptual models. *Forest Ecology and Management*, 200(1), pp.249–261.

Lund Johansen, B., 2014. *TRÆ 69 - Træarter* 1. udgave,. Træinformation, ed., Kgs. Lyngby: Træinformation.

Madsen, S.F., 1990. *Skovbrugstabeller 1990* [2. udgave., Lyngby: Statens forstlige Forsøgsvæsen.

Martínez-Alvarado, O. et al., 2012. Sting jets in intense winter north-atlantic windstorms. *Environmental Research Letters*, 7(2), p.24014.

Matthesen, P., 2000. *Ny skov efter stormfald* P. Matthesen & S. Naturstyrelsen, eds., København: Skov-info.

Mauer, O. & Palátová, E., 2012. Root system development in douglas fir (Pseudotsuga menziesii [Mirb.] Franco) on fertile sites. *Journal of Forest Science*, 58(9), pp.400–409.

Mayer, P. et al., 2005. Forest storm damage is more frequent on acidic soils. *Annals of Forest Science*, 62(4), pp.303–311.

Meilby, H., Strange, N. & Thorsen, B., 2001. Optimal Spatial Harvest Planning Under Risk of Windthrow H. Meilby, ed. *Forest Ecology and Management*, 149(1), p.15.

Miljøstyrelsen, 2018. *UDKAST: Danmarks nationale skovprogram*,

Miller, D.R. et al., 2000. A demonstrator of models for assessing wind, snow and fire damage to forests using the WWW. *Forest ecology and management*, 135(1–3), pp.355–363.

Mitchell, S.J., 2013. Wind as a natural disturbance agent in forests: a synthesis. *Forestry*, 86(2), pp.147–157.

Møller, C.M., 1977. *Vore skovtræarter og deres dyrkning* 2. udgave., Kbh: i kommission hos Dansk Skovforening.

Naturstyrelsen, 2018. Lokale enheder i Naturstyrelsen. Available at: http://naturstyrelsen.dk/lokale-enheder/.

Nicoll, B.C. et al., 2006. Anchorage of coniferous trees in relation to species, soil type, and rooting depth. *Canadian Journal of Forest Research*, 36(7), pp.1871–1883.

Nicoll, B.C. & Ray, D., 1996. Adaptive growth of tree root systems in response to wind action and site conditions. *Tree Physiology*, 16(11–12), pp.891–898.

Nielsen, N.W., 2014. To “efterårsstorme” i 2013. *Vejret*, 138(1), pp.1–13.

Nord-Larsen, T. et al., 2017. *Skove og plantager 2016 Forest statistics 2016*, Frederiksberg.

Nørgård Nielsen, C., 2014a. Hvad betyder kulturteknikken for langsigtet stormstabilitet? *SKOVEN*, 3, pp.132–135.

Nørgård Nielsen, C., 2014b. Hvordan påvirker hugst stormstabiliteten? *SKOVEN*, 3, pp.142–145.

Nørgård Nielsen, C., 2014c. *Stormfald, hvordan mindsker du risikoen for stormskader?* 1. oplag. P. Hilbert, ed., Frederiksberg: Skovdyrkerne.

Omule, S.A.Y., 1980. Personal bias in forest measurements. *The Forestry Chronicle*, 56(5), pp.222–224.

Paillet, Y. et al., 2010. Biodiversity differences between managed and unmanaged forests: meta-analysis of species richness in Europe. *Conservation biology*, 24(1), pp.101–112.

Pawlik, Ł., 2013. The role of trees in the geomorphic system of forested hillslopes — A review. *Earth-Science Reviews*, 126, pp.250–265.

Peltola, H., Kellomäki, S., Väisänen, H., et al., 1999. A mechanistic model for assessing the risk of wind and snow damage to single trees and stands of Scots pine, Norway spruce, and birch. *Canadian Journal of Forest Research*, 29(6), pp.647–661.

Peltola, H., 2006. Mechanical stability of trees under static loads. *American journal of botany*, 93(10), pp.1501–1511.

Peltola, H., Kellomäki, S. & Väisänen, H., 1999. Model Computations of the Impact of Climatic Change on the Windthrow Risk of Trees. *Climatic Change*, 41(1), pp.17–36.

Podrázský, V. et al., 2014. Effects of Douglas-fir (Pseudotsuga menziesii [Mirb.] Franco) on understorey layer species diversity in managed forests. *Journal of Forest Science*, 60(7), pp.263–271.

Podrázský, V., 2015. Potential of Douglas-‐fir as a partial substitute for Norway spruce – review of the newest Czech literature. *Beskydy*, 8(1), pp.55–58.

Pukkala, T., Laiho, O. & Lähde, E., 2016. Continuous cover management reduces wind damage. *Forest Ecology and Management*, 372, pp.120–127.

Quine, C., 1995. *Forests and wind, management to minimise damage* C. Quine, ed., London : HMSO.

Quine, C.P. & Gardiner, B.A., 2007. *Understanding how the Interaction of Wind and Trees Results in Wind-Throw, Stem Break-Age, and Canopy Gap Formation*,

Rahbek, C.A., 2003. *Statistiske analyser af spredet stormskader i rødgranbevoksninger*. København : Den kgl. Veterinær- og Landbohøjskole, Institut for Økonomi, Skov og Landskab, Sektion for Skovbrug.

Rich, R.L., Frelich, L.E. & Reich, P.B., 2007. Wind-throw mortality in the southern boreal forest: effects of species, diameter and stand age. *Journal of Ecology*, 95(6), pp.1261–1273.

Riguelle, S., 2016. Dealing with storm impacts on the forest sector through integrated and systemic approaches at the regional level; Gestion des conséquences des tempêtes sur la forêt et la filière bois au travers d'approches systémiques et intégrées J. (Superviser) Hebert et al., eds.

Rodrıguez, G., 2007. Chapter 3 Logit Models for Binary Data. In *Lecture notes on generalized linear models*. Princeton University.

Rold Skov savværk A/S, 2018. Korttømmer - Kvalitetsbeskrivelse og leveringsbetingelser. Available at: https://www.roldskov.dk/raatrae/korttoemmer [Accessed June 25, 2018].

Da Ronch, F., Caudullo, G. & de Rigo, D., 2016. *Pseudotsuga menziesii in Europe: distribution, habitat, usage and threats* J. San-Miguel-Ayanz et al., eds., Luxembourg: Publication Office of the European Union.

Ruel, J.-C., Mitchell, S.J. & Dornier, M., 2002. A GIS based approach to map wind exposure for windthrow hazard rating. *Northern Journal of Applied Forestry*, 19(4), pp.183–187.

Ruel, J.C., Pin, D. & Cooper, K., 1998. Effect of topography on wind behaviour in a complex terrain. *Forestry: An International Journal of Forest Research*, 71(3), pp.261–265.

Rykiel, E.J., 1985. Towards a definition of ecological disturbance. *Austral Ecology*, 10(3), pp.361–365.

Sanderson, P.L. & Armstrong, W., 1978. Soil waterlogging, root rot and conifer windthrow: oxygen deficiency or phytoxicity? *Plant and soil*, 49(1), pp.185–190.

SAS Institute Inc., 2010. *SAS/STAT® 9.22 User's guide*, Cary, NC: Sas Institute Inc.

Schack Pedersen, S.A., 2011. Digitalt kort over Danmarks jordarter 1:200 000, version 2, geologisk kort over de overfladenære jordarter i Danmark. Available at: https://frisbee.geus.dk/geuswebshop/index.xhtml.

Schelhaas, M.-J., Varis, S. & Schuck, A., 2001. Database on Forest Disturbances in Europe (DFDE), European Forest Institute, Joensuu, Finland.

Schelhaas, M., Nabuurs, G. & Schuck, A., 2003. Natural disturbances in the European forests in the 19th and 20th centuries. *Global Change Biology*, 9(11), pp.1620–1633.

Schindler, D., Bauhus, J. & Mayer, H., 2012. Wind effects on trees. *European Journal of Forest Research*, 131(1), pp.159–163.

Schmid, M., Pautasso, M. & Holdenrieder, O., 2014. Ecological consequences of Douglas fir (Pseudotsuga menziesii) cultivation in Europe. *European Journal of Forest Research*, 133(1), pp.13–29.

Schmidt, M. et al., 2010. An inventory-based approach for modeling single-tree storm damage experiences with the winter storm of 1999 in southwestern Germany. *Canadian Journal of Forest Research*, 40(8), pp.1636–1652.

Schütz, J.-P. et al., 2006. Vulnerability of spruce (Picea abies) and beech (Fagus sylvatica) forest stands to storms and consequences for silviculture. *European Journal of Forest Research*, 125(3), pp.291–302.

Shen, J., 2009. Latent class model or mixed logit model? A comparison by transport mode choice data. *Applied Economics*, 41(22), pp.2915–2924.

Silen, R.R., Olson, D.L. & Weber, J.C., 1993. Genetic variation in susceptibility to windthrow in young Douglas-fir. *Forest Ecology and Management*, 61(1–2), pp.17–28.

Skogstyrelsen, 2006. Stormen 2005 – en skoglig analys. *Meddelande*, 1, p.199 (in swedish).

Skov- og Naturstyrelsen, 2010. *Skov- og Natur i tal 2010*,

Skov- og Naturstyrelsen, 1999. *Skov- og Naturstyrelsens træartspolitik*, Copenhagen. Available at: https://www2.skovognatur.dk/udgivelser/1999/traepolitik/index.htm.

Skov- og Naturstyrelsen, 2005. Skov og Natur i tal 2005 Om Skov- og Naturstyrelsen. Available at: https://www2.skovognatur.dk/udgivelser/2005/87-7279-625-1/html/kap01.htm.

Skov- og Naturstyrelsen, 2008. *Slåensø Silkeborg Vandretursfolder nr. 12*,

Skovsgaard, J.P. & Vanclay, J.K., 2008. Forest site productivity: a review of the evolution of dendrometric concepts for even-aged stands. *Forestry: An International Journal of Forest Research*, 81(1), pp.13–31.

Solomon, S. et al., 2007. Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change, 2007.

Subramanian, N. et al., 2016. Adaptation of forest management regimes in southern Sweden to increased risks associated with climate change. *Forests*, 7(1), pp.1–18.

Suursaar, U. & Sooäär, J., 2006. Storm surge induced by extratropical cyclone Gudrun hydrodynamic reconstruction of the event, assessment of mitigation actions and analysis of future flood risks in Parnu, Estonia. *Risk Analysis V: Simulation and Hazard Mitigation.*, 1, pp.241–250.

Telewski, F.W., 2012. Is windswept tree growth negative thigmotropism? *Plant science*, 184, pp.20–28.

Telewski, F.W., 1995. Wind-induced physiological and developmental responses in trees. *Wind and Tree*, pp.237–263.

Ulanova, N.G., 2000. The effects of windthrow on forests at different spatial scales: a review. *Forest Ecology and Management*, 135(1), pp.155–167.

Ulbrich, U. et al., 2012. Three extreme storms over Europe in December 1999. *Weather*, 56(3), pp.70–80.

Ulbrich, U., Leckebusch, G.C. & Pinto, J.G., 2009. Extra-tropical cyclones in the present and future climate: a review. *Theoretical and Applied Climatology*, 96(1), pp.117–131.

Urban, J. et al., 2013. Tree allometry of Douglas fir and Norway spruce on a nutrient-poor and a nutrient-rich site. *Trees*, 27(1), pp.97–110. Available at: https://doi.org/10.1007/s00468-012-0771-y.

Valinger, E. & Fridman, J., 2011. Factors affecting the probability of windthrow at stand level as a result of Gudrun winter storm in southern Sweden. *Forest Ecology and Management*, 262(3), pp.398–403.

Wallentin, C. & Nilsson, U., 2013. Storm and snow damage in a Norway spruce thinning experiment in southern Sweden. *Forestry*, 87(2), pp.229–238.

Weisberg, S., 2005. *Applied linear regression*, John Wiley & Sons.

Wichmann, L. & Ravn, H.P., 2001. The spread of Ips typographus (L.) (Coleoptera, Scolytidae) attacks following heavy windthrow in Denmark, analysed using GIS. *Forest Ecology and Management*, 148(1), pp.31–39.

Woetmann, N.N. & Hansen, S.B., 2003. A numerical, high-resolution study of the life cycle of the severe storm over Denmark on 3 December 1999. *Tellus A*, 55(4), pp.338–351.

Yin, R. & Newman, D.H., 1996. The effect of catastrophic risk on forest investment decisions. *Journal of Environmental Economics and Management*, 31(2), pp.186–197.