Survival of juvenile Sitka and Lutz spruces planted in Iceland

an environment-based model

Gestion Forestière
Forest management

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Cover picture: Lucile Delfosse

SURVIVAL OF JUVENILE SITKA AND LUTZ SPRUCES PLANTED IN ICELAND

AN ENVIRONMENT-BASED MODEL

Résumé

Après des centaines d'années d'érosion de son patrimoine boisé, l'Islande a mis en œuvre au 20e siècle divers programmes pour protéger et augmenter son patrimoine boisé. Si les forestiers misent autant que possible sur la régénération naturelle dans les forêts de bouleau, les résineux sont presque systématiquement plantés. L'Epicéa (*Picea Sitchensis* et *Lutzii*) a montré une croissance et une capacité de production de bois d'œuvre uniques, ce qui en fait l'essence résineuse la plus plantée. Cependant les taux de survie sont variables ; de plus les dépérissements surviennent surtout lors de la phase d'installation des plants, alors dits « juvéniles ». S'il est parfois possible de connaître les causes du dépérissement des plants, il serait préférable de disposer d'un outil permettant d'identifier les sites à haut risque d'échec avant plantation. La présente étude s'est appuyée sur le réseau de placettes permanentes de l'Icelandic Forest Inventory (IFI) et a sélectionné 138 placettes de plantations d'Epicéas juvéniles. L'environnement de chacune a été caractérisé au travers de 47 variables. Une régression logistique a ensuite permis d'identifier 10 variables corrélées à la présence d'épicéas morts. Ces variables concernent le sol, le couvert végétal, la topographie, la géographie et la force du vent. Ainsi les types de sol et de couvert végétal bas ainsi que le pourcentage de recouvrement des couverts arboré et végétal bas joueraient un rôle sur les dépérissements. Une corrélation positive entre les dépérissements et la distance à la mer a été mise en évidence, ainsi qu'une corrélation négative avec l'altitude. Enfin l'importance de l'exposition par rapport aux vents dominants a été montrée. Ceci a permis d'établir un protocole visant à déceler les sites les moins favorables. Cependant de nombreuses variables n'ont pas pu être précisément ou suffisamment échantillonnées ; les conclusions sont donc partielles ou hypothétiques, demandant à être confirmées.

Abstract

After centuries of deforestation and soil erosion, Iceland started in the 20th century several afforestation programs. Natural regeneration works from native or settled birch woodlands, but planting remains the most used solution to create or extend resinous tree forests. The interesting results obtained with Sitka and Lutz spruce (*Picea sitchensis* and *lutzii*) in terms of growth and timber production make it the most planted resinous species. But survival rates vary twofold among sites, with a majority of diebacks occurring when trees have not overcome the juvenile stage. The present thesis aimed to highlight variables of the environment that are responsible for presence or absence of diebacks. The Icelandic Forest Inventory provided 138 permanent plots from which a range of 47 variables and the presence of death spruces were known. Logistic regression was used to identify the 10 predictors linked to the occurrence of dieback. These were the maximum wind speed, topographic exposure to main winds, geographic variables, altitude and distance to sea, soil class and vegetation. The analysis of predicted dieback probabilities, based on the different selected predictors, provided elements explaining the nature of the correlation with diebacks. This allowed building a diagnostic protocol. The most unfavorable sites are therefore more likely to be detected. The hypotheses concerning possible improving combinations between factors were developed, for example between low vegetation and soil. The data was insufficient to indentify the numerous possible combinations of variables that are found in Iceland. Conclusions are therefore limited to few cases and call for further research.

Acknowledgments

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Introduction

Iceland has a short historical background for forestry, but the history of Icelandic forests begins million of years ago. The country was then widely afforested with both conifers and leaved trees. Drastic reduction of forests started with settlement of humans. For hundreds of years, Iceland has been experiencing severe land degradation and desertification and in the 18th century, the lowest cover of forest was reached, less than 1%.

In the beginning of 20th century, the first forest institution was created: the Icelandic Forest Service (IFS). The initial goals were protecting birch woodland and stop soil erosion. Later, planting on areas devoid of trees also became part of the activities of the IFS. Sitka and Lutz spruce (*Picea sitchensis* and *Picea lutzii*) were two of the newly introduced species and were planted in many of the numerous new forest areas that have been created all around Iceland, and are still planted today.

The Icelandic forest inventory (IFI) started in 2001 and gathers data on all woodlands in Iceland. The analysis of spruce plantations reveals large differences in survival, as some sampled places have full survival, others have 100% diebacks. Most diebacks occur while trees are still in their juvenile stage. During this period growth is very slow since the root system is not fully efficient. This stage is often quite long in Iceland, up to 20 years, until trees reach approximately 2m height. In the IFI, 95% of deaths concern spruces smaller than 2.6m. The main causes suggested to explain these inequalities in survival are differences among provenience, nutrient deficiency, lack of suitable ectomycorrhiza, seedling quality, planting techniques, quality of planting sites. This last category will be studied in the present thesis.

Afforestation is practiced on various places. The areas that are submitted to extremely rough conditions are not chosen as planting sites; but remain a wide range of potential sites whose properties are variable. These properties are reflected by descriptive predictors, such as pedogenic, topographic, climatic and vegetation. Field observations allowed identifying some dieback causes, but such statements cannot be generalized to the whole country, in addition, trees are then already dead. The most valuable information for the forester would be to know if a potential site is favorable or not before planting. The present thesis aims to provide guidelines to help on this matter.

The study's aim is to identify, from a detailed list of environmental descriptors, those that are responsible for dieback of juvenile Sitka and Lutz spruces. In addition, the goal was to understand if the variable has positive, negative or more complex effect on the dieback. . Results of assessments of 138 plots with Sitka and Lutz spruce sampled by the IFI, described through a shared list of predictors and characterized by the presence/absence of dead juvenile spruces have been analyzed.

The first part of the thesis presents afforestation in Iceland. The chapter describes the Icelandic climate, the soil context, forests and forestry participants. A second part details on the one hand the dataset building, reasons why predictors have been added to the dataset and brief presentation of their origin. On the other hand the variable selection method is explained. The choice of a binary variable to be explained led to using logistic regression to highlight significant predictors. The selection is based on successive iterations testing the significance of a new variable, according to the result of a series of tests, choice is made to keep it or exclude it. The third part deals with results of the selection process. The fourth and last part intends to convert the results into guidelines for planting site choice and discusses the thesis method, both on the variables origin and selection process, and also deals with the scope of the study.

1. Iceland: rough conditions, but a realistic afforestation

1.1.A subarctic climate made of contrasts

1.1.1. A mild but changing climate

Iceland is located in the Atlantic Ocean, just south of the Arctic Circle. The total area of the country is 103.100km². Despite its latitude, Iceland has a relatively mild coastal climate. Indeed, a branch of the Gulf Stream — the warm North Atlantic Drift — flows along the south eastern coast of Iceland, greatly moderating the climate (Veðurstofa Íslands). The climate is characterized by cool summers and mild winters. In the lowlands, the climate is cold-temperate with an annual mean temperature ranging from 2°C to 5.7°C (Einarsson, 1984); but in the highlands, the climate is arctic and colder in the winter (Arnalds, 2008).

The sea currents are mainly controlling the climate of Iceland. One of the branches of the warm Drift named Irminger current encircles the south, west and north coasts. On the other hand the cold East Greenland current coming from North splits into two currents north of Iceland. The main current passes between Iceland and Greenland and other named East Icelandic current flows south along the east coast. As shown on Figure 1**,** these currents collide off the northwest and southeast coasts, creating two temperature fronts. This brings mild Atlantic air in contact with colder Arctic air resulting in frequent cyclones in the vicinity of Iceland. The proximity of these disturbances is responsible for frequent large pressure variations, bringing frequent changes in weather and storminess (Veðurstofa Íslands; Einarsson, 1984).

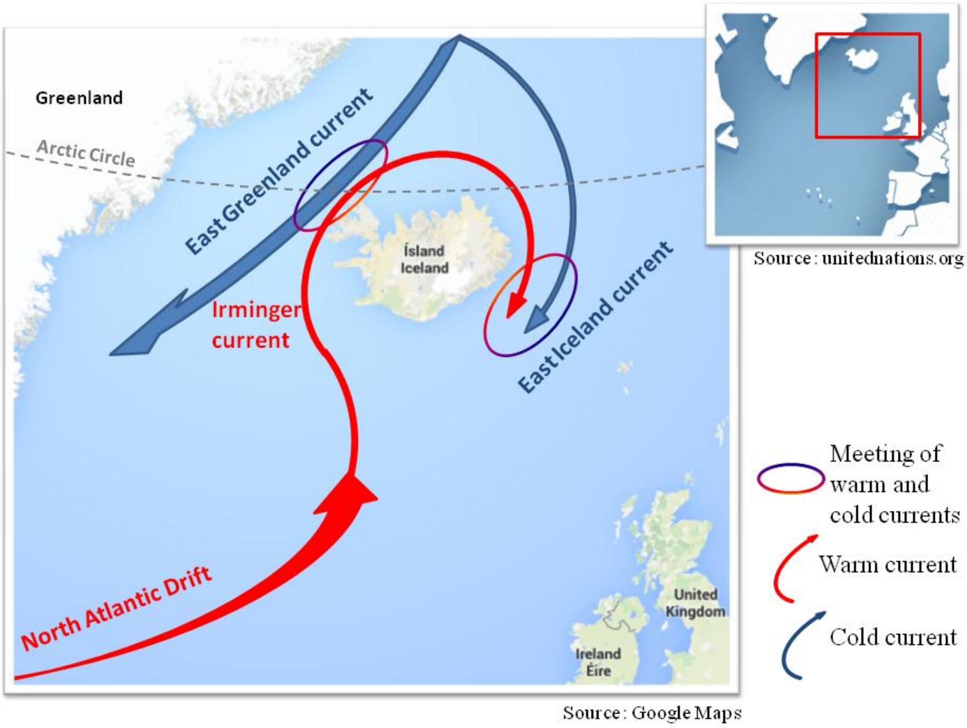


Figure 1: Sea currents surrounding Iceland, main controlling factors of the Icelandic climate. The collision of warm and cold currents is responsible for frequent cyclones in the vicinity of Iceland, inducing frequent changes in weather and storminess.

Another example of contrast in Icelandic living conditions is day duration. Because of the island's latitude, the day length varies considerably between winter and summer. In the southern part of the country, where the least difference is observed, the shortest day length varies from 4h30 to 20h37 (Einarsson, 1984). Vegetation is enjoying long hours of light in the summer, but the temperature remains low even late in the spring; the growing season is therefore quite short. In the lowlands, the growing season is normally ranging from late May and to late September. Freeze-thaw cycles are also frequent; they have a great influence on soil transformation (more detailed in 2.2.1.3.2.).

The weather varies in time and also spatial dimensions. It depends on the course of the low pressure cyclones as mentioned above, but at a given time and given cyclonic conditions, different weather types can be observed. These types are formed by wind direction and topography; Einarsson (1984) distinguishes 8 common types. Each weather type is described by certain global wind and pressure conditions and gives the weather that will be observed in different parts of the country. The limits of these country parts mostly correspond to topographic obstacles. For example, the *Southeastern* type occurs when cyclones approach Iceland from the southwest and ahead of them the southeast winds increase. The weather is then likely to be rather warm, with most precipitations found in the southern or southeastern or western part of the country but higher chance for dry weather in the northeast.

Topography is even controlling weather at a smaller scale. Primarily because temperature is descending by height above sea level. Secondly because mountains may stop air masses, preventing maritime air to reach the inland. These are in some areas the first factors ruling the cloudiness and precipitations. In addition, wind speed and direction depends considerably on the shape and direction of valley and fjords.

1.1.2. A particular soil context

Icelandic soil environment is unique in Europe, due to distinctive environmental conditions for soil development. These specific conditions include the volcanic origin of the parent material, the constant action of wind on volcanic products and numerous freeze-thaw cycles transforming frost-susceptible soils. More precisely, the soils are altered by mixing of materials from various horizons down to the bedrock due to freezing and thawing, also called cryoturbation.

Icelandic soils form in parent materials that are of recent volcanic origin, mostly basaltic tephra. This special origin gives to these soils distinctive characteristics that separate them from other types of soils. Thus, Iceland has the largest area in Europe that is dominated by Andosols (Arnalds, 2007). Icelandic soils were formed at the Holocene age, but have been deeply modified by eolian transport of materials, erosion, cryoturbation and frequent volcanic tephra deposition.

These factors are also partly responsible for the development of deserts: indeed, Iceland has extensive barren desert areas despite the cold-humid climate. If man settlement was the main cause for desertification, volcanism and erosion processes are enhancing the phenomenon. Desertification can be measured through many examples, such as birch woodlands surface: they used to cover a large proportion of the country (25–40%, see Aradóttir and Eysteinsson, 2005) but now represents only about 1.5% due to land degradation processes (Snorrason 2015, unpublished data). The extension of deserts is still going on in some areas of the country.

1.1.3. Wind, a factor that cannot be neglected

Windy days are the common in Iceland and calm days are rare.

The most frequent wind direction is from north east to south east, and this is most common at the coasts from south to northwest. However the wind directions remain irregular in the rest of the country as the wind is mostly determined by local conditions, landscape, fjords and location and direction of valleys. In addition, the time of year also affects the wind direction: for example the sea breeze during the summer (Einarsson, 1984).

The average wind speed is usually ranging from 6-7 m/s (21-25 km/h) at the coasts in the winter compared to 4-6 m/s (14-21 km/h) in summer. Extreme wind speeds —more than 30m/s — occur in most years in many parts of the country and the highest wind speed recorded was 62.5 m/s (223km/h) for a 10-min average in the highlands of Iceland (Veðurstofa Íslands). However at the interior lowlands the wind speed is usually lower. Guts depend greatly on topography and are most likely to be found near mountains.

1.2. The Icelandic tree cover: from ancient forests to contemporary plantations

1.2.1. History of the forest: from one extreme to another

1.2.1.1. A widely afforested country… in the past

The succession of glaciations has considerably reduced the amount of species that are found in the Icelandic forests. Millions of years ago, pine, spruce, larch, fir, birch, beech and alder were found in Iceland. Only downy birch (*Betula pubescens*), rowan (*Sorbus aucoparia*), few stands of aspen (*Populus tremula*) and tea-leaved willows (*Salix phylicifolia*) have reached Iceland after the last ice age. The forest cover in Iceland is estimated to have been around 25% of the land surfacebefore the settlement of humans.

1.2.1.2. Evolution after man settlement

The first settlers came to Iceland mainly from Norway and Ireland during the 9th century. Wood was then used to build houses, produce wooden coal as firewood and the new opened lands were grazed by domestic animals. The constant pressure of animal grazing combined with regular volcanic activity and rough climate limited greatly natural regeneration. The forest cover consequently decreased the forest had almost disappeared: in the 18th century, as the cover was less than 1% of total (Skógrækt Ríkisins (1)). The forest clearance and intensive grazing that followed man settlement also initiated large-scale soil erosion. This resulted in a very common landtype in Iceland: eroded, poor in nutrients, submitted to extensive frost heaving and active erosion processes.

1.2.2. The recent afforestation policy

The interest for restoring and protecting the old forests in Iceland came back in the end of the 19th century. At that time, Iceland had its own constitution and home rule, under the Danish king. At the beginning of the 20th century, Iceland was experiencing severe problems of soil erosion. The Danes had been fighting soil erosion at home for more than 100 years and were using tree planting as an efficient solution to stop the erosion. Thanks to the initiative of Danish pioneers and enthusiasm of the Icelandic minister Hannes Hafstein and others, forestry became a matter of national interest for Iceland. An act on forest protection and soil conservation was initiated in 1907 and the Icelandic Forest Service (IFS) was founded in 1908. A Danish forester was hired as the director of forestry in Iceland to restore the old birch forests by natural regeneration. The initial work of the forest director was to protect birch woodlands from grazing and stop soil erosion (Skógrækt Ríkisins (2)).

Forests protection consisted in preventing sheep grazing within the forest areas and controlling wood cutting. This resulted in slow extension of the birch woodlands.

The IFS has been operating since 1908 and has today forest areas on various places in Iceland both with exotic plantations and native birch forests. In the 1990's new farmer projects were initiated which granted farmes to plant in their own land. Thanks to the new afforestation programs, large increase has been in planting during the past 25 years and numerous new forest areas have been created all around Iceland.

1.2.3. About spruce and its use in Iceland

Different spruce speciess have been introduced in the afforestation programs of the IFS. Sitka spruce (*Picea sitchensis*) is the most used now; Lutz spruce (*Picea lutzii*, hybdrid between *P. glauca* and *sitchensis*) can also be found. *P. abies* was planted in larger numbers, and smaller numbers of *P. glauca* and *Englemanii.* The natural distribution area of Sitka spruce goes from Alaska to California, mainly in oceanic climate. Due to the similar climate of Alaska and Iceland Sitka spruce was expected to survive and grow in Iceland. The first tested seeds' provenience was Denmark from the 1920's, then Norway and later Alaska. The best results have been obtained with seeds originating from the Kenai

Figure 2: location of Kenai Peninsula, Alaska. So far the best provenience for Sitka spruce seeds.
Sources: unitednations.org; GoogleMaps.

Peninsula, Seward and Cordova, Alaska (Skógrækt Ríkisins (3); see Figure 2). Sitka spruce is found up to 200 km from the shore, where it hybridizes with other species, like white spruce (*Picea lutzii*) and Engelmann spruce (*Picea Engelmanii*) (Carrière, 1855).

Its tolerance to salt spray and moist soils makes it quite adapted to Iceland.

Planted spruce gave excellent results all around Iceland in terms of survival, growth and shape and so became the most planted spruce species. Measured growth values range from 6.8 to 11 m^3/ha/year, according to the site, the age and the density of trees. The site of Haukadalur provides a comparison: a plantation of *Picea sitchensis* is growing of 6.8 m^3/ha/year after 47 years, while a forest of *Picea abies* aged of 45 years and planted on the same site is growing of 3.9 m^3/ha/year (Benedikz and Freysteinsson, 1997). Spruce is also the first species that shows timber production. The largest and most productive spruce forests are found in the west and south Iceland, with the highest tree in Iceland, almost reaching 27 m height and still growing. The use of Sitka spruce is not likely to reduce, and therefore it is important to improve knowledge about the factors affecting its survival after planting.

1.3.Forestry in Iceland — many participants for many goals

1.3.1. The Icelandic Forest Service (IFS), a multiple-role institution

Until 1990's, the main activity of the IFS was planting on state owned land. These areas commonly had birch forests remnants. The IFS is today divided into main office, research station, and four forestry divisions in each part of the country (figure 3).

The most common tree species in south and west districts are Sitka spruce (*Picea sitchensis*), black cottonwood (*Populus trichocarpa*) and lodgepole pine (*Pinus contorta*). The most common species in north and east districts are sibirian larch (*Larix sibirica*). Birch is the most common species for afforestation on eroded soils. The planting in south Iceland in the 1950's until 1980's was most frequently done with exotic species like Sitka spruce, Norway spruce and lodgepole pine and these were most commonly planted in the shelter of existing birch woodlands. In east Iceland, planting on barren or unsheltered land started in the 1970's with Siberian larch and birch (*Betula pubescens*). From the 1990's, planting of shelterbelts became more and more common. At the same time, the planting of local forestry associations was getting more important. At the same time, partnerships with farmers, regional afforestration projects and protection projects that do not directly belong to the forestry like Heklaforest (see 1.4.1.: forest, a multifunctional entity) also developed. These new actors do today most of the afforestation in Iceland (see 1.3.2 and 1.3.3). The part of afforestation in the Iceland forestry service's activities has therefore decreased, and the main activities became exploitation and protection of national forests, and advice to local afforestation projects. The market of wood products from thinning of the IFS forests increased after the 2000's. Quality timber is now regularly harvested, and the steel industry is buying large part of the timber for wood chips. National forests are also under protection by the Forest Act from 1955. The IFS protects forest areas from sheep grazing, especially within the most fragile areas like ancient birch woods and new plantations.

At the very beginning, in the early 1900's, forest managers were also leading field trials mostly to know which species were able to grow and which were not. At that time, the only native species in terms of growth and ecology was birch. Nurseries were established in few places in Iceland in the early 19s in order to produce seedlings of birch, larch, spruce and rowan that would be tested. In 1961, the forest research station at Mógilsá near Reykjavík was founded. The station is still active today.

A part of the IFS aims is to advise all parts that participate in afforestation and woodland management in Iceland. The IFS used to grow seedlings in the nurseries and sell those but now private nurseries have taken over the market, and the IFS contribution is limited to advice.

In only a hundred years of existence the structure and missions of the forest service have evolved, both due to the increasing understanding of the importance of forests for the country and to the multiplication of actors.

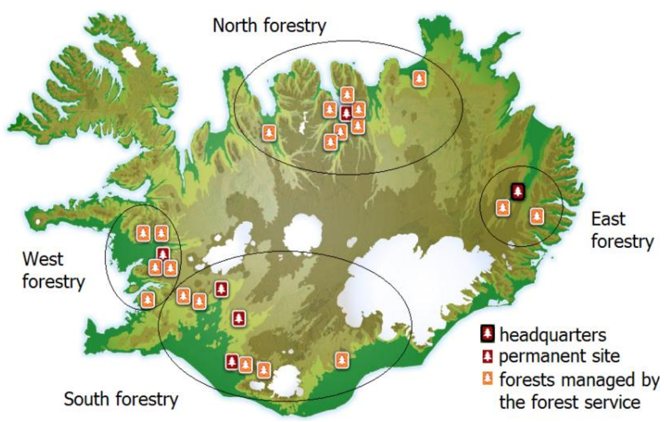


Figure 3: locations of national forests in Iceland
Adapted from Þjóðskógarnir, skogur.is

1.3.2. Forest associations and regional afforestation projects are irreplaceable actors of afforestation

The afforestation effort is now mainly done by the Icelandic Forestry Association (IFA) and the regional afforestation projects (RAPs). Their roles and actions are detailed in figure 4a. The IFA is a national umbrella organization for 58 local and regional forestry associations throughout Iceland, who together form one of the largest non-governmental organizations in Iceland (Skógrækt Ríkisins (4)). The IFA was founded in 1930. Local forest associations were founded by private people all around Iceland in the 1940-50's. The main purpose of the Forest associations is giving a structure and organizing people that are convinced of the positive impact of forests and want to plant trees. Their importance has been increasing and they are now large actor of forests extension. Many forests from IFA are also popular recreation areas, especially around Reykjavík and the larger towns.

The Regional Afforestation Projects are based on partnerships between land owners, mostly farmers, and the state. The idea of involving farmers into the afforestation effort in Iceland was partly due to the increasing difficulties for the IFS to find land for afforestation and matched the need for new money incomes for the sheep farmers. Land owners of a minimum of 20 ha got the possibility to ask for afforestation on their land. This new afforestation benefits to both farmers and Iceland, creating a money income for the farmers? and developing forest resources.

The first state supported farmer afforestation project started in the 1970's in east Iceland. Today projects are operating under the control of 5 regional offices. The land owners and the state sign a contract where the land owner is obligated to afforest a certain area and manage the forest in the following years. In the future the land owner owns the forest and the income from thinning and final harvest. The farmers get grants from the state that cover 97% of the whole cost of the afforestation. Today, 80% of new planted areas originate from this program.

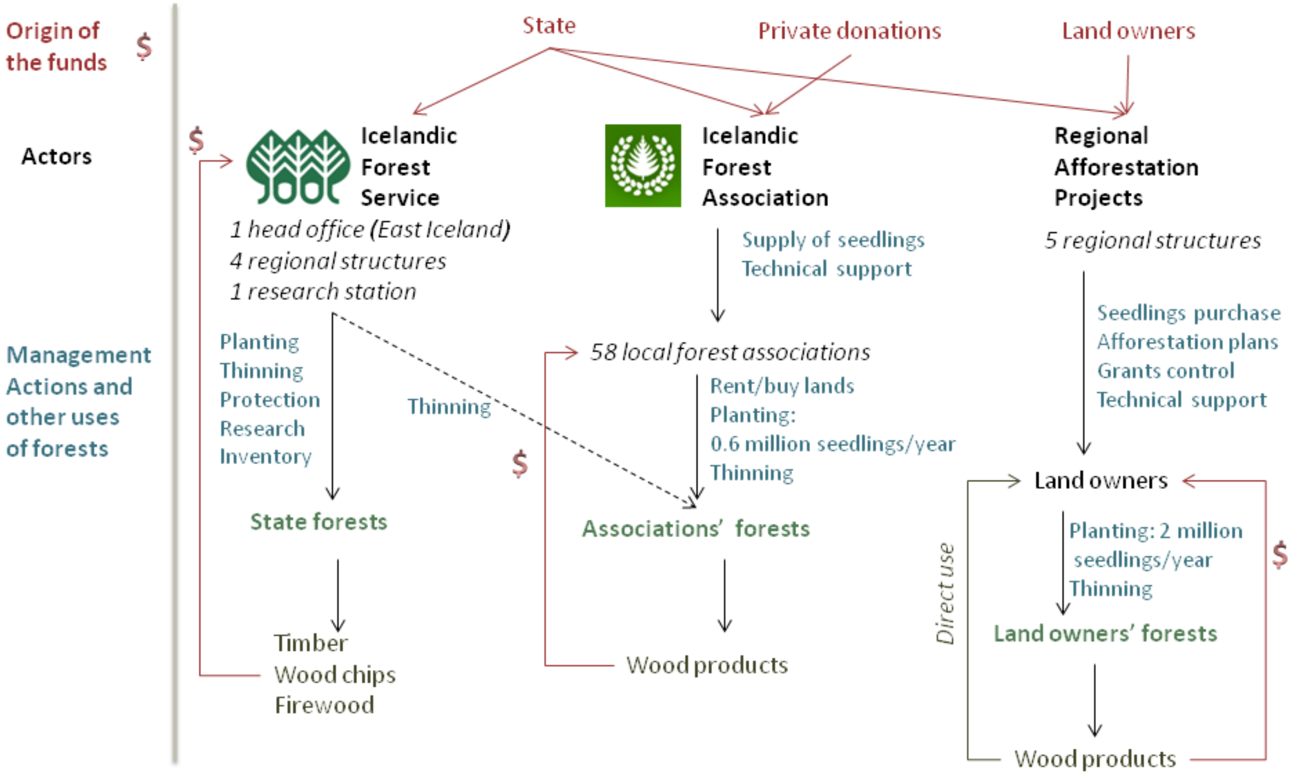


Figure 4a: actors of the forestry in Iceland: roles and interactions.

The total surface of wood and scrublands is 189600 ha, which represents 2% of the whole country's surface according to the most recent data from IFI.

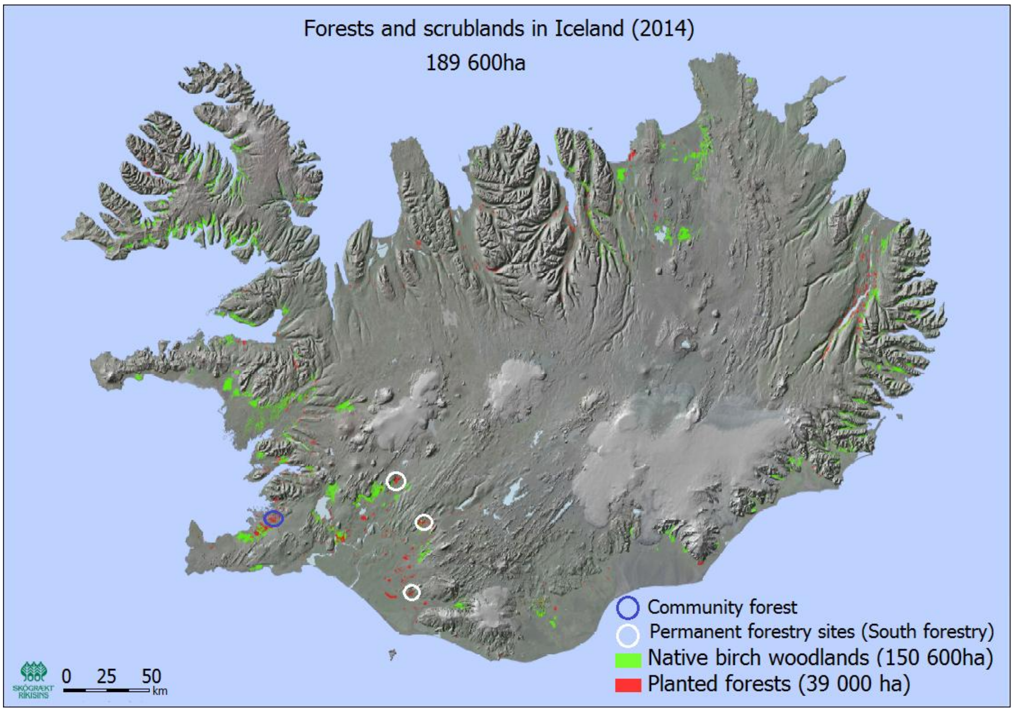


Figure 4b: location of forests in Iceland & examples of forest origins: national forests, association forests, restoration project. adapted from Ræktað skóglendi og náttúrulegt birk, skogur.is

1.4. Many planting sites and variable success rates

1.4.1. The forest, a multifunctional entity

The Icelandic forests have several roles and different goals. There is no nationwide hierarchy between them, as some could be more important than other but the order depends on the location and composition of the forest. The following list has therefore no pretention to prioritize forest roles.

The forest is of course providing wood products. Some forests have now both conifers and broadleaved trees mature to be cut for timber, mostly Sitka spruce (3495 ISK/m²; 25€/m²), lodgepole pine, black cottonwood (3443 ISK/m²; 23€/m²) and Siberian larch (*Larix sibirica* and *suckaczewii*, 39€/m²). Prices show timber cut into board wood sold by the IFS.

Iceland is traditionally importing most of the timber it needs, however the timber traders are beginning to buy Icelandic wood and architects are starting to use Icelandic wood for new constructions.

The Icelandic wood is also sold both as firewood and wood chips. Firewood is made mostly from birch (*Betula* pubescens), poplar and pine (*Pinus contorta*) and sold for 30 000ISK/ m^3 (200€/ m^3), while chips are produced from Sitka spruce, larch, poplar and willow (*Salix alacxensis* and *hookeriana*) and sold for 10000ISK/ m^3 (70€/ m^3). Largest part of the timber in Iceland is sold as wood chips for local silicon iron production. The figure 5a presents the evolution of volumes sales for the different wood products.

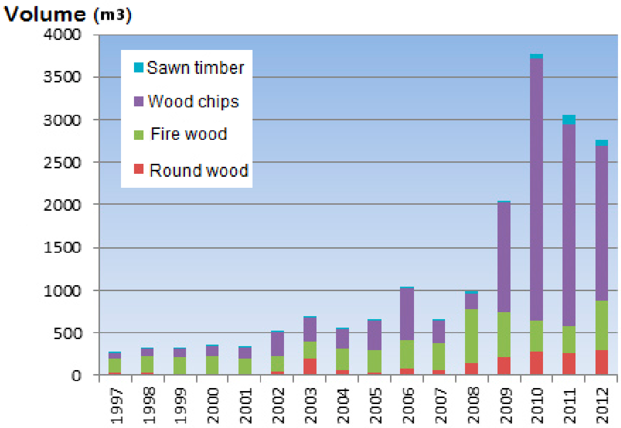
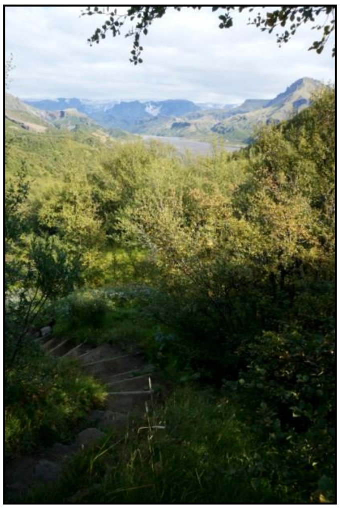


Figure 5a: global wood volumes and wood products volumes produced by the IFS. adapted from Skógrækt Ríkisins (1)

Forests play a very important role in soil protection. For example afforestation around the Hekla volcano (Heklaforest project, in Icelandic Hekluskógar, see below) are mostly composed of willow and birch, and their main purpose is to protect soils from erosion. Icelandic soils are fragile by nature and in addition submitted to intense erosive forces. Vegetation cover and especially forest contribute to maintaining relatively fertile and stable soils, and limit the extension of deserts (see 2.2.1.1.). Tall vegetation like trees seem able to survive a thick volcanic products deposition event, like after eruption of mount Hekla in 1104 AD. The trees managed to survive >30cm tephra while in this area 1cm deposit has strong impact on low vegetation like mosses. Ecosystem recovery is strongly dependent on survival rates, the higher they are, the more limited the disturbance will be (see 2.2.1.1.2). The project mainly aims to improve the ecosystem resilience to volcanic materials deposits and trap these deposits in order to limit secondary distribution by water and wind. It has been shown that a large area in the vicinity of the volcano used to be covered with birch woodlands by the time of settlement in Iceland; it was also found that most of volcanic deposits were stabilized on the forest floor. 90000 ha are concerned by the restoration project; seen the importance of the surface, the projects relies mainly on the combination planted small islets + colonization rather than large-scale planting. This method carries good success hopes since natural colonization has already been witnessed in the vicinity of native birch forests. The project started in 2007; in 2014, over 2.3 million seedlings had been planted both by forestry workers, volunteers and 210 landowners. The afforested area covers more than 1200 ha so far and self-seedling is already witnessed.



1. *Thinning in a spruce forest, Tumastaðir, south Iceland*
2. *Protection forest: Heklaforest Background: witness pre-project Foreground: after man intervention*
3. *The popular recreation forest of Þorsmörk, south Iceland*

Figure 5b: illustration of forest roles in Iceland. Photos: L.D. (1&3); Hrafn Óskarsson (2)

As mentioned at 1.1.3, Icelanders constantly have to deal with wind. Trees provide shelter for houses and crops; willow, poplar and spruces hedges are commonly found.

Finally, forests are also recreational areas. Surveys have shown that most Icelanders positive towards forests and woodlands are very appreciated as camping, hiking or playing places both by locals and tourists.

1.4.2. Despite suitable conditions, survival rates can vary significantly

Planting of tree seedlings is used for afforestation, but success rates vary significantly among sites. Areas submitted to obvious rough conditions such as arctic climate or swamps are not considered as potential planting sites. But despite apparently appropriate choices for the planting sites, death rates can vary from 0 to 100% within spruce plantation. Most diebacks occur when the trees are small. In the national dataset, 95% of dead trees were measured less than 2.6m. This corresponds to the common limit between settlement stage and full growth stage, often given at 2m. Plantations can therefore be successful with trees overcoming the planting stress and starting their growth, or fail with trees never really starting to grow and dying early. The pictures below (figure 6) show typical vitality stages found on young spruces, from the relatively healthy tree whose survival is not put in question to the needleless spruce that might never reach the full growth stage.

Figure 6: Different vitality stages for juvenile spruces of same age and height from good (left) to almost dead (right).
Approx. tree height: 40cm. Location : Mógilsá, Reykjanes peninsula, south west Iceland. Photos: L.D.

Despite rough climatic conditions, growing forests in Iceland is possible. The nation has now a hundred years of experience in forestry. Several actors are involved in different aspects of forest management from planting to transformed wood products selling. Among these products, timber production is developing and relies largely on spruce. Since planting is so far the main way to grow spruces and seen the induced costs, the survival of seedlings is a matter of concern. The origin of the dataset on which the analysis will be based is presented in the following part.

2. Materials and methods

2.1.Mortality among spruces: a national sampling

2.1.1. Variables to be explained: definition

The study aims to identify, from a list of environmental descriptors as exhaustive as possible, those that are responsible for dieback. When new planting sites have to be evaluated, it would be then possible to put all chances by our side through the sampling of few variables identified as significant. As said upper (1.4.2.), diebacks are most likely to occur in the early years, or at least as long as the trees are still in their settlement phase (called “juvenile stage” here, hence the name “juvenile trees”). The variable I want to explain is therefore the presence of death juvenile spruce on a stand. Juvenile trees are defined through their height, with a threshold often given at 2m height. Here, in order to give a statistical meaning to this limit, the value under which 95% of deaths are observed has been chosen: 2.6m.

Among all sites showing juvenile spruces in Iceland and sampled by the Icelandic forest Inventory (see below, 2.1.2), those presenting a minimum of 3 juvenile spruces were kept. The choice of a threshold at 3 observations has been made to face 2 opposed needs. On the one hand, seen the high amount of variables to be tested, feeding the dataset with numerous observations is essential and the lower the minimum of trees is, the higher the number of plots. But on the other hand the observation of dieback and survival should rely on the sampling of a spruce population, not on a single individual, hence the need for a minimum of observations. The minimum of 3 spruces is therefore a trade-off between the need for the highest possible amount of plots and the will to detect real dieback situations.

Then, if at least one of these spruces was dead, the plot was given the value “1” for the variable to be explained, “0” else. The exact variable to be explained is therefore the value”1” or “0” of plots. Next the analysis was trying to link the fact that dead tree(s) is (are) found on a plot and the values of predictors.

2.1.2. Presentation of the plots network: the Icelandic Forest Inventory

The Icelandic Forest Inventory (IFI) has been run since 2001 by the Icelandic Forest Research. The data was collected mainly for carbon accounting but can also be used for other projects such as the present thesis. The IFI is the first inventory in Iceland offering overview of both natural woodlands and planted areas. The field measurement started in 2005, with a sampling grid for plantations of 0.5 x 1.0km. The forest areas are also mapped and have also been added with simple attributes to the CORINE 2006 land cover database of the European Environment Agency (Traustason and Snorrason, 2008).

The national definition of forest in Iceland has recently been set to meet the obligations of the Kyoto Protocol. It differs only for minimum height at maturity from the reference definition of COST Action E43 where the chosen value is 2 m instead of 5 m.

A systematic sampling design with a single plot at each grid intersection is used for the IFI field inventory. The plots are permanent and re-measured every 5 years. The size of the plantation inventory plots is chosen according to the density of the plantation and can be 50, 100 or 200 m2. If the number of trees or/and seedlings is less than or equal to 20 in 50 m2 or 100 m2 plots, then a larger size is chosen to increase the number of trees for the plot.

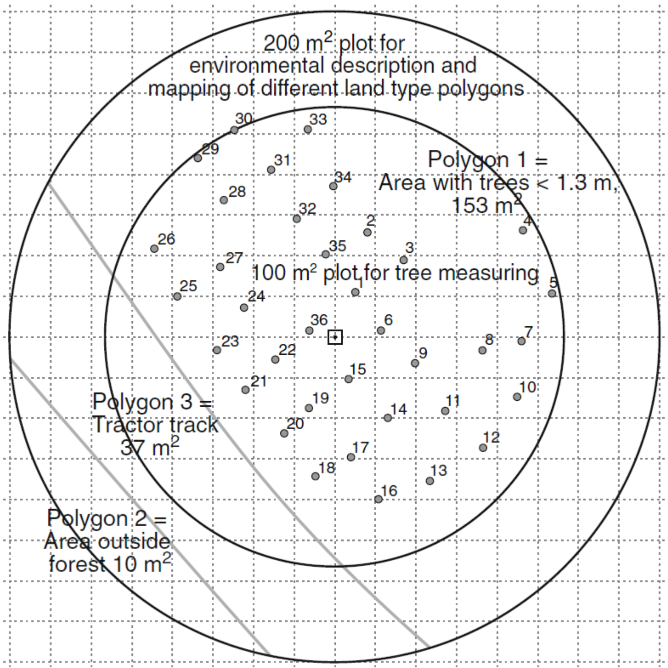


Figure 7: A sample plot of the IFI, trees measured within a 100m² circle, environment and landtypes defined within a 200m² circle (3 different landtypes identified here). One mesh represents 1m². source: Snorrason (2010)

The environment is described and mapped in a 200m² plot. If different land types can be distinguished within one plot, each land type is represented with a polygon and further described with respect to trees, vegetation, soil, and other variables.

For the present study, I wanted to focus on the spruces; two speciess are present in the inventory, Sitka and Lutz spruce (*Picea sitchensis* and *Picea lutzii*). Making accurate distinction between these speciess on the field is rather difficult, so they were reported in a common category. Their behaviors and reactions to predictors are assumed to be similar.

The dataset shows 138 plots (their location is shown on figure 8) 54 have the value “1” and 84 carry the value “0”. These 138 plots represent 1753 juvenile spruces, 1574 alive and 179 dead. For each plot, a range of biotic and abiotic variables is available from the national inventory IFI. To this list were added indicators calculated from them and also new variables of other origin. All variables will be described in the next paragraph.

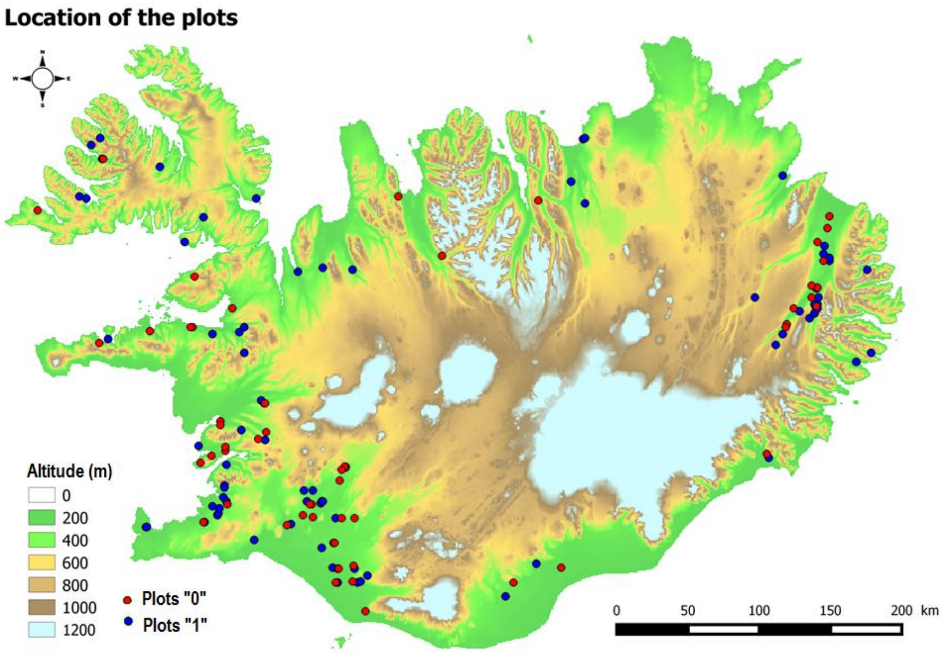


Figure 8: location of the 138 selected plots.

2.2.Presentation of the dataset: explanatory variables

Environment can be described through an endless amount of variables. In order to build the dataset, I needed to gather those explanatory variables that were likely to have effect on diebacks and the form under which they could be sampled. The list of variables was established from recorded causes of diebacks, which provided clues for possible involved predictors, and completed with bibliographic research. The inventory provided all data concerning soil and vegetation plus a part of topographic data, from which they were developed in 2.2.1. To this wind, extra topographic, temperature and geographic data from different origins were added and presented in 2.2.2.

2.2.1. Selection of variables from the inventory

The inventory offered a wide range of predictors that were classified as follows:

Table 1: variables originating from the Icelandic Forest Inventory included in the dataset

Plot vegetation		Pedogenic variables of the planting site	Planting site description	Topography/geography
Shrubs and low vegetation	Trees			
- Vegetation cover (%) - Vegetation type	- Densities - Canopy cover (%) - Age structure - Proportion of needle trees - Speciess mixture	-Surface type -Soil type -Soil depth -Soil base type	- Soil preparation - Use of land before planting	-Topex -Slope direction -Distance to forest border, 4 cardinal directions

2.2.1.1. Plot vegetation: a multi-angles description

Since one of the goals of the Icelandic Forest Inventory was carbon counting, all vegetation types were measured through adapted methods. Two main vegetation types were distinguished as woody and non-woody vegetation.

2.2.1.1.1. Description of the woody vegetation population

The present thesis did not aim to study particularities between trees; this is why no distinction was made among them, except of course their death/alive status. But the survival of one individual can be influenced by the properties of the whole group, for several reasons.

First, vegetation cover allows reducing wind erosion; indeed, the sheltering effect provided by plants to the soil surface partly absorbs the wind force, and even more so that the surface roughness increases (Stockton and Gillette, 1990).

The **density of living trees**, all trees and also only juvenile living trees, were added to the predictors. The frequency of density categories are given in figure 9.

The **forest size**, the **distance to the forest border** and **forest age structure** may also affect the survival, through moderating the shelter provided to younger trees. In addition the presence of trees that are not anymore in their juvenile phase give information about the possibility for trees to survive and grow, and about the duration the considered land has been used for forestry. The year of plantation was provided in the data, but was not reliable.

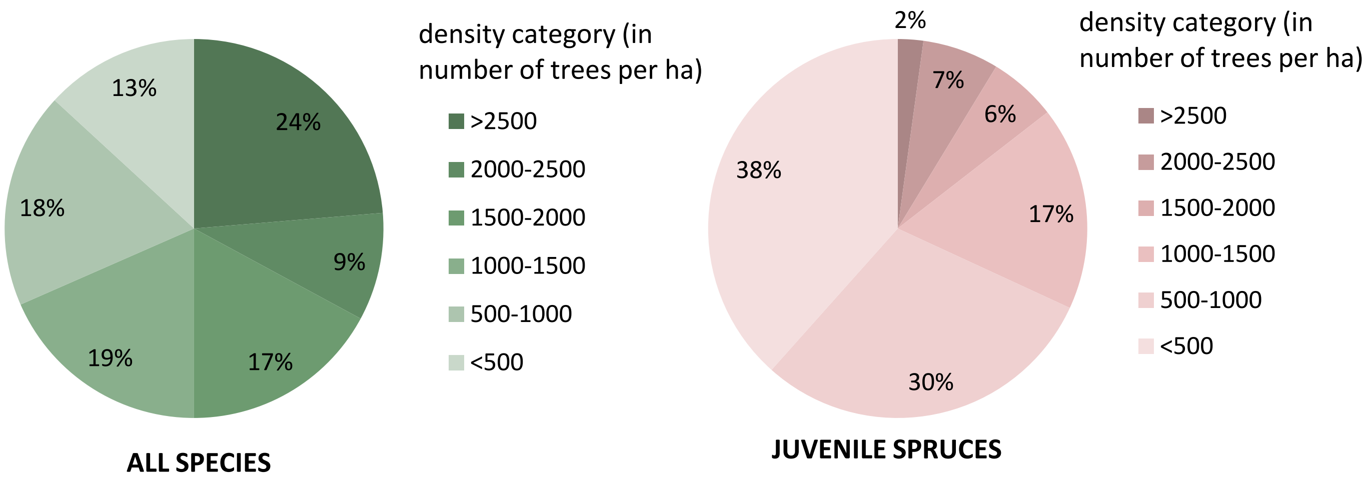


Figure 9: density categories for all species (left) and juvenile spruces only (right) shown in the dataset and their frequency

2.2.1.1.2. Description of the non-woody vegetation population

This section contains description of low vegetation and shrubs, both vegetation preceding the planting and vegetation found on the plot in present day. Firstly the reason why vegetation is of interest for the study is developed. Secondly, description of how vegetation was sampled in the inventory, i.e. the vegetation cover in % and the vegetation class.

2.2.1.1.2.1. Vegetation cover and type partly alter the impact of soil quality on tree survival

Climate conditions affect vegetation cover, which in turn influences many processes related to the soil. This alteration has direct influence on trees' living conditions.

Impact of vegetation on nutrient and water availability

Soil is at a given time offering a certain nutrient and water stock and a limited possibility of regeneration through cycling processes. The coexistence of low vegetation and trees can then be seen as a competition. Despite the high water retention properties of Andic soils, lack of water can occur when the soil is widely covered by vegetation or if climatic/topographic conditions are not refilling the water stock. Part of the water might be unavailable due to retention forces, combined with a high demand by vegetation overcoming the offer, thus leading to a shortage. For recently settled trees with limited distribution of the root system, this competition can cause diebacks.

Similarly, nutrients deficiency on poor soils can be limiting. Nitrogen deficiency might for example lead to inability for the tree to complete settlement.

The type of vegetation might determine the severity of the competition. Soil preparation might reduce vegetation competition after tree planting, thus enhancing their survival chances.

Role of past and present vegetation in soil disturbances and resilience ability

As mentioned above, vegetation absorbs wind force, thus limiting wind erosion. The influence of low vegetation can be also taken into account for the same reasons: it opposes a shield to mechanical action of the wind on the soil, thus preventing material removing (Stockton and Gillette, 1990).

Vegetation cover also plays a role after volcanic event. No vegetation can resist direct destruction by lava flows or extreme tephra deposits, but a bit further from the volcano, tephra deposit is less thick and can lead to disturbance whose severity is variable. According to factors such as burial depth, frequency of deposition events, time of year, height and composition of vegetation, its survival is more or less threatened (Aradóttir et al., 2010). Damages occur because the burial prevents photosynthesis, affects microbial activity and nutrient cycling by restraining the oxygen flow (Maun, 1998) and exerts a mechanical compaction force on plants.

Figure 10: The birch forest of Þórsmörk covered with ash from Eyjafjallajökull eruption of 2010. The forest survived and healed in few weeks. Photo: Hreinn Óskarsson

The nutrient deficiency that often follows tephra deposit can be moderated by appropriate vegetation cover. Indeed, this lack depends among others on the previous ecosystem and the survival rate of its components. For example, on sites previously covered by nitrogen-fixing pioneer plant such as lupines, the deficiency induced by tephra deposit is balanced (del Moral and Wood, 1986; Russel, 1986). They are used in Iceland with significant results.

Seen possible long and short terms effects of low vegetation, both past (before planting) and present vegetation should be included in the dataset. The vegetation cover before planting is not precisely known, but an indication is given by the previous land use. This variable can also be seen as an answer to "what type of land has been selected as planting site?" and developed in that way in 2.2.1.2. The type of vegetation sampled in the IFI inventory is presented below.

2.2.1.1.2.2. Vegetation cover rules soil-air exchanges

Another possible effect of vegetation cover concerns the temperature above the ground. There exist a heat flux between soil and atmosphere that affects the plants, all the more for small individuals. The radiation stored by the ground during the day can be released at night, thus providing a protection against moderate freeze. This flux is influenced by presence of a vegetation cover such as moss or grass. The cover traps the radiations, preventing them to reheat the low air layer and thus preventing small trees to benefit from smoother temperature. This specific effect of vegetation cover highly depends on the % of surface covered and can also be moderated by soil preparation (see 2.2.1.2.).

Both long and short term effects can be expected from variations in vegetation cover. This factor is involved in long processes as nutrient storage and ecosystem recovery, and also in limited events such as night freeze. Both percentage of cover, nature of the present and past cover are involved in the nature and intensity of the effect.

2.2.1.1.2.3. Vegetation class: description of the variable

In the IFI data the low vegetation is often described through the type of land, reflecting a typical vegetation cover rather than an exhaustive inventory. For example, instead of a complete list of present species, the term "Half wetland" ("Hálfdeigja") is used as a base for several types and each is then distinguished by adding the name of one specific species or group of vegetation. The same method has been applied to mói (Icelandic word for heathland).

The list of vegetation classes is nevertheless quite long, and it was decided to gather related vegetation classes into coarser categories. For example in the IFI dataset, a distinction was made between "mói" with different species of willow, but they are expected to offer similar conditions for spruces. Same for the different species growing on "Half wetlands" or "Wetlands". The context of a wetland vegetation is assumed to rule the environment for spruces, more than the small differences in proportion for grass species growing on.

The original vegetation class data has been converted into new categories and both original (Vegetation Class) and new category (Vegetation Class 2) list have been added to the dataset. Table 2 shows the grouping process.

Table 2: the vegetation classes found among the selected plot, gathered by similarity of their influence on tree growth.

Icelandic class	English translation: Vegetation Class	Number of plots	Vegetation Class 2	Number of plots
Blómlendi	Flower field	1	Flower field	1
Skógargróska 2a	Forest yield class 2a	4	Forest	6
Skógargróska 2b	Forest yield class 2b	1		
Skógargróska 3b	Forest yield class 3b	1		
Smárunnagraslendi	Dwarf shrub and grasses	11	Grassland	54
Graslendi	Grassland	43		
Runnamýri	Wetland with dwarf shrub	2	Half wetland/ Wetland	15
Graslendishálfdeigja	Half wetland with Grasses-*Carex*	10		
Gulvíðishálfdeigja	Half wet land with tea-leaf willow	1		
Hrossanálarhálfdeigja	Half wetland with *Juncus articus*	2		
Lúpínustóð	Lupin	7	Lupin	7
Hrísmói	Mói with dwarfbirch (*Betula nana*)	7	Mói	16
Gráðvíðismói	Mói with *Salix arctica*	1		
Þursaskeggsmói	Mói with *Kobresia/Juncus*	1		
Mosaþemba	Thick moss cover	3		
Gulvíðismói	Mói with tea-leaf willow *(S. phylicifolia)*	2		
Loðvíðismói	Mói with wooly willow (*Salix lanata*)	2		
Lyngmói	Mói with small shrubs (berry/heather (*Calluna*))	32	Mói with berry tree	39
Bláberjalyngmói	Mói with berry shrubs cover	7		

2.2.1.2. When man design land and forest: land use, soil preparation and species mixture

Tree breeding in Iceland is designed as to maximize the ability of the seedling to resist planting stress and thus survive. But the choice of species blend and the planting site, more precisely its previous use and preparation, might also have their role to play. Concerning the planting area, the importance of the existing vegetation cover has been described and role of soil will be detailed further (2.2.1.3.). Remain the history of the land and soil preparation. Concerning the plot's history, the inventory provides a category of use before planting. 60% of plantations (for our plot selection) occurred on a "dry land on mineral soil" ("Þurrlendi"), highlighting the recent protective purpose of planting. Categories representing an already vegetated land ("Woodland" ("Lágskógur"), "Shrubland"("Kjarrlendi"), "Forest"(" Háskógur"), "Hayfield" ("Tún" and "Tún framræst votlendi") weight together only 5% of situations, while ditched wetlands ("Framræst votlendi” and “Votlendi framræst til skógræktar”) — that cannot be used for agriculture — represent 17% of cases. All these previous uses mean differences in terms of water, nutrient and mycorrhiza content, therefore possible differences in survival.

Concerning soil preparation, situations range from no preparation (shown in 54% of cases) to plough of the whole plot surface (“Heilplægt”, translated “integral plough”: 1%). As said above, vegetation traps the radiation, so a positive effect can be expected for important soil preparation, such as plough or surface removing. But the organic layer often present under the vegetation cover has a positive role, as it limits the frost heaving. Thus, it is expected that the “good” preparation would remove the vegetation cover without disturbing the organic layer underneath. This could be found for two preparations named “scarification”, which is removal of the 1st 20cm approximately, on the whole row (“Rásun” translated “Scarification (row)”, 16% of cases) or on spots (“Flekkjun” translated “scarification (spot)”, 17%). Soil preparation might affect the living conditions for the trees in several ways, and a given type of preparation could possibly affects both in positive and negative way the survival.

The species blending ranges from a single species of tree in a stand to an even mix of species. The mix of species is expected to have influence on survival for many reasons, i.e. best resistance to parasites, possible shelter if given species grows faster, and possible interactions between species.

2.2.1.3. Many soil descriptors for many implications in vegetation survival

The favorable or unfavorable characteristic of the pedogenic context of a plot depends on the combination of several soil descriptors. Four have been used here, each describing a different layer from the surface to the base. First is the surface class, followed by the soil type and its thickness, and finally the soil base. Since it is the combination of predictors that is expected to be significant, with 8 different soil bases, 4 thicknesses class, 5 soil classes and 8 surface classes, there are 1280 possible combinations. Less than 6% (69 combinations) are shown in the dataset, with an average of 2 observations for each combination. In order to get more observations per combination, categories have been made for several soil descriptors: each category gathers predictor values expected to have similar effect on young spruces. The number of possible combinations is then 80, 31% (25 combinations) are shown in the sample with an average of 5.52 observations.

2.2.1.3.1. The surface layer

The surface layer is directly in contact with the low vegetation and, in case of bare soils, with the atmosphere. Since spruce has a root system mostly located close to the surface, the properties of this upper layer were chosen for the study. The data shows a wide range of surface types, as they offer different conditions in terms of water retention, nutrient amount and stability since they are more or less sensitive to frost heaving. The following table (Table 3) shows the category creation process. Surface classes were positioned from most to least favorable in terms of nutrient and water content.

The influence of the surface layer was tested through 2 predictors, both qualitative: the surface class as given in the inventory, and a surface category created from these classes as explained in Table 3.

Table 3: surface classes, translation and conversion to simplified classes

Icelandic name	English translation	Description	Properties +	Properties -	Category
Mold	Bare soil	Transformed organic materials	High organic content, directly available		**Mold/Sóp**
Sóp	Litter	Organic materials layer, not transformed into minerals yet	High organic content		
Möl	Gravel	Sand and small rocks layer	let roots grow easily	- possible severe drought - low nutrient amount - high risk of frost heaving	**Möl/ Sandur/ Melur**
Sandur	Sand	Sand layer	- let roots grow easily - better organic and water retention than gravel	- possible severe drought - low nutrient amount high risk of frost heaving	
Melur	Gravel & Vegetation	Ash/sand/gravel layer, few vegetation growing	let roots grow easily	- possible severe drought - low nutrient amount high risk of frost heaving	
Grjót	Stone	Mostly big stones, possibly with sand in between		often sterile land, unless presence of sand	**Grjót/ Klöpp**
Klöpp	Rock floor	Impermeable rock floor, unless opened by cracks		often sterile land	
Ekkert	None	no surface layer	-		**none**

2.2.1.3.2. The soil class

Soils of Iceland are formed by climatic and volcanic factors. The majority of Icelandic soils are Andosols, but few other types are found. This brings on the first question of classifying the soils and secondly finding out if a difference of soil type might be involved in different survival rates. A first level of classification distinguishes two main groups of soils, soils with vegetation cover (Andosols and Histosols) and desert soils (Vitrisols). The majority of Icelandic soils belongs to these groups, but there also exist, to a very limited extend, permanently frozen soils (Cryosols), Regosols and Leptosols. A second level allows separating different Andosols and Histosols according to eolian & tephra input on the one hand and drainage on the other hand (Arnalds, 2004). Figure 11 illustrates the separation of Icelandic Andosols and Histosols with drainage on X-axis and eolian input on Y-axis.

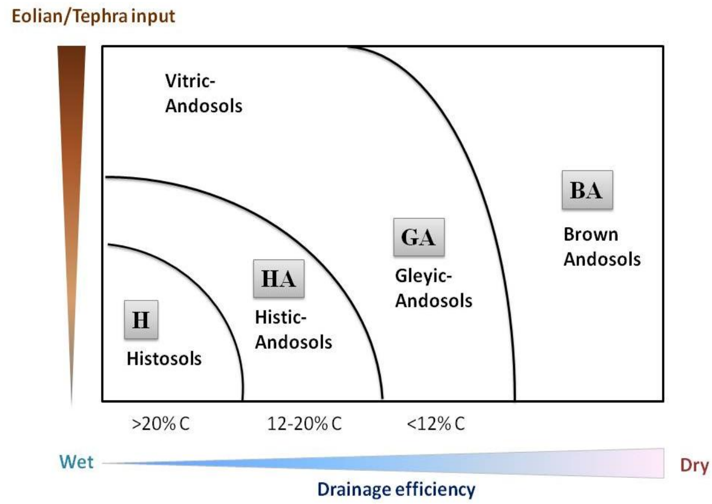


Figure 11: Classification of Andosols and Histosols according to drainage and tephra input. Adapted from Arnalds, 2008.

The closer you get from the left-bottom corner of the diagram, the further you are from active volcanic zone or sources of eolian materials. Since both drainage and tephra inputs are likely to influence the presence and development of vegetation, the soil class has been included in the study. The following paragraphs provide a description of each type.

Andosols are soils of active volcanic areas: they are submitted to regular parent material deposit events. They have in common a low bulk density : <0.9g.cm-3. This results from the combination of high organic content (the %C allows distinguishing different sub-types of Andosol, see below), aggregation of soil materials and possible presence of tephra materials. The basaltic tephra often present as layers in Icelandic Andosols is weathered rather quickly: dissolved products are removed or re-precipitate as poorly ordered clay minerals characteristics of Andosols (allophane, imogolite and ferrihydrate). These non-phyllosilicates clay minerals contribute to Andosols' low bulk density but also other specific physical properties such as high porosity, large soil water retention (Kimble *et al*., 1998) and thixotropy.

As a result of these properties, Andosols have low bearing capacity and are very susceptible to wind and water erosion when the surface cover is removed or degraded (Arnalds, 1990; Kimble et al., 1998). Disturbances can make them reach the liquid limit due to their thixotropic property, leading to possible landslides. They are also very susceptible to cryoturbation processes induced by freeze-thaw cycles. Such events are frequent due to the northerly oceanic climate of Iceland. Disturbances are particularly strong for Andosols because of their high water retention capacity and their lack of cohesion. Cryoturbation induce specific features like hummocks and desert pavement due to frost heaving (Arnalds, 2008).

The typical form of erosion of Andosols is an erosion escarpment, named rofabard (see figure 12) in Icelandic. They form because of the lack of cohesion that characterizes Andosols. The escarpment shaped by erosion retreats as a unit, with fully vegetated soils on top, but leaving barren desert behind (Vitrisols). Andosols are also threatened by desert extension. Wind brings particle that bury and destroys the vegetation. This process makes the soil unstable and ready to be moved in turn by wind; new desert area is created and landscape has been lowered, sometimes more than 2 m thick soil cover has been eroded away.

Figure 12: on the foreground, a typical rofabard. Grassland regresses and bare rock (here volcanic ash and tephra) is left.
Markafljótsglúfur, south Iceland.photo: L. D.

Histosols (H) and Histic Andosols (HA)

The soils showing the highest rate of organic contents are Histosols and can be described as wetlands under decreased eolian input. The Icelandic Histosols are often thick, up to 7m. Histic Andosols are found in similar poorly-drained conditions but their C content is below 20% (Arnalds, 2008).

Gleyic or Hydric (WA) and Brown Andosols (BA)

Gleyic (also named Hydric) Andosols include a range of soils with organic C < 12% in surface horizons. The term "hydric" is used for Andosol with very high water retention ability (Encyclopedia of Soil Science, 2009).This soil type is dominant in wetland areas in the central highlands where eolian deposition is relatively rapid (Arnalds, 2008).

When not disturbed by thick tephra deposits, the Icelandic Brown Andosols contain around 6% C.

Vitrisols

The Vitrisols are the soils of the deserts, these black areas dominated by basaltic tephra. They lack the vegetation cover that is necessary for the formation of Andosols; they are therefore infertile, contain limited amount of organic carbon (<1%) and are subjected to intense surface processes such as erosion. The Vitrisols have typical physical characteristics of sandy soils, such as low water holding capacity and rapid water infiltration in summer.

The absence of andic properties makes Vitrisols less sensitive to freeze-thaw cycles than Andisols, but a specific cryoturbation process can evenly occur. Freeze-thaw cycles are heaving the rocks to the surface, leading to the creation of typical desert pavements (Arnalds, 2008).

Vitrisols are rather different from the other soils found in the sample; but soil classes have nevertheless been kept separated, without creation of categories and so for two reasons. First because no sufficient bibliography have been found on the effect of soil class to allow any comparison; second because Vitrisols show the lowest number of observations and can't be gathered with any other class. Making groups with other classes and leaving Vitrisol alone would do nothing but stress the existing unbalance between observations.

2.2.1.3.3. Soil thickness and soil base

The favorable or unfavorable characteristic of the surface is not enough to qualify the whole ground. The soil class and its thickness also have a role to play; then the involvement of soil base depends on the soil thickness. In case of a thick soil (more than 50cm), roots probably never reach the base layer. The properties of the might be much more influent than the soil base's. But in the situation of a thin soil, then soil base might rule the risk of summer drought and winter drought. With an impermeable layer that neither roots nor water can cross, water stagnation or drought could occur since the soil's water capacity is easy to fill or empty, especially when there is no surface (mold) or under a surface of sand or pumice. It also means no possibility for roots to pump liquid water when the upper part of the soil is frozen, thus enhancing the risk of winter drought. This is even more likely to be true for spruce, since its root system is located close to the surface. If spruces manage to grow anyway, then their limited root system makes them more sensitive to wind snap.

Soil thickness was initially showing 4 types: 0-25cm, 25-50cm, 50-100cm and >100cm. A new predictor has been built, showing 2 types: <50cm and >50cm. The limit of 50cm has been chosen because when Christmas tree spruces (which always correspond to juvenile spruces) are dug up, their root system has never been found after 50cm deep.

Concerning soil base, the main interesting property could finally be its impermeability to roots and water. The 8 classes have thus been split into two groups to create a new predictor: "likely to be impermeable" (simply named "impermeable") and "non impermeable" base layer. The table 4 shows the original and new classes for soil base.

Table 4: soil base classes of the inventory and their corresponding new categories

Icelandic name	English translation	Category
Urð	Scree	Non impermeable
Jökulruðningur	Moraine	Non impermeable
Möl	Gravel	Non impermeable
Sandur	Sand	Non impermeable
Skriða	Mountain slide	Non impermeable
Hraun	Lava	Impermeable
Klöpp	Rock floor	Impermeable
Móhella	Solid ash/sand plate	Impermeable

This description of the main Icelandic soils and their evolution is valid between volcanic episodes, with a given amount of materials at the soil surface. Soil class is likely to affect vegetation through its inherent properties, such as water retention or nutrient availability. Soil class has therefore been chosen as a predictive factor. However, the description of soil at a given time is not enough when considering vegetation development. Iceland's history and present are marked by frequent volcanic eruptions that affect soil properties and ecosystems.

2.2.1.4. Shelter from mechanical aggressions and micro-climate variations: topographic factors

Just as soils, vegetation is submitted to climatic and damaging factors. Wind brings both dust and ice particles that physically damage the leaves, and in addition might bring salt that penetrate in the leave and generate other damages. Finally wind can cause desiccation of seedlings. Factors controlling the severity of such phenomenon can be separated into two groups, those that cause damages and those that provide shelter against them. The first group, mechanism and context in which these damages occur, will be developed in the next paragraph dedicated to wind action and climatic factors. Concerning the shelter, vegetation cover has already been mentioned as non-negligible factor. At a broader scale, micro and "macro" topography should also make a plot exposed or sheltered. The selected indicators for topography are, from broadest to smallest scale, Topex (contraction for "topographic exposure"), slope direction, curvature and surface roughness.

2.2.1.4.1. Topographic exposure: TOPEX

Exposure and climatic variables are strongly linked. Indeed, exposure is defined as the positioning of a location in relation to climatic variables (Whittow, 1984). In the inventory context, a "location" is a plot. Each plot can be defined in terms of altitude and aspect; altitude controls the temperature with respect to lapse rates, whereas aspect modifies temperature by controlling the quantity of short wave radiation received at the surface. Variations in local climate due to altitude and aspect can be quite considerable. For example, Oke (1987) states that south facing slopes in Turkestan receive three times more short-wave radiation than north-facing slopes. So goes on for other climatic variables such as precipitation and wind. Exposure information can then be combined with other predictors to determine its exact role in tree survival.

Measuring exposure

Determining this exposure is not easy, largely because each obstacle causes an impact on local airflow.

TOPEX is one of the methods developed to assess topographic exposure and was developed by Pyatt (1969). TOPEX is an empirical method which provides a numerical measure of the degree of shelter. This measure is an index derived from the quantitative assessment of horizon inclination Despite its simplicity, the technique provides a good approximation of exposure; TOPEX values are closely correlated with wind-shaped trees such as the Sitka spruce which grows above 200m in Britain (Quine, 1989).

The scores lie in the range of 0 to 720, with low values indicating a lack of local shelter. For example, 0 would represent a situation upon the apex of a hill.

Assessment method

For each plot, the angle of elevation to the horizon was measured (negative angles count as zero). The process is then repeated for all eight of the cardinal compass directions. The final TOPEX score is the sum if the eight inclinations. This method is therefore rather adapted to sites showing young (small) trees, since they are not causing any trouble to match the horizon. In addition to this original method, a specific application was developed here: a double Topex. Two measures were taken:

- a "local" Topex, obtained with measuring the angle of elevation to topography in a 50m circle (named Topex50).
- a "regular" Topex, obtained classically with the angle to the horizon.

Transforming the index into qualitative exposure

At what value does an area become exposed? The classification suggested by Wilson (1984) is shown in Table 5 with the threshold for exposure here being set at 60.

Score	TOPEX Class
0–10	Very exposed
11–30	Severely exposed
31–60	Moderately exposed
61-100	Sheltered
>100	Very sheltered

Table 5: Topex values and their interpretation.
adapted from Wilson (1984)

The use of classes provides the advantage of multiplying observations for one value of the predictor and giving a "reality" to the index.

Three predictors for Topex were finally included in the dataset: Topex 50 and Topex (quantitative), Topex class (qualitative).

The slope direction has also been assessed and mentioned as qualitative factor with 9 possible values, one per cardinal direction plus one "undefined".

2.2.1.4.2. Slope direction

The main slope's direction has been evaluated and qualified in terms of cardinal direction. This gives qualitative indication for the topography of the plot.

2.2.2. Presentation of variables non-originating from the inventory

The following predictors have been added; their origin and interest will be presented below.

Table 6: variables not originating from the Icelandic Forest Inventory included in the dataset

Climate	Wind	Topography/geography	
-Mean temperature -Frost probability	- Wind speed - Wind direction - Topex for wind direction	-curvature -Slope -Altitude	-Surface roughness -Distance to the sea

2.2.2.1. Local exposure: curvature, slope, altitude and surface roughness

Topex was already providing information about how local climate might be changed, but its scale was too rough to reflect micro-alterations. For example, the slope's profile can reveal the possible presence of stagnant water. The selected predictor was a topographic index named curvature. Curvature has been calculated with a GIS software (ArcGis) using a numerical elevation model. The model was provided by the Icelandic Forest research station and has a 20 m resolution. The Curvature tool calculates the second derivative value of the input surface on a cell-by-cell basis — in other words, the slope of the slope. The curvature can be used for example to describe the physical characteristics of a drainage basin, giving among others the acceleration/deceleration of flow and, therefore, erosion and deposition likelihoods. The unit of the curvature for a given point is here 1/100th of meters. Three types of curvature are available: the profile will say if a surface is concave, convex or linear and follows the direction of maximum slope. It provides therefore information on the acceleration/deceleration of a flow. The plan curvature works perpendicularly to the maximum slope and relates to the convergence and divergence of flow across a surface. Finally, the "standard" curvature is a combination of both plan and profile curvatures. The figure 13 illustrates the "physical" meaning of these curvature indexes.

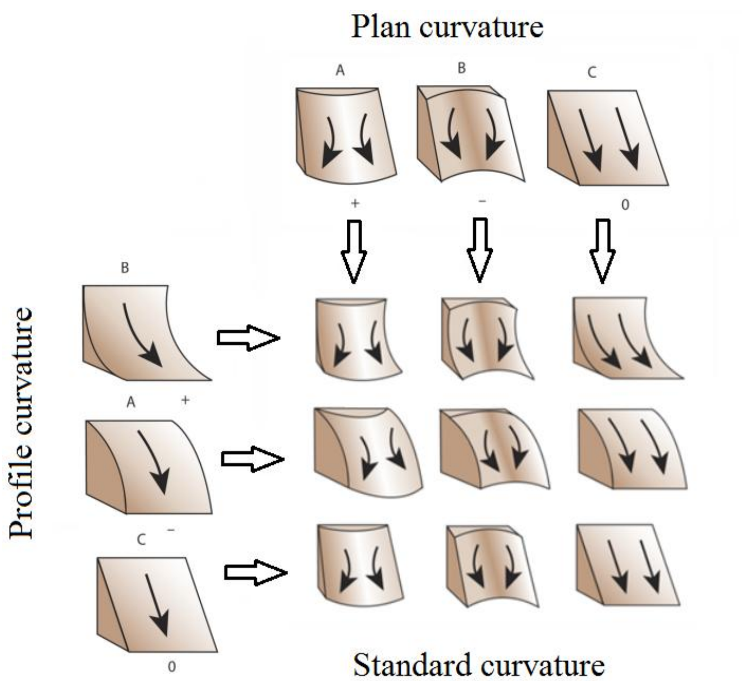


Figure 13: sign of profile, plan and standard curvatures and corresponding surface shapes
source : ArcGis for desktop

The calculation is made for each pixel, using the 8 surrounding pixels. Since the elevation model was 20x20m unit, the area used for each curvature value is 60x60m, or 3600m². This surface is larger than any plot surface (maximum 200m²). The curvature has also been calculated on 120x120m and 180x180m by applying an aggregation operation to the elevation model. 3 scales thus have to be tested.

Even at a smaller scale, the surface's aspect is defined by obstacles such as trees and rocks. The presence and type of obstacles can be sum up by an indicator: the surface roughness. This surface roughness has to be taken into account when estimating the local wind speed: indeed, vegetation provides a sheltering effect to the soil surface in that it absorbs a fraction of the wind force, and this effect increases with increasing surface roughness (Stockton and Gillette, 1990).

The slope value, in %, has also been calculated from the elevation model; same for the altitude. Altitude can be related to many biological processes or other predictors: temperature, frost in the soil, snow cover, etc. Its meaning is not direct but could give a certain lightening on dieback causes revealed by other predictors.

In order to estimate this surface roughness, the following classification has been used (Table 7) as a base. But the surface roughness had to fit the inputs asked for the wind model (see 2.2.2.2.): only values of 0, 0.03, 0.1, 0.4, and 1.5 were possible. 0 and 0.03 are not realistic values for any plot: therefore, only 0.1, 0.4 and 1.5 were possible. The original table as therefore been adapted to fit this wind model: the adjustments are shown on the right column of the table. The detailed method followed in the thesis, using the information provided by the inventory (concerning trees and presence of rocks on the surface) is shown in figure 14.

Table 7: field description and corresponding surface roughness length
adapted from WebMET.com: The Meteorological Resource Center

Terrain Classification in Terms of Effective Surface Roughness Length, Z_O		
Terrain Description	**Surface roughness**	**Surface roughness used in the study**
Open sea	0.0002	---- (no plot located in the sea)
Open flat terrain; grass, few isolated obstacles	0.03	0.1
Low crops, occasional large obstacles	0.1	0.4
High crops, scattered obstacles	0.25	0.4
Parkland, bushes, numerous obstacles	0.5	0.4
Regular large obstacle coverage (ex: forest)	0.5 – 1	1.5

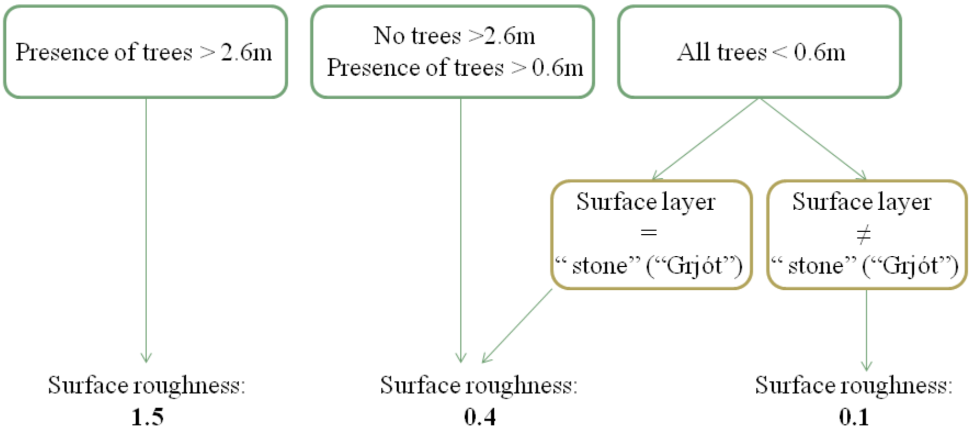


Figure 14: method followed to find out the surface roughness best value for each plot

Exposure has been described at different scales, the largest being defined by the horizon and the smallest by human-sized obstacles such as stones and trees. Exposure might have influence on water flow, temperature and wind force.

2.2.2.2. Wind, a factor both destructive and improving

2.2.2.2.1. Wind has influence on soil properties

Wind is highly involved in soil formation and evolution in Iceland. Active eolian processes lead to a steady flux of eolian materials: source areas show massive depletions, while sink areas' surface level rise at a rate ranging from less than 0.001 to more than 1 mm/yr (Arnalds, 2000). The source of the eolian materials is mostly sandy desert areas located on the active volcanic zone, and glacio-fluvial floodplains. Distribution covers large areas, both oceans and terrestrial surfaces (Arnalds, 2013); ecosystems benefit of these additions. Pelzer *et al.* (2010) even proved rejuvenation with nutrient rich materials to be necessary to prevent ecosystem retrogression. The organic rich surfaces are buried by these constant inputs, increasing the total content of organic materials in the soils. The surface is therefore young, eolian processes continuously modifying the soil environment by recharging the system with fresh parent material and cold climate slowing pedogenic processes.

Deposition can occur simply because of gravity, but also on the occasion of precipitation episode. Low wind speed and high surface roughness encourage the deposition. The materials are more likely to stay if they are dropped on a water body, moist ground or a vegetated surface. Indeed, particles deposited on bare surfaces have a high probability to be moved again, notably by saltation. Saltation is transmission of movement from partciles to other: the collision of moving particles causes new ones to be lifted up briefly before they hit the ground, causing further collisions; this is the most aggressive form of wind erosion (Ravi *et al*, 2011). At a broader scale, annual changes in the amount and seasonal distribution of precipitation, modulated by vegetation growth or die-off and by change in the physical and chemical state of surface sediments, should be important controls on dust accumulation rates (Reheis, 2006).

Topography is also a major factor ruling the deposition of particles, and more precisely the relationship between wind system and topography. For example, low-level wind systems tend to favor dust deposition when the air reaches a topographic barrier (Pye, 1995).

Both wind direction, to be put in relation with topography, and wind speed have to be tested.

2.2.2.2.2. Wind is directly involved in several dieback processes

Several damages can be related to wind action: desiccation and impact of wind-transported materials, mostly ice and salt. Such impacts induce abrasion, which may cause water stress, death of needles and a consequent reduction of the photosynthetic area of the plant (Alder *et al*., 2013).

Desiccation occurs when a warm and dry wind blows on trees standing on a frozen soil. Such winds — named föhn or foehn winds — form when an air mass is releasing its water on a mountain side, before going over the mountain and warming up when going down the slope. Elevated wind speeds are said to remove the moist boundary layer of the needle, thus bringing dry air in contact with the epidermis. The resulting increase in vapor pressure gradient elevates the transpiration rate (Baig and Tranquillini, 1980). Few days of high warm wind blowing on frozen soils is enough to induce severe damages. The effect of wind is exponential and affects all the more trees that they are small, due to their limited water stock. A desiccation event is therefore temporary and will induce diebacks only under very high wind conditions, when a föhn wind is moving at high speed.

Even if the conditions are met, desiccation can be significantly tempered if vegetation is sheltered. Topographic exposure and surrounding vegetation have already mentioned as possible sheltering factors, to which snow can be added: trees covered by snow are at 100% humidity and protected from wind.

Salt damages can be very impressive, but once again special conditions need to meet for a salt event occurs. Salt can injure trees by mechanical or chemical action; nevertheless spruces are quite salt-tolerant so the chemical effect probably not very important. The concerned factors are:

- air humidity:
  - under 75%, the droplets forming above the sea dry out instantly and release their chlorine, which therefore is transported under a solid form. These particles might cause damages by mechanical action, bombarding the needles' surface.
  - if 75 < humidity <100%, the chlorine is transported in the droplets; their size and concentration in chlorine are functions of humidity, with a maximum around 80%. If droplets reach the buds' surface, a diffusion phenomenon occurs. Salt accumulates under the impermeable layer that protects the primordia. At bud beak, the impervious layer is dissolved, water exchanges occur and the salt reaches the primordia.
  - at 100%, droplets get too heavy and fall and are therefore not transported any further.
- wind flow type and speed: turbulent flow favors the transport; the higher the wind speed is, the more particles are accumulating in air masses. Extreme speed episodes are causing the most severe damages.
- rain: a precipitation episode would wash the air from its salt, thus preventing any further damage to vegetation.

Sand, ash and pumice can also have a negative mechanical action on trees, severely affecting growth on small trees (less than, say, 4 meters high) and even killing the smallest. Once again, a combination of factors is necessary, here mostly involving wind speed and particles availability. Precipitation records would have been a plus, unfortunately no reliable records were available for all plots.

Wind is the vector of several harm or dieback causes; a combination of conditions has to be met for the event occurs, and a significant wind speed is always one of them; the higher the speed will be, the more intense the impact will be. Only an extreme wind episode or the repetition of high wind speed episodes may be enough to cause diebacks and therefore be visible in our sample. In other words, the occurrence of high and wind speeds is more likely to induce a high dieback rate than mean wind speed. The extreme values of wind speed will therefore be selected for the dataset.

The wind direction also turns out to be important, in the way that it determines if the damaging agents are on its trajectory or not. Is the wind frequently blowing from the sea? From a glacier? From a volcanic area?

It was unfortunately impossible to make statistics from direct wind measurements neither on wind direction nor on the frequency of high wind speed episodes, since several plots are located too far from wind stations. Wind speeds and directions values were obtained from a model: the Wind Atlas.

2.2.2.2.3. Origin of the wind data

The Icelandic Meteorological Office is offering a free use of the Wind Atlas, a model recently build on the base of the Weather Research Forecast (WRF) model. The WRF model integrates mainly air temperature, wind speed and air pressure measurements and a ground elevation model. Records have been assimilated and analyzed to build a model that is then discretized, spatially and temporally, and values are spread on grids (Skamarock et al., 2008). A 3km grid-point spacing has been used in the wind power assessment project for Iceland: the Wind Atlas.

The Wind Atlas is locally providing some coefficients that, once crossed with altitude and surface roughness, allows to calculate the maximum wind speed for 12 directions (from 0 to 320, with 60° pace). Two wind speeds have been kept for the dataset: the highest and the maximum speed for the most frequent wind direction.

For more detailed explanation concerning origin of the Wind Atlas and wind speed calculation, please refer to Annex 2.

Seen the origin of the data, these wind speeds might include on the one hand global topography such as large valleys or major mountains and on the other hand very local variations through surface roughness. But the presence of smaller relief is probably not taken into account. This is another interest of using topex, and especially the values corresponding to selected wind directions: it might have influence on the wind speed provided by the wind model, as summed up on figure 15.

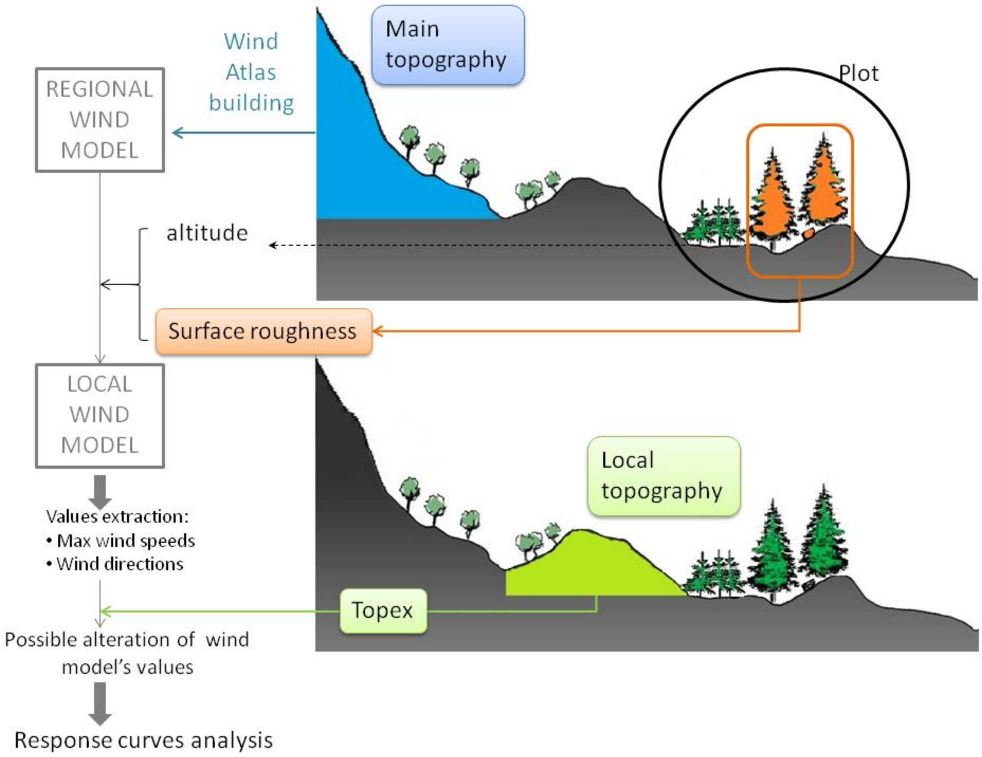


Figure 15: origin of the wind data and possible alteration of the values. Wind data was obtained through wind model that request input of altitude and surface roughness. The values of wind speed calculateed by the model might be altered by local topography, represented by Topex.

2.2.2.3. Influence of the proximity to the sea

If wind is the vector of damaging particles such as salt and if exposure might be responsible for the degree of sheltering, some plots might also be protected from salt damage due to the remoteness from the sea. The relation between distance to the sea and death is not expected to be simple, but this distance could be part of the group of factors that control the exposure to damaging agents (with topographic exposure, wind speed, etc).

Therefore, the shortest distance from each plot to the sea was calculated in ArcGIS 10.3.1.

2.2.2.4. More exposure factors: Topex and wind

A new indicator, a particular version of Topex, has been created to isolate the influence of Topex on wind for each plot. Since the global Topex is the sum of 8 Topexs, one per cardinal direction, it is possible to pick for both wind directions (direction for maximum wind speed and most frequent direction, see 2.2.2.2.4.: From the WRF model to the Wind Atlas) the corresponding Topex. For example if the wind is blowing from north, the Topex for north will be picked. Since I focused on local influence, the Topex at 50m has been chosen.

A high value of Topex could mean a good shelter for this plot from this wind direction. But in certain cases like föhn winds, the worst position is actually the slope itself, since the wind is flowing down from the top of the mountain. This is probably concerning the highest values of Topex.

2.2.2.5. Mean temperature: a global mean

Evergreen trees are likely to suffer from frost all year around. In the winter, desiccation might occur as soon as the ground is frozen; in the spring and summer, for actively growing individuals, a frost reaching -3°C causes damages on flushing shoots (Örlander, 1993). Indeed, shoots are then dehardened and likely to experience frost damage. Such damages affect especially small trees, since their resilience to partial dieback is very limited. In addition, young trees are likely to produce a late summer flush of growth; contrary to srping shoots, the late shoots are very sensitive to frost (Mc Cracken *et al*, 1985). Concerning winter frost, the idea was to pick occurrences of situations possibly leading to frost of the ground: several days of intense frost. About spring and summer frost, the aim was to pick frost episodes (at least -3°C) following a warm period.

A network of stations measuring daily temperatures exists in Iceland. The Icelandic Met Office provided all monthly averages available, recorded between 1970 and 2015. Each plot has been linked to a weather station. Unfortunately, there were so many records missing that building the hoped dataset turned out to be impossible. A coarser temperature dataset has therefore been built. For all years offering 12 monthly averages, a yearly mean has been calculated; then a global mean with all available yearly means has been put in the dataset. All plots have a global mean temperature, based on several years of records — at least 5, up to 10 for some plots. The sampled years are variable; the temperature evolution due to global warming has been considered as negligible for the sampled period.

2.2.2.6. Impact of frost during the growing season: a frost probability model

The variability of low summer night temperatures is of crucial concern for the survival and progress of young trees as shown, for example, by Christersson (1971) and the implications of frost during the peak of the growing season is of specific importance for the establishment and development of conifer saplings (Li and Sakai, 1981). Direct temperature measures were not allowing a research for frost episodes; but a model giving the probability of occurrence of frost in August has been built for Iceland (Þórbergur Hjalti Jónsson and Björn Traustason, unpublished). This model is available under GIS software; the probability of frost has therefore been extracted for all the plots.

2.3.Data analysis: methodology

2.3.1. Objective: a predictive model

All predictors that were assumed to have an influence on dieback have been introduced. The variable to be explained was binary: 0 if no juvenile spruce was found dead on the plot, 1 if at least one death was observed. Then, I wanted to bring out the underlying concept that links some of the predictors to our binary variable, which could be done through regression. More precisely since the response variable was Bernoulli-distributed and there were more than 3 predictors to test, I used multiple logistic regression. The statistical analysis was assumed to help me finding out which predictors were actually responsible for the observed death and survival in the sample. Then, according to the strength of the model, this selection of significant variables could be converted into guidelines for future planting sites' choices. The objective was therefore to get a predictive model and know within what limits conclusions could be drafted and adapted to future plantations. The model was used as a selective tool in order to get a qualitative result; the formula was not a result in itself. The values of parameters have not been analyzed. The model has not been build to quantify their respective actions through the regression's parameters. Concerning the reasons why selected variables have actually been picked, or in other words how each selected factor is affecting the trees, hypothesis could be made but causality seeking was not the purpose of the model.

The dataset is showing 47 predictors, 25 are quantitative and 22 are qualitative. The list with summary of meanings is given in Annex 1.

Firstly, the variable selection method will be described. Secondly the model evaluation process will be detailed, both in terms of statistic validity and in terms of efficiency.

2.3.2. Variables selection: a two-step method

The 50 predictors were gathered because all of them were assumed to be related to the death of juvenile spruces. I could therefore simply use automatic selection to highlight those that really had influence on our variable to be explained. Then according to possibility to give an interesting meaning to each selected variable, a second selection was made. This method was adapted to the exploratory context in which the thesis is taking place. But this method relied entirely on the information carried by the sample, which by definition represented only a partial truth and carried a part of randomness. Despite its apparent rigor, the process then showed weaknesses. First the variable selection would have then been purely statistical, based on mathematic criterions whose value might change from a sample to another due to the part of randomness (Rakotomalala, 2014). The conclusions then might have reflected some reality that would have actually been nothing but a specificity of the sample, and not a global truth that could have been generalized to the whole country. This was all the more true here since the present dataset had quite few observations compared to the amount of variables. Second the automatic selection is disconnected from biological or practical considerations. The result would have been nothing more than what the dataset could say; if a high number of predictors were necessary to explain the sample, the resulting overfitting would have made interpretation quite rough and generalization impossible (Occam's razor principle).

Another option was then manual selection. Predictors that were most suspected to be involved in spruce dieback were tested in priority and added to the model if they turned out to be statistically significant. The assumption of involvement was based on a clear and rational hypothesis concerning the biological action of the predictor, supported by bibliographic research and/or expert suggestion. The selection was here made before the statistic test, contrary to the automatic selection. With that method, some tested variables were selected despite a weight that might be only average, thus confirming some hypothesis that automatic selection would have ignored. But some other predictors that have important statistic weight can then be missed, if they were not assumed to be so important when hypothesis were built. There are several possible reasons for this: the predictor the possible biological meaning is not obvious, only little bibliography found about it...In addition, all predictors have been added to the dataset because they were assumed to have some influence; if bibliographic research could allow prioritizing few predictors, there might be a remaining soft underbelly that bibliographic knowledge does not allow to rank.

Both methods had pros and cons; in the present thesis, they have been combined. I did not want to make a "blind" selection only based on pure statistical analysis and I did not either have enough background knowledge to support a selection only manual. Some hypothesis concerning predictors most likely to be significant could nevertheless be made, and these predictors have been manually tested first. This resulted in a temporary model. Then this model was used as a base for automatic selection. The steps are summed up on figure 16 (see 3.1: Selected predictors), with the number of predictors kept at each stage.

Several criterions have been used to decide, for each variable, if it was kept for the model or not.

2.3.2.1. Manual selection

2.3.2.1.1. Choice for variables: hypotheses

Bibliographic research and experts' observations allowed building few hypotheses on factors most likely to be linked with our survival probability.

Factors were gathered into categories according to the influence they might have on tree life:

- Pedogenic and vegetated context
- Topographic context of the planting site
- Factors that tend to disturb this context
- Sheltering factors that oppose to these disturbing.

In each category, the influence of some predictors has already been studied or at least noticed. They have been therefore tested in priority:

- Pedogenic and vegetated context: as soon as they are planted, seedlings are submitted to several stresses: for water, nutrient, root system settling. Thus the **type of surface** and **soil** might be highly important to explain early diebacks. **Soil thickness**, **Soil base type, Vegetation class** and **% of cover** have to be tested too since they are also ruling the water and nutrient content, the last two as competitive and stability factors.

- Topographic context of the planting site: **Topex** and **slope** are partly controlling the water and nutrient content. They were also tested as sheltering factors.
- Disturbing factors:
    - wind was highly foreseen as a possible cause for dieback due to its involvement in direct damages and its erosive action on the environment. **Maximum wind speed**, absolute and for the post frequent wind direction, has therefore been tested.
    - Frost during growing season might be responsible for diebacks even in apparently favorable sites; hence the **probability of frost** occurrence in August has been tested.
- Sheltering factors: since wind was studied, shelter from its effects had to be tested.
    - Shelter provided by topography: **curvatures** and **indicators** based on Topex
    - Shelter provided by vegetation: vegetation class and cover have already been mentioned; the **age structure** was also added, the presence of high trees and different stages being expected to provide safer conditions than even-aged and very young forests.

2.3.2.1.2. Selection iterations

The selection procedure was rather simple: starting from a null model, a first predictor has been added and the new model was tested. If the test was negative, the predictor was removed and another was tested. If the test was positive, the variable was kept and a new one was added to the model, this second model was tested as the first had been and the process repeated until all of the 19 predictors had been tried.

2.3.2.1.3. Criteria for manual variable selection

Here the different tests performed at each iteration will be described. The test was based on two principles: model fitting (to the dataset) and comparison of nested models. The goodness of fit has been tested through 3 parsimony criteria: Bayesian and Akaike (regular and corrected) information criterion (respectively BIC, AIC and AICc.) All are based on the logarithm of the maximum likelihood with a penalty added for the number of model parameters. The BIC is more sensitive to the number of parameters, and the AICc is recommended in case of low number of observations compared to the amount of factors (Hurvich and Tsai, 1995).

The parsimony criteria of the null model has been calculated and used as a reference for the first variable selection. When the first variable was kept, the new model became the reference.

The null model has also been used to help decision when the result of parsimony criteria was not entrenched. The temporary model's efficiency was then evaluated through a likelihood ratio test.

Manual selection was therefore based on statistical criterions but the decision was also taken considering biological hypotheses. A variable strongly assumed to be significant and moderately convincing statistically speaking could be kept.

Automatic selection was then performed starting from the manually built model.

2.3.2.2. Automatic selection

Since predictors had not been controlled to be studied separately, many models were possible, corresponding to the possible predictors' combinations. These combinations included direct effect on the dieback and interactions between predictors. Hypotheses for manual selection were mostly concerning direct effect; if certain variables have not been tested because no strongly supported hypothesis could be made about them, they could actually be significant when combined to others. And of course some predictors that were not expected to be that significant could have turned out to be rather important. In order to avoid such lack in the model, automatic selection has been performed. The input model was the result of manual selection; then automatic iteration was performed by the software. The process was basically the same as manual selection: one predictor was added, tested with AIC criterion, and automatically accepted if AIC lowers/rejected if AIC remains steady or increases.

2.3.3. Variable response: model predictions

Once variables selection was done, I knew which have an influence on dieback but remained the question: how? Could I find a positive, negative or changing correlation between death probability and the factor?

The model aimed to give a qualitative appreciation of each selected predictor's role. It had not been build to quantify their respective actions through the regression's parameters. The influence of predictors has been analyzed through response curves, showing the predicted probability of dieback according to the predictor's values.

Using the model, a prediction of the 138 dieback probabilities was calculated for each predictor: the calculation was run using its original values while the other selected factors are fixed to their mean (for quantitative factors) or the mode (for qualitative factors). It was then possible to draw a graphic representation of the dieback's response to each predictor. The figures 16a and 16b provide comparison between the simple graphic display of the variable to be explained against, here, maximum wind speed; and the predicted probability of the variable to be explained, still against maximum wind speed.

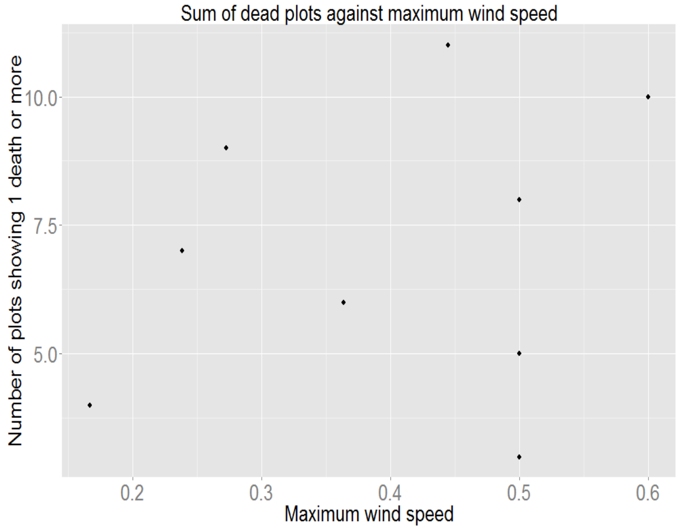


Figure 16a: sum of values of the variable to be explained (O/1) against the maximum wind speed.

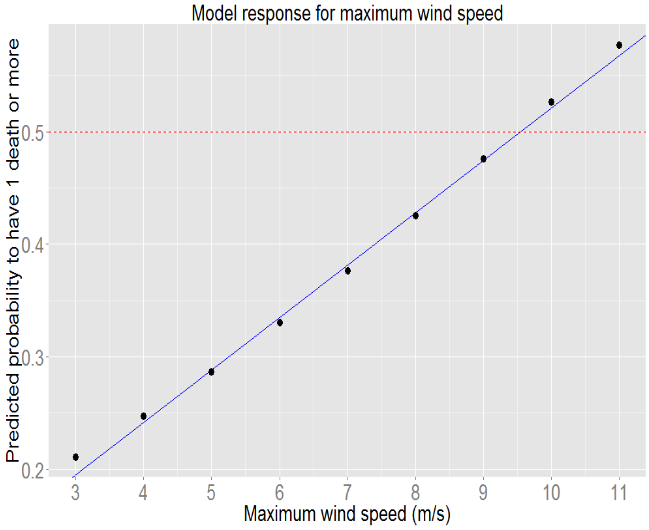


Figure 16b: predicted probabilities to get value "1" against maximum wind speed

2.3.4. Model evaluation

The model has been evaluated according to two axes: its validity statistically speaking (hypotheses concerning the variables' distribution are valid) and its quality (ability to predict values that are comparable to the initial dataset (goodness-of-fit) and number of abnormal values).

Validity was checked through several tests based on:

- mathematical expectation:
  - hypothesis: the expectation of a variable chi-2-distributed is equal to its degrees of freedom
    - ⇨ test: $\frac{deviance_{model}}{deg.freedom_{model}}$
- Residuals analysis:
  - hypothesis: the sum of square residuals tend to a chi-2 distribution.
    - ⇨ Pearson residuals test
    - ⇨ Hosmer – Lemeshow test
    - ⇨ Deviance residuals test
- Pseudo-R^2 calculation

The model quality was evaluated through:

- Classification tables
  - ⇨ indicators: sensitivity, specificity, Matthews coefficient
- ROC curve and AUC calculation

The abnormal values were detected through:

- Normalized Pearson residuals analysis
- Cook's distance.

3. Results

3.1. Selected predictors

After manual and automatic selection, 10 predictors were kept.

Manually selected predictors:
- Vegetation Cover
- Vegetation Class
- Soil Class
- Topex against most frequent wind
- Curvature for 120x120m area
- Maximum wind speed

Automatically selected predictors:
- Topex against wind with highest speed
- Altitude
- Canopy cover: the % of soil covered by projection of trees' crown
- Distance from the plot to the sea.

The low vegetation composition (Vegetation Class) has been selected through manual process; however if this factor was included in the base model for automatic selection, then the automatic process was leading to overfitting with null residual deviance. The automatic selection has therefore been run with a base model from which vegetation class had been removed. When automatic process was completed, the result was a 9-variables model, to which vegetation class was added again to get the final model with 10 predictors.

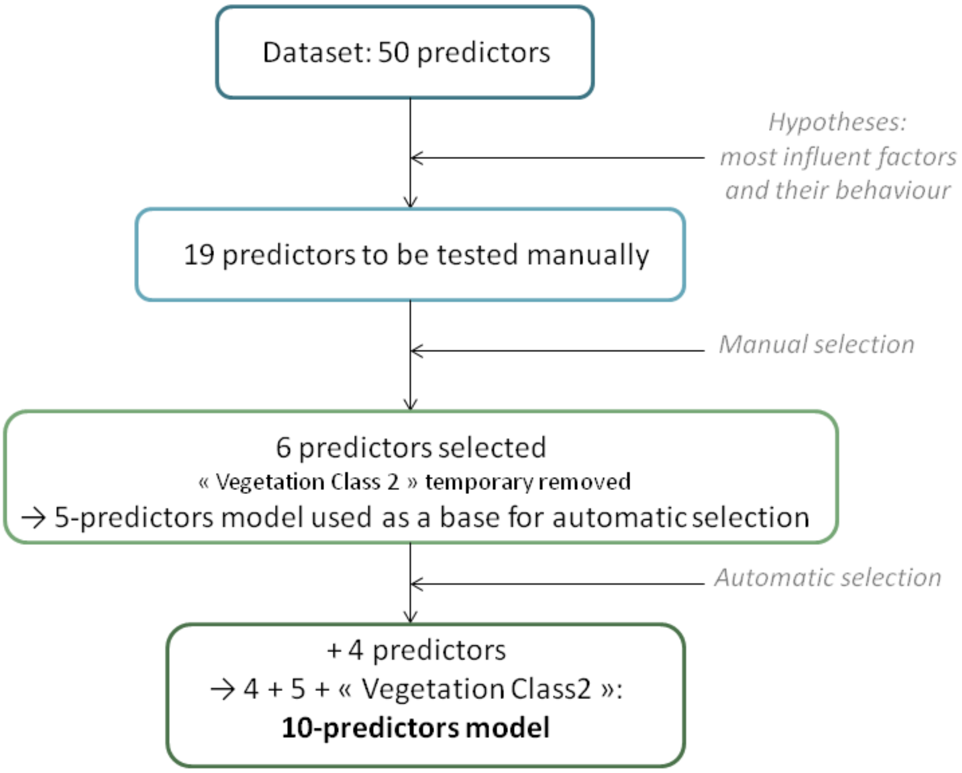


Figure 17: variables selection process and number of variables kept at each step.

As mentioned above, several indicators were used to run the manual selection; in case of contradictory results between these indicators, choice had to be made. The following table deals with the different steps of the manual selection and gives the arguments used in decision taking.

Table 8: manual selection iterations. Starting from the null model, one variable w as added and the new model was evaluated. Red values mean unfavorable test (the previous model was better), blue mean favorable (adding the new variable is improving the model), grey means the new predictor is considered neither improving nor not improving.

	AIC	AICc	BIC	Lrtest pvalue	Argument and decision
Null model	186.73	186.76	189.67	_	_
+ SurfaceClass	197	198	220	0.76	rejected
+VegetationClass2	**184.97**	**185**	**205**	**0.03**	**kept**
+Vegetation Cover	**180**	**182**	**209**	**0.003**	**kept**
+Soil class	182	186	**223**	**0.004**	Soil class is not improving the model according to parsimony criteria but the LR test is good. In addition it gave the best result of all pedogenic factors : **kept**
+Soil base	191	199	252	0.01	rejected
+ Soil depth	185	190	235	0.005	rejected
+Vmax (max)	183	187	227	**0.004**	Same as soil class**. kept**
+Age Structure	187	194	243	0.009	rejected
+Vmax (most frequent wind direction)	184	188	231	0.005	Does not improve the model and a wind speed factor has already been taken (Vmax(max)) : rejected
+Augustfrost probability	189	190	218	0.0767	rejected
+curvature 60x60	188	190	218	0.0722	rejected
+curvature 120x120	183	187	**230**	**0.0039**	Curvature seem to have importance; curvature 2 is showing the best indicators**: kept**
+curvature3 180x180	182	188	241	0.005	rejected
+Topex most frequent wind	183	188	233	**0.004**	**kept**
+ Topex max. wind speed direction	185	190	234	0.006	Not improving and a very close predictor has been kept: rejected
+ slope	184	191	240	0.004	rejected

The automatic selection finally kept the Topex against the fastest wind, in addition to altitude, canopy cover and distance plot-sea. The response curves for all these predictors were also calculated, and the interest and use of the predictors will be discussed in chapter 4.

3.2. Model evaluation

3.2.1. Model validity

All the validity tests mentioned above turned to be satisfying. The results are displayed in the table 9 below. The model can therefore be used for prediction and analysis of variables' response.

Table 9a: model validity tests and their results

	Mathematical expectation	Residuals analysis			Pseudo-R^2 (Mc Fadden)
Test	$\frac{deviance_{model}}{deg.freedom_{model}}$	Pearson residuals test	Hosmer-Lemeshow test	Deviance residuals test	$\frac{deviance_{null} - deviance_{model}}{deviance_{null}}$
Criterion	≈ 1	p-value > 0.05	p-value > 0.05	p-value > 0.05	> 0.2
Result	1.16	0.14	0.35	0.11	0.26

3.2.2. Model quality

In order to compare the model predictions and the original data, a classification table has been built (Tables 9b and 9c). The predicted probability to observe a dieback is compared to a threshold (or cutpoint) and hence converted into a predicted observation. Here the cutpoint is 0.5: every time the predicted probability was less than 0.5 the value "0" was kept, "1" else.

Table 9b and 9c: classification table (meaning and obtained values)

		Data value	
		0	1
Predicted	0	True Negative	False Negative
	1	False positive	True Positive

		Data value	
		0	1
Predicted	0	70	22
	1	14	32

To analyze this table, several indicators have been calculated (Table 9d).

Table 9d: quality indicators based on classification table and their result

Sensitivity	Specificity	Matthews correlation coefficient
Ability to predict the occurrence of death	Ability to predict the occurrence of survival	-1: model predicts opposites values from the data 0: random prediction 1: prediction matches perfectly the data
$\frac{TP}{TP + FN}$	$\frac{TN}{TN + FP}$	$\frac{(TP * TN - FP * FN)}{\sqrt{((TP + FN) * (TN + FP) * (TP + FP) * (TN + FN))}}$
0.59	0.83	0.44

The comparison of sensitivity and specificity showed that, for a cutpoint of 0.5, the model was satisfying in terms of survival prediction but less efficient for diebacks predictions. This could be caused by the unbalance in the dataset in favor to 100% survival situations (54 against 84). The evolution of sensitivity against (1-specificity) for cutpoints varying from 0 to 1 has been be displayed through ROC curve (Receiving Operating Characteristics), presented on figure 17. The straight line represents a random model, with a discrimination of 0.5. The discrimination is the estimated probability that, under the fitted model, a plot showing "1" will be given a higher death probability than a plot showing "0". It is reflected by the area under curve (AUC). The closer the AUC gets to 1, the better. Hosmer *et al.* (2013) describes the following rule of thumb often used to qualify the model discrimination (Table 10). The calculated AUC for the model was 0.82. According to the classification, the model discrimination was thus "excellent".

Table 10: Values of AUC and corresponding discrimination level. The AUC obtained was 0.82, which is said to be "excellent". Adapted from Hosmer et al., 2013.

AUC	Discrimination
AUC = 0.5	No discrimination (model gives same result as randomness)
0.5 < AUC < 0.7	Poor
0.7 ≤ AUC < 0.8	Acceptable
0.8 ≤ AUC < 0.9	Excellent
AUC ≥ 0.9	Outstanding

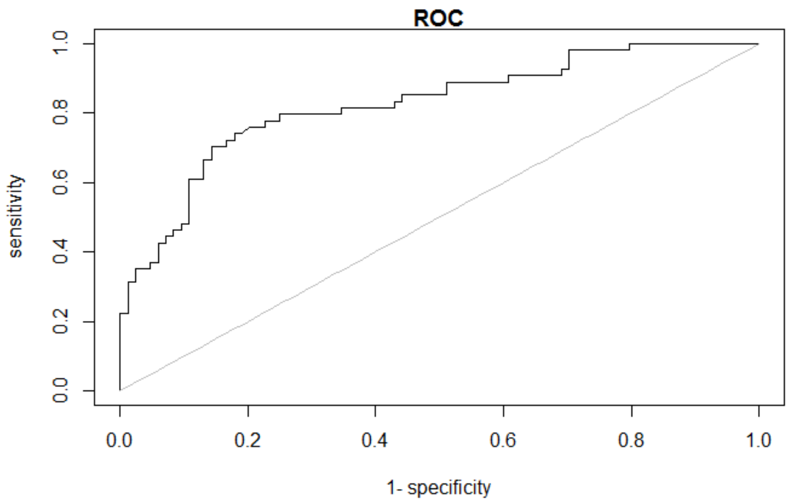


Figure 18: ROC (Receiving Operating Characteristics) curve for the dieback predictive model. The straight line illustrates the result of randomness; the area between the curve and the live (AUC for Area Under Curve) is here 0.82.

3.2.3. Abnormal values detection

The representation of normalized Pearson residuals (Figure 20) allowed seeing abnormal values, here for a threshold of |2|. This corresponds to a 95% confidence interval; 7 plots are concerned, which was not so serious. But the graphic (figure 18) suggested a segregation in the data on either side of the value 55. This corresponded to the two groups of plots: the 54 firsts showing value "1" and the following 84 showing value "0". Abnormal values were mainly found in the first group.

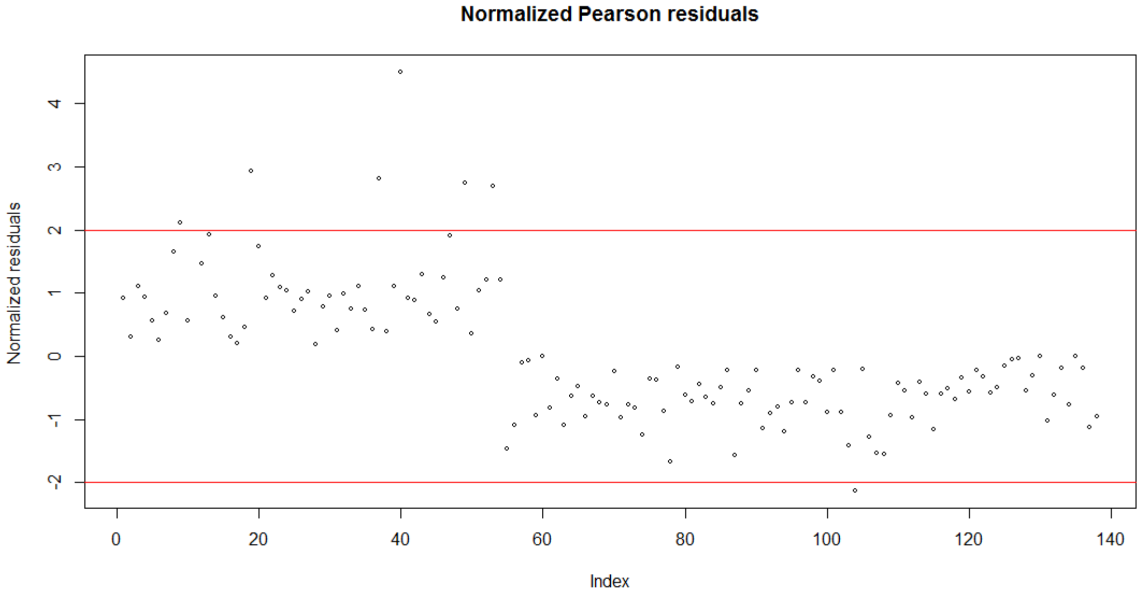


Figure 19: normalized Pearson residuals and threshold lines.

3.3.How selected variables affect the survival: predicted probabilities

After these tests, the model was considered usable: it was fitting statistical hypotheses and its efficiency was correct. A new response has been predicted from this model, a prediction for each plot of the probability to observe at least one dieback. This response was calculated separately for each 10 selected predictors. Each predictor's response could be displayed individually: the calculation was run using its original values while the other selected factors were fixed to their mean (for quantitative factors) or the mode (for qualitative factors). Obtained values are presented in table 11. The obtained graphics were showing the evolution of dieback probability against the different values of the predictor. A value "1" on the y axis meant that 100% of the plots concerned by this predictor realization have been predicted as "1". Modalities associated with a probability of 1were therefore the least favorable for young spruces. The red line displayed on the graphs separated probabilities under 0.5 and probabilities over 0.5, which is the cutpoint used here to convert the probability into predicted value of survival (0) or dieback (1).

The calculation of the probability p was based on the equation obtained by logistic regression:

$$p = \frac{1}{1 + e^{-\beta_0 - \sum_{j=1}^{p} \beta_j \cdot X_j}}$$

with $\beta_0, \ \beta_1, \dots, \beta_j$ the coefficients of the regression and $X_0, \ X_1, \dots, X_j$ the selected variables.

Each value of qualitative variable has been considered as a variable; this is why there was a coefficient per soil type, per vegetation class and cover.

The values of coefficients are given in Table 11, with the averages or modes of each predictor used for the response curves calculation.

Table 11: fixed values of selected predictors used for predictions (2nd line, blue background) and regression coefficients (3rd line, white background).

Vegetation cover	Altitude	Topex (most freq. Wind)	Topex (max wind)	Vegetation class	Curvature	Canopy cover	Vmax wind	Distance to sea	Soil class
91 – 100%	97.63 m	1.49	2.7	Grassland	-0.0058	11%	6.83m/s	16046m	Brown Andosol
	-8.802.e-03	-0.1248	0.009171		1.721	-0.004426	0.2035	4.319.e-05	

Vegetation cover:

34-66%	67-90%	90-100%
17.94	18.59	17.44

Soil class:

Histic Andosol	Histosol	Hydric Andosol	Vitrisol
0.8332	-1.653	-0.2612	0.8566

Vegetation class:

Forest	Lupin	Mói with berry trees	Grassland	Mói	Half wetland/ wetland
-17.12	-17.13	-16.3	-15.35	-14.34	-16.18

The selected predictors related to pedogenic and vegetated context are Vegetation Class, Vegetation Cover in % and Soil Class. To begin with the vegetation class (figure 19), since the variable was qualitative, I got the mean dieback probability for each class. Lands covered with lupine or forest were predicted as the most favorable. Slightly over came "mói with berry trees". The vegetation class "Half wetland/Wetland" also showed quite low dieback probability. A more visible step separated this last category from "Grassland". With a difference even more marked, simple "mói" was less favorable; the apparently worst cover was "Flower field".

The response for vegetation cover (figure 22) showed that dieback probability was null for the lowest cover. The dieback probability increased with the % of cover until 67-90%, and then decreased.

The canopy cover response (figure 23) showed a decreasing curve, with highest dieback probability obtained for 0% cover and predicted probability reaching 0 for 100% cover.

The soil class showing least dieback probability was Histosol, followed by Hydric Andosol, Brown Andosol, Vitrisol and with highest probability Histic Andosol (figure 24).

The predictors that concern wind and its effect were maximum wind speed, topex against most frequent wind direction and topex against the direction of the strongest wind. Dieback proability increased with wind speed. Results for Topexs were opposed: the topex for most frequent wind had negative correlation with dieback probability (the most sheltered places are less likely to experience diebacks) but positive for Topex against direction of maximum wind speed (the plots with low value of Topex are predicted to show the lowest dieback rate). Still concerning topography and geography, altitude, distance to sea and curvature have been selected. The altitude was negatively correlated to dieback whereas the distance to sea and curvature were positively correlated.

4. Discussion: model interpretation, weaknesses and scope of the study

4.1. Model interpretation

4.1.1. Pedogenic and vegetated variables: a combination leading to more or less favorable situations

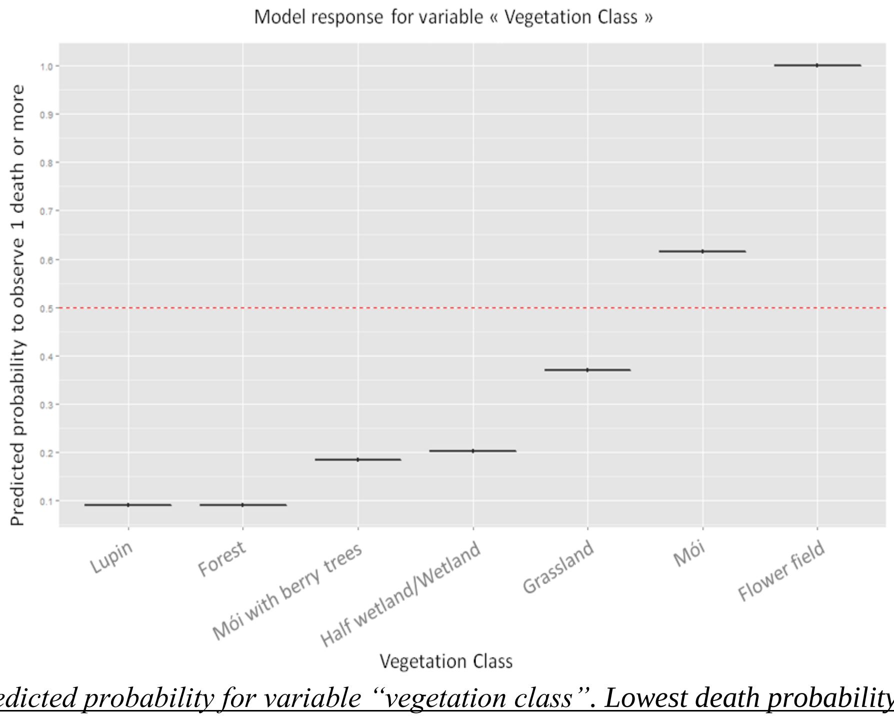


Figure 20: predicted probability for variable "vegetation class". Lowest death probability are obtained with lupine and forest cover, whereas mói and flower field are the less favorable.

The good results obtained by forest and lupines could reflect their improving on soil quality. Indeed, the importance of access to nutrients after planting is a decisive factor for post-planting stress (Groosnickle, 2000). The presence of lupines is leading to significant difference of N content in the soil; forests' soil is more likely to show high organic content, both thanks to the already existing vegetation and to its trapping role for nutrients brought by the wind (see 2.2.2.2.1.: Wind has influence on soil properties). Soil decomposers are also more likely to be present, inducing more active nutrient cycling and thus stimulating the development and the browsing activity of the seedling's root system. In addition, forest is synonym of shelter: seedlings are then less submitted to damaging agents and frost drought that goes with wind. Indeed, Gillette (1979) has shown that the efficiency of the protection provided by vegetation depends on ground surface characteristics like vegetation type, presence of rock…that have influence on surface roughness and that forest appears as the most efficient cover type in terms of limiting the particles export (*Breshears* et al, 2003, figure 21a). Less particles export means less mechanical damage to vegetation, limited lost of soil and thus limited lost in growing surfaces.

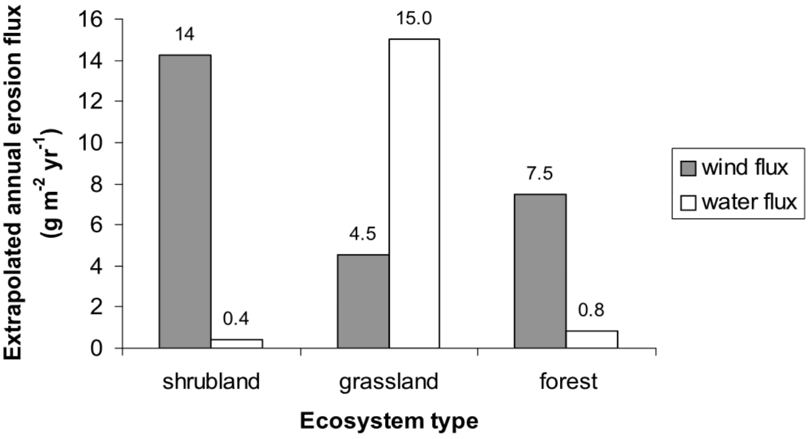


Figure 21a: Annual erosion rates of wind and water among three ecosystems types. Forests offer the 2nd best protection against wind fux and 1st againt water flux. (Breshears et al., 2003)

Before concluding on the positive effect of forest and lupines, it was necessary to check that their presence was not systematically associated with fertile soils. But since the predictor for soil class has also been selected, no obvious correlation should exist. Forest and lupines were found in the dataset mostly on brown andosols but also on histosols and vitrisols. If histosol is a very fertile soil and brown andosol relatively fertile, vitrisol is extremely poor and in addition was here covered by a poor surface (Möl/Sandur/Melur). The low predicted probability of dieback was then certainly due to the favorable pedogenic micro-environment that goes with forest and lupines. Thanks to that, seedlings might overcome more easily the settling stress and increase their survival chances.

Slightly over forest and lupines in terms of dieback probability was "Mói with berry trees". Mói refers to frost heaved land and often poor nitrogen content. The differences in predicted probabilities between "Mói with berry trees" and simple "Mói" were rather interesting: the predicted dieback probability was 0.18 for the first and 0.62 for the second. As shown on figure 21b, this difference was not due to the type of soil: both Mói, with and without berry trees, were distributed on different soil types.

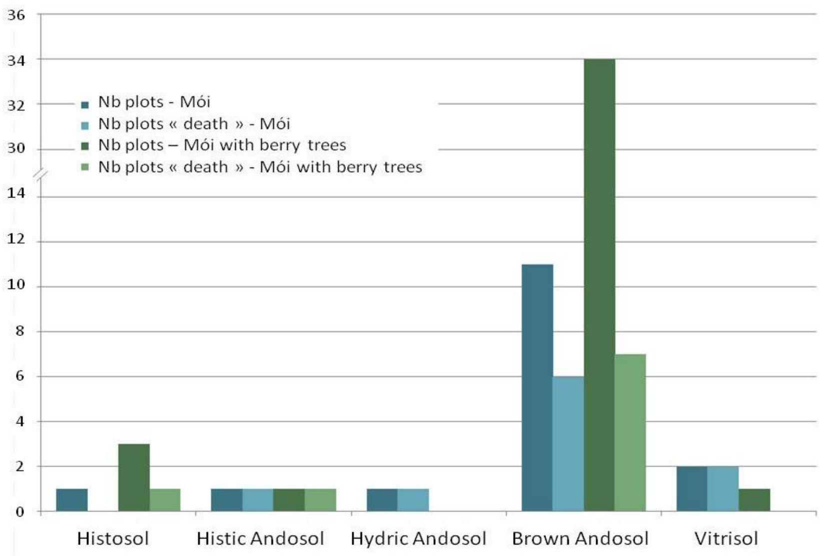


Figure 21b: number of plots and number of "death" plots for 2 vegetation classes: mói with and without berry tree. Both classes were distributed on different types of soil, excluding the possibility that the differences in predicted dieback probabilities would be due to soil type.

The only soil showing enough occurrences to allow comparison was brown andosol. Then the proportion of plots classified "1" (called "death plots" in the graph) for simple mói was 55%, against only 21% for mói associated with berry trees. In order to check this difference cannot be attributed to a correlation with surface class, this variable has been plotted for brown andosol on figure 21c. Once again I did not observe any segregation in the distribution, both vegetation types being found on several surfaces and in similar proportion. For the surface mold/sóp (bare soil/litter), the proportion of “death” plots was higher for simple mói than mói with berry trees. On rougher context (Grjót/Klöpp/Hraun, in english rocks/lava), the tendency also went for presence of berry trees but the low amount of observation did not allow solid conclusion. It can nevertheless be said that for similar pedogenic contexts, the presence of berry trees is likely to improve living conditions for spruce seedlings.

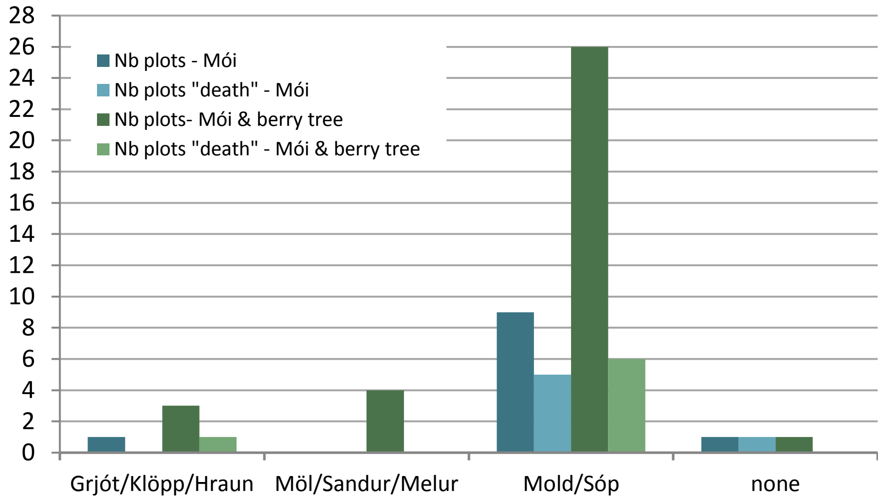


Figure 21c: comparison between plots showing mói with berry trees and simple mói standing on brown andosol, for different surface classes.No correlation can be found.

According to Grau *et al* (2010), the presence of mycorrhiza induced by shrubs could explain the difference of results between “Mói with berry trees” and simple “Mói”, and also with “Grassland”. The early presence of forest or shrubs can induce very local favorable conditions. Grau *et al.* (2010) have shown that in the early and mid succession stages, the presence of *Empetrum* facilitates the recruitment of pine seedlings. But the effect turns negative for late development, supporting thus the hypothesis that the facilitation is effective to overcome a stress such as planting stress. Presence of shrubs turns into negative (due to competition) when conditions are exempt from stress, like in mature forests. Facilitation occurs through several mechanisms: shrubs trap snow and thus provide protection for conifer seedlings, have a direct sheltering effect against wind, enhance soil organic matter content, assure soil development and stability, moderate temperature fluctuations, keep moisture in the soil and induce presence of mycrohiza. More precisely, in case of *Empetrum*, the presence of ectomycorrhizal fungi was enhanced. But for mature forests, the organic soil layer is thicker and retains more allelochemicals, enhancing allelopathic effects of the mycorrhizal symbiosis. By favoring mycrohiza weight, *Empetrum* is aggravating allelopathic effects for mature forests. This *Empetrum* is likely to be present for vegetation class “Mói with berry trees” and all the positive effects described above might be effective, since I focused on young trees.

By definition, a wetland or half wetland do not offer good conditions for trees; but firstly these sites have been artificially dried out more or less intensely, recently or a long time ago; secondly, since spruce has a root system staying close to the surface, a thin and relatively dry layer could be enough. When considering the soil and surface class, all plots turned to be located on fertile soils with favorable surface (Mold/Sóp, in English bare soil/litter). This combination of good nutrient content and litter could constitute good living conditions for spruces. In addition when the soil preparation is taken into account it reveals that from the 15 cases, 8 have benefitted of plough or scarification. 3 of them are “death” plots. When no preparation has been observed, 2 plots up to 6 are “death”. Soil preparation did not show obvious improvement, but could become more useful when root development reaches a certain threshold: if the dry layer is 50cm thick due to the soil preparation instead of only 10 or 20, this could induce better survival through better root development and better stability.

The predicted probability for grassland was 0.37, an average result. Such cover might have both positive and negative sides: resistance to wind erosion and good organic stock but competition for water and nutrients and no shelter. The degree of competition and thus the induced dieback might be leveled by the % of covered soil; the analysis of vegetation cover response goes in that direction (see below).

Finally, concerning the class "flower field", it has been kept as the original category because it was not possible to gather it with other classes but this occurrence appears only once in the dataset. No conclusion can be drawn from this result.

The response for vegetation cover (figure 22) showed that dieback probability was null for the lowest cover. This result was based on only 3 observations; the predicted probability was therefore not usable for itself. In the dataset, the "11-33%"was associated with a cover of "Mói with berry trees" or "Grassland" which were not the best possible cover but not a real threat either, as mentioned before. A good survival rate could be expected on this vegetation classes under the condition of limited cover: competition would be bearable for trees and they could benefit from ground radiation and the mycorrhiza/dust trapping. The dieback probability increased with vegetation cover until 90% and then decreased. This last result for cover of 90 to 100%, based on 88 observations, could be due to the protection that vegetation thus provides to trees against wind erosion, especially saltation which is the most aggressive form of wind erosion. If the soil is covered by vegetation, the aeolian processes induced by saltation (deflation, sediment transport along the surface, airborne dust (suspension), and sedimentation) are limited. Since these processes damage ecosystems and often prevent natural regeneration of vegetation (Armbrust and Retta, 2000; Maun, 1998), vegetation cover indirectly contributes to improving the growing context for seedlings.

Extreme cover values seemed therefore to be the most favorable option; but the result for situation of vegetation cover inferior to 33% had to be confirmed by more observations.

The role of canopy cover (figure 23) seemed to be limited since no dieback probability goes over 50%. The response nevertheless underlined the sheltering effect of surrounding trees; the absence of inversion indicated that even at 100% of cover no competition effect is occurring. This predictor could also be much straightforward — and less useful: a large cover reflects numerous trees, therefore high survival. It could then simply be a direct expression of survival rate.

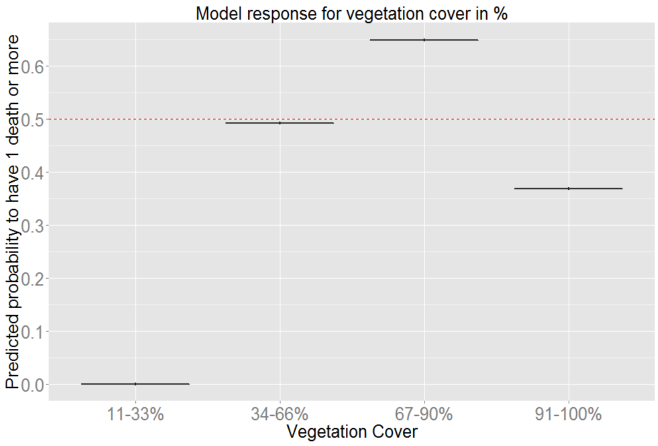


Figure 22: predicted probability for variable "vegetation cover". The maximum dieback is predicted for a cover ranging from 67 to 90%.

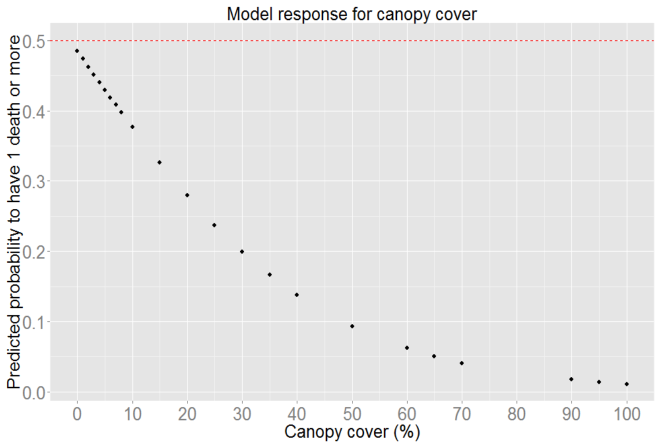
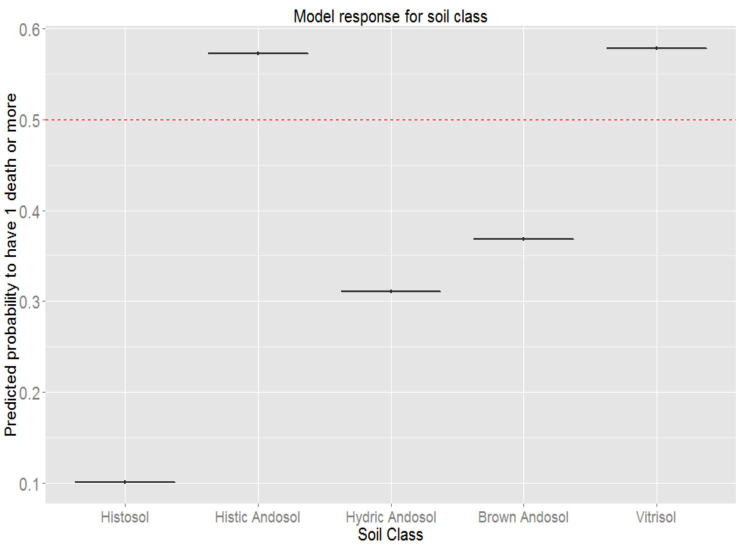


Figure 23: predicted probability for variable "canopy cover". The highest the cover is, the lowest the dieback is predicted to be.



When considering the soil class (figure 24) predictions followed the hierarchy in terms of drainage and organic matter content, with an exception for histic andosol. This astonishing result could be explained on the one hand by the low number of observations (7 plots) and on the other hand by the fact that these few observations also show unfavorable vegetation classes. All predicted probabilities remained under 0.5 except for histic andosol and vitrisol. This result for Vitrisol was not surprising considering its unfertility (see 2.2.1.3.2.), but was also based on only 7 observations.

Figure 24: predicted probabilities for variable "soil class". The most favorable soil was Histosol, the least werevVitrisol and Histic Andosol.
The result for Histic Andosol was nevertheless based on very few observations, thus not significant.

The improving role of the vegetation context has been illustrated through the example of brown andosols, for which the number of observations is satisfying (100plots, which represents 73% of all observations). For equal soil class, the proportion of "death" plots is decreasing when the vegetation class gets better (figure 25).

Given the low diebacks probabilities for Histosols, Hydric Andosol and Brown Andosol, these soil classes are not limiting factors for choosing a planting site. This information is rather a base inducing more or less preparation for planting, rather than a discriminating factor. In other words, it is not necessary to limit the choice of sites to best soils; good results should be obtained on brown andosols with a favorable low vegetation context.

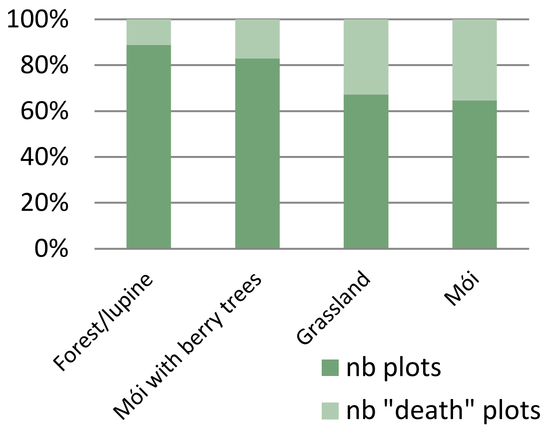


Figure 25: Proportion of "death" plots for Brown andosol and various vegetation classes. The proportion of "deaths" is increasing from Forest/lupines class to "Mói", suggesting the improvng role of forest and lupine on a site.

This improving role of vegetation was not visible for Vitrisol, but such soils have already been reported to turn into Brown Andosol after being covered by vegetation. Only bare Vitrisol should therefore be a difficult planting place.

The influence of pedogenic and vegetated variables can be quite significant, either in positive or negative ways. Some single predictors' values seemed to be a warranty of good living conditions like presence of histosol, lupine or forest cover, but on the other hand none resulted in 100% dieback prediction. Some "average" soils that can be improved by a right combination of other factors: for example brown andosol could offer a range of success rates but if covered with forest or lupine the dieback probability was lowered; just like a grassland cover's bad sides were cancelled when the % of cover remains under 30%. This result is quite interesting when considering the proportion that brown andosols and grasslands represent in Iceland.

This analysis was run under steady conditions for wind and topography, which are now going to be discussed.

4.1.2. Damaging factors: the major role of wind

Wind has been represented in the variables selection through different angles. The most direct was probably wind speed. The maximum value of wind speed has been kept, and according to the predictions when wind speed increased of 1 m/s the dieback probability was multiplied by 0.0465 (regression line, figure 26). The possible reasons for wind speed to be a significant factor are mainly winter drought, salt and particles damage. The response of the distance to the sea was excluding the salt damage hypothesis: indeed the closer from the sea, the better (figure 31). In addition spruce is rather salt tolerant species. The hypothesis of winter desiccation was reinforced by the predictions for the indicator "Topex for maximum wind speed direction". The predicted probabilities were maximal for high value of Topex (figure 27), which meant on the field plots located on a slope or close to a hill with fastest wind blowing from this hill or down this slope.

This corresponds to the definition of föhn winds typically involved in seed dying.

The winds involved here were not necessarily the most frequent, only those with highest speed according to the Wind Atlas. This was indicating a wind action through frost drought: flat lands or exposed slopes are not suffering much from high intensity wind episodes, while slopes with wind flow are submitted to specific föhn wind responsible for seed drying. If among all possibilities of damage frost drought is causing enough dieback to impose its influence through the response curve — to the point of hiding potential diebacks on exposed areas — shall definitely not be neglected.

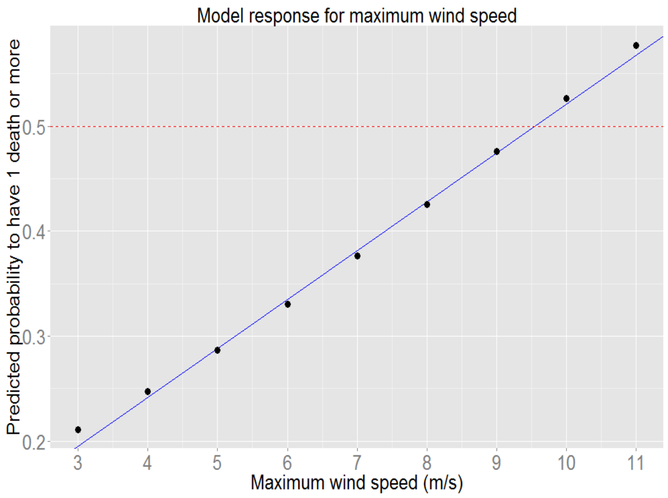


Figure 26: predicted probabilities for maximum wind speed

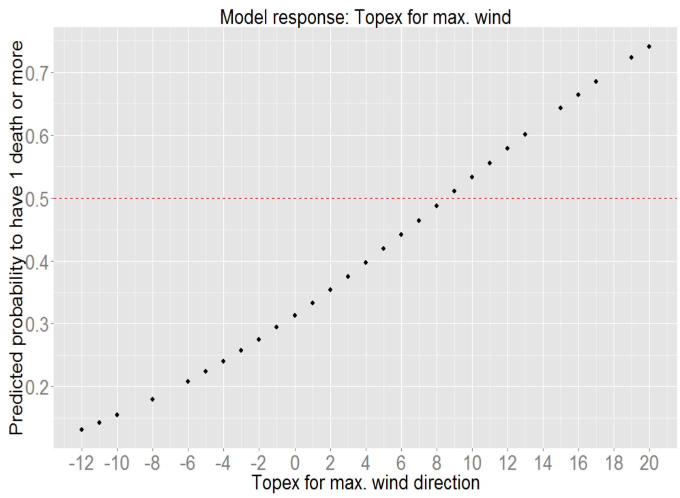


Figure 27: predicted probabilities for Topex of max. wind direction

The result for the distance to sea was more complex to interpret since many variables could stand behind.

Sea proximity could be associated with a hypothesis of smoother temperatures, of a moderate climate; with a soil frozen for a shorter time than in the highlands and the absence of föhn winds, the conditions for frost drought would be rarely met.

The selection also highlighted the Topex for most frequent wind direction. As shown on figure 28, the associated response curve was reversed compared to maximum wind direction Topex. The concerned wind speed was this time the maximum wind speed for the most frequent wind direction.

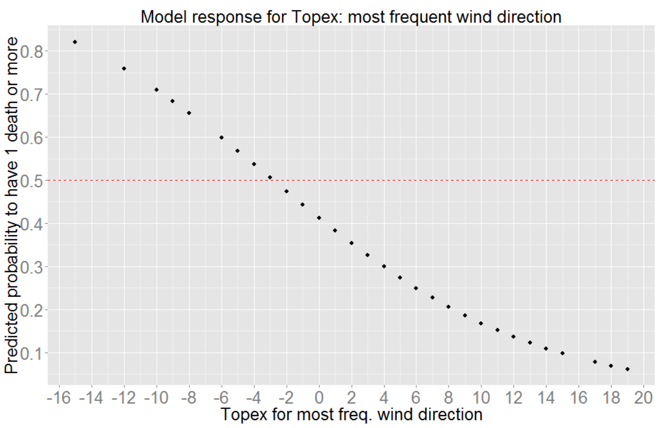


Figure 28: predicted probabilities for most frequent wind direction Topex

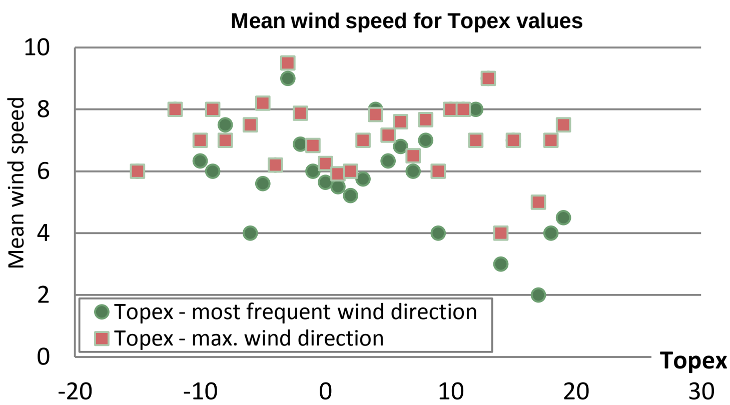


Figure 29: mean wind speeds calculated for their respective Topex value

Just as for Topex for maximum wind direction, there was one more time a dichotomy between highly exposed or flat lands and sheltered contexts. These frequent winds could this time be responsible for another type of damage like mechanical impacts; the repetition of such events due to the high wind frequency could then lead to damages severe enough to cause dieback. The lower the topex, the higher the exposure to such episodes; while positions very sheltered would almost never be submitted to the damaging agents. This shelter role of topography was underlined by the non-correlation between Topex values and wind speed. The low Topex could have been associated to plots for which maximum wind speed (that comes from the Wind Atlas model, and does not integrate local topography reflected by Topex (see figure 15 at 2.2.2.2.5.) is high, but the distribution of wind speed against Topex (figure 29) shows no link between these factors.

The responses for wind confirmed the positive correlation between wind speed and dieback, relationship that appears here proportional. The moderating role of topography evaluated through Topex on the effective wind intensity on the plot seemed however less straightforward to interpret. According to these results, a sheltered position is an advantage for winds blowing frequently but a handicap for high-intensity episodes. An hypothesis is that these events are mainly föhn winds that by definition flow down slopes and therefore are maximum impact on plots with high Topex. Seen the associated predicted probabilities — between 0.9 and 1 — the identification of places submitted to föhn winds seem quite worth it.

The response curves for topographic factors could help to clarify and complete the definition of favorable environment.

4.1.3. Topographic and geographic considerations

A first element of geography was provided by the response to the distance plot-sea (figure 31): best locations are close to the shore. The response for altitude (figure 30) was giving precisions: low lands are the least favorable. According to these results, a planting site could be quite high but close to the shore. Taking the 50% probability as a limit, choosing a plot from 0 to 30km to the shore seemed acceptable as long as the altitude was over 50m — a situation never found in the dataset.

The "good" distance or altitude actually depends on each other. For prediction in regards to distance to sea, the altitude was constant at 97m (see table 11), which corresponds to a favorable situation if I considering a short distance as positive factor. But if the prediction was run with 0m altitude, then the threshold of 50% probability was reached for distance to sea of 20km instead of 30. Similarly if distance to sea was set at 0km — an encouraging value — then all altitudes give a probability lower than 50%. Conversely a distance to sea set at 50km moved the threshold to 200m with dieback probabilities reaching 80%, while 50m were enough for first distance of 16km and probabilities did not go higher than 60% (see figure 31).

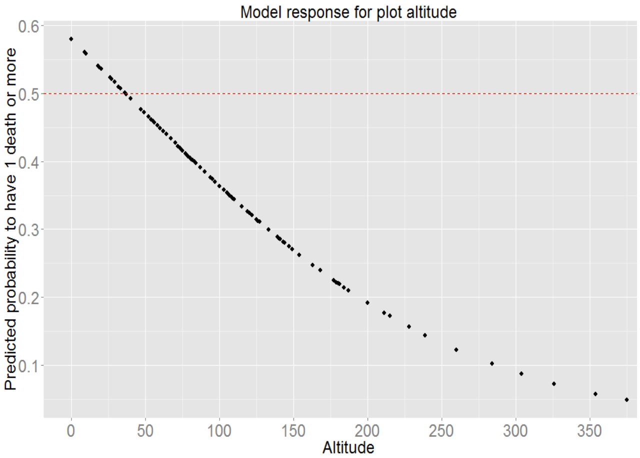


Figure 30: predicted probabilities for plot altitude

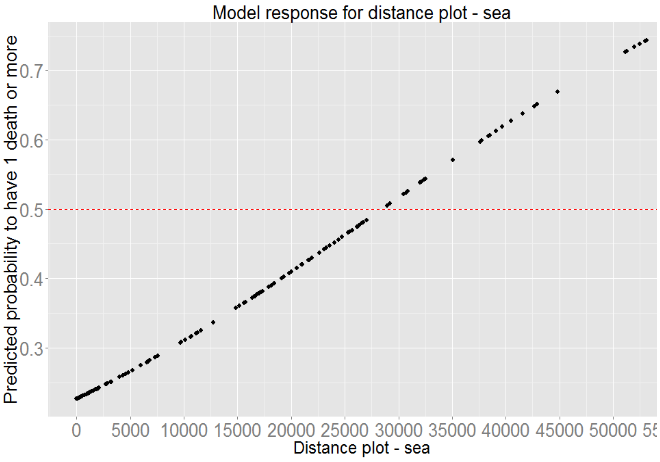


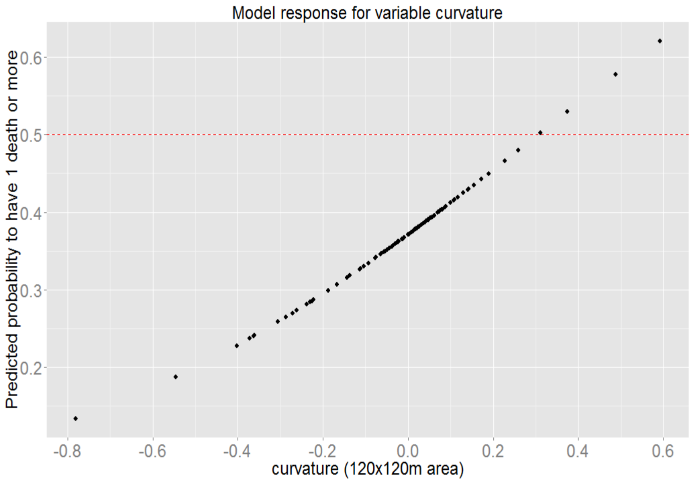
Figure 31: predicted probabilities for distance from plot to sea

Altitude was probably reflecting another predictor and the reason of its selection was then little less straightforward. Slope could be one possible factor behind altitude: from 0 to 50m the land is quite likely to be flat. A recent study (Þ. H. Jónsson, unpublished data) has shown that summer frost episodes occur more frequently on low flat lands than on high lands; crossing this information with the response for distance to sea lead to conclude that a site with a slope close to the shore would constitute satisfying option. However the dataset had a slope predictor that has not been selected.

Altitude can also be synonym of snow cover. Trees covered with snow are protected from several aggressions such as winter desiccation and air-transported particles (Alden *et al*, 2013).

This factor remained quite difficult to explain due to the multiplicity of variables that followed on from it. But this result could at least be used as a confirmation that altitude was not a limit by itself in Iceland; high sites could be settled and chances of success could be increased by using information provided by other selected predictors.

The last factor for topography, curvature, was highlighting the importance of shelter in survival. The figure 32 shows its response curve; as a reminder value 0 meant an even surface, positives go with convex and negatives with curved, concave surfaces (see figure 13, 2.2.2.1.).



Curvature was positively correlated with dieback. Several hypotheses could be made about the role of this very local sheltering: they are a sink area for sediments, keep snow longer and thus protect trees, they are sheltered from wind… This also meant that extremely exposed areas are not places to be chosen for planting.

Figure 32: predicted probabilities for variable "curvature".

4.1.4. Advice for planting site choice

According to the predicted probabilities and behaviors of the variables, they could be classified into 3 groups carrying 3 types of rules, to be applied to any potential planting site:

- limiting factors: if unfavorable, the usability of the site is seriously put in question. Each factor of the group has to be checked independently; only one negative result makes the possibility of planting for this site quite uncertain.

- combinations of improvable and improving factors: the unfavorable value of firsts can be balanced by values of seconds. The values of factors should be put in relationship with values of others before drawing conclusions. This analysis is to be ran only if all the tests for limiting factors are positive.

    - Soil and vegetation: no frankly bad situation was identified through the analysis; but some improvements can be made to maximize survival chances. The first factor to sample is soil class. The presence of Histosol or Hydric Andosol do not request any further investigation, since these soil classes are considered as enough favorable. In case of Brown Andosol, it is preferable to look at the vegetation type. Forest or lupine are improving factors. The presence of grassland could be a benefit, depending on the % of covered soil. A high cover (>30%, since the best category was 11-33%) leads to consider the option of soil preparation. Vitrisols do not appear in this classification since the data was insufficient for conclusion.

    - Altitude and distance to sea: other predictors might be hiding behind, result have therefore to be taken with reservations. Nevertheless if I strictly consider the statistical results, they are involved in survival rate. Since they both belong to geographic factors and that prediction of one depends on the value of the other, they are presented together here.

- "bonus" factors: variables that have influence but trees might grow even for worst value they take. Checking them is going with the idea of putting all chances by our side.

These 3 categories aim to identify sites that show high risk of fail, versus sites whose context is *a priori* not showing major obstacle to survival. They are no warranty of success; but they might help to identify sites that are highly risky and thus probably not profitable. The aim was not to give a hierarchy between situations either. First because the number of possible combinations was so high that this task was at first sight unrealistic; second because the dataset did not offer enough observation to transform hypotheses made that way into certitudes. Finally, all considerations previously mentioned won't be found in this classification, because due to insufficient statistical proofs, they will remain hypotheses.

The figure 33 presents the categories and conclusions. The results based on insufficient observations, hence only hypotheses, are in orange.

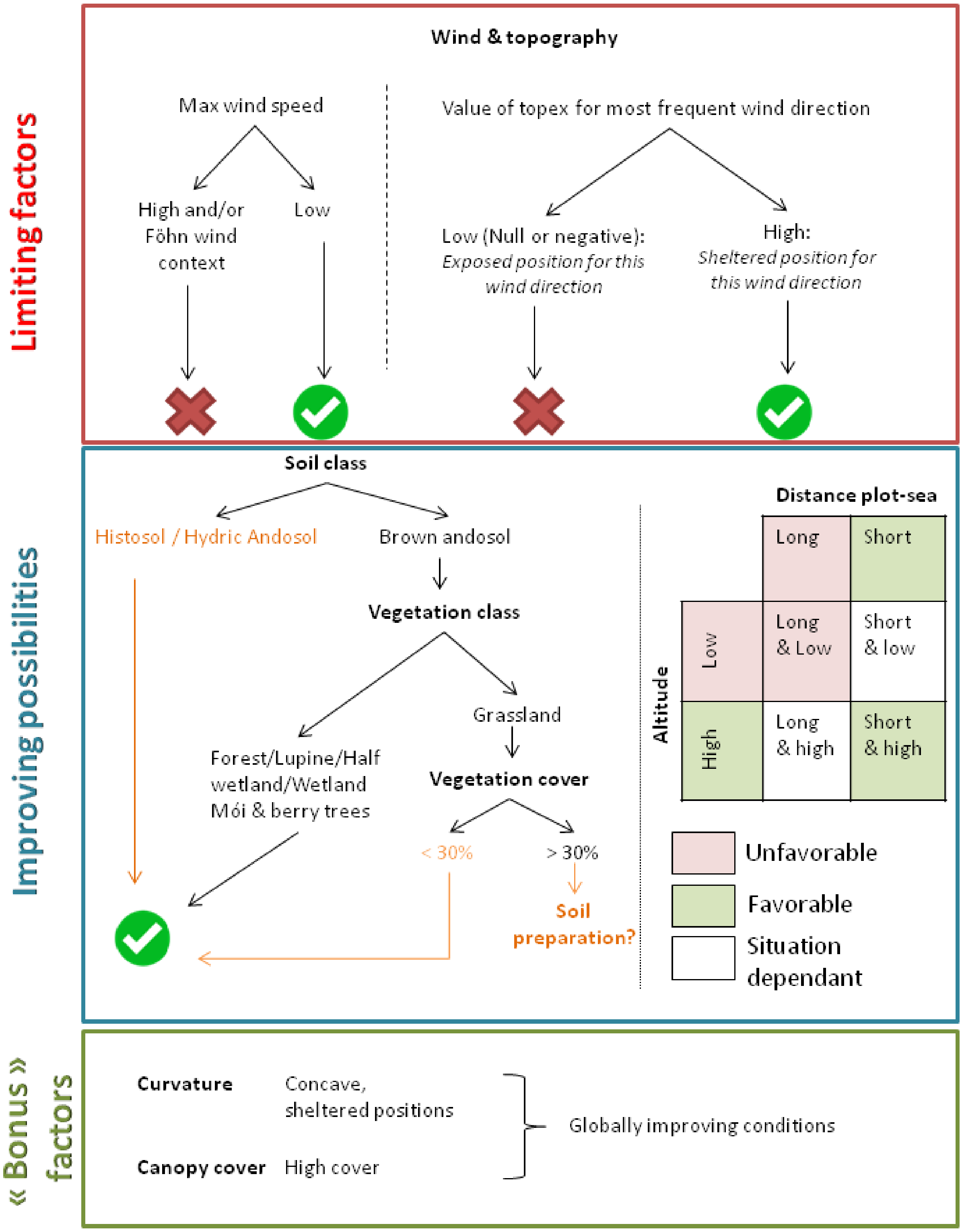


Figure 33: site choice key. Significant factors are divided into 3 groups of rules: limiting factors (only one negative test puts serious doubts for this site), improving possibilities (in case of unfavorable value of a factor, what other factors should man look at to expect improvements or what man can do to increase the probability of survival), and "bonus factors" (variables to be sampled, a favorable value is then encouraging but an unfavorable value is not crippling).
In orange, results remaining hypothetic due to insufficient data.

4.2.Various considerations about the dataset

4.2.1. Limits induced by the variable to be explained

The variable to be explained was binary and took value 1 if at least one juvenile spruce was found dead, 0 else. The choice of a binary variable forbade from the beginning to introduce any notion of gradation between the situations. The study was therefore limited to identification of "environment possibly inducing diebacks" and "environments with 100% survival" — at a given time. This choice was made because a classification of environments would request a higher amount of observations, which mean a sampling campaign that was not makeable in the 6 months given for the thesis.

The threshold of one tree to attribute the value 0 or 1 to a plot is also questionable. If only very few trees are dead, the cause could be "accidental" — not due to the environment. But setting a higher limit was reducing too much the amount of plots. In addition, few deaths can also announce more diebacks; and the plots showing only one dead tree represent a minority. Choice was therefore made to include plots in a large extend.

In order to get a better dataset, two options are to be considered:

- if the same amount of variables and their values is kept, the national inventory data has to be completed with extra sampling. It would probably also allow setting a threshold at 3 diebacks per plot.
- if the same amount of observations is kept, then the combinations of variables value that have too few observations should be abandoned.

4.2.2. A wide range of variables

The dataset presented many predictors for proportionally speaking very few observations. But taking into account only a restricted family of factors would lead to possibly wrong conclusion considering the aim of this study. Indeed, I wanted to understand what factors in the environment are influencing dieback. If the dataset was reduced to, say, vegetation and pedogenic predictors, the selection would have enhanced the influence of some of them while in reality their action is negligible compared to wind.

Seen the plot amount, the attempt of global characterization brings inevitably an under-representation of certain predictors combinations. No solid conclusion could be drawn for these, but results could nevertheless be obtained for some contexts. In addition, if these contexts were well represented in the dataset, it was probably because they were also quite frequent in Iceland: even if they were only partial, these results actually fitted a high proportion of situations.

4.2.3. Specific limits related to selected predictors…

4.2.3.1. Predictors with limited accuracy

4.2.3.1.1. TOPEX

The simplicity of TOPEX has paved the way for many criticisms of the technique. Quine & White (1994) believe that TOPEX can often overestimate the degree of shelter afforded to a location due to its failure to identify the potential for topographic funneling of winds in valleys. But here Topex is strictly used as topographic indicator then applied to already modeled wind speeds. Moreover, its measure is very simple to take: the application for new planting sites search is direct and easy.

4.2.3.1.2. Wind speed

Wind speed was a factor that was highly expected to be influent. No exact measure of wind speed was available; therefore the values were only estimations. Several trade-offs had to be done so that every plot get a value, with the same method. Therefore these wind speed were almost qualitative, reflecting "high", "moderate" or "low" speeds rather than exact values. The results can nevertheless be used (they confirm the both the influence of wind and its paramount nature) but no threshold wind speed could be defined.

The use of direct measures should bring such precisions.

4.2.3.1.3. Temperature

The absence of role for temperature is quite questionable and could be caused by the use of an inadequate variable. The aim was, at the beginning, to extract from daily temperature records the episodes of intense frost (under -3°C) following a warm episode. Unfortunately the raw data was not exhaustive enough to reach that goal. Decision was therefore made to use a coarser indicator.

4.2.3.2. Limits induced by insufficient representation of certain values

4.2.3.2.1. Vegetation variables

The effect of the age structure might be difficult to see with this dataset, since the majority of plots showed an even aged population. This was due to the relative youth of plantations. In the future, the presence of different ages of trees might occur, and effect then be assessed.

The low vegetation cover (11-33%) was not very present, and the absence of cover wasn't even shown. Concerning vegetation class, several categories couldn't be studied enough for the same reason.

4.2.3.2.2. Soil variables

The most common soil in Iceland was here the only one being well represented: Brown Andosol. Encouraging results were obtained with Histosol and Hydric Andosol, but needed to be confirmed with more observations. However the interest of such knowledge highly depends on the future priorities in land use: Histosols are the most fertile lands, and they will maybe not be attributed to forest. Investigating more the last type, Vitrisols, would probably be more useful. Indeed it has been reported that these soils turn to Brown Andosols after being covered by vegetation. Forest could be an interesting solution to improve these unfertile lands.

4.2.3.3. A difficulty for analyzing effects of non-direct predictors

Some variables are describing the plots and are not to be skipped, but the way they have influence was not straightforward. For example, the distance plot-sea, altitude, Topex but also vegetation and pedogenic context. They might reflect hidden factors, that have to be identified to get more accurate and soli response. For now, only hypotheses could be made: altitude reflecting slope or snow cover, distance to sea for temperature, vegetation and soil predictors for nutrient and water content and competition… Specific sampling is necessary to confirm this. But taken separately none of the factors' behavior is in contradiction with previous studies or empirical rules, which gives grants to the analysis. For example it is already advised to avoid planting in flat land, competition for nutrients has already been reported, etc. Thus, even if the explanation remained uncertain, the selection of these non-direct factors gives a trail for future studies.

4.2.4. …and limits related to missing predictors

Several aspects of trees' living conditions have been considered but could not be added to the dataset. Firstly, about the trees, the provenience, year of plantation and planting technique were missing. According to their genetic background, trees might react differently to a given environment. Year of plantation gives the time trees have spent on the field, and thus provide information on the dieback intensity and possible missing trees for old planting sites. Possible abnormal values thus can be explained. The planting technique and operator can also highly weight in the dieback rate. It is now known that a seedling not properly planted has great chance for not developing efficient root system.

Second, the temperature data is probably insufficient. The first objective was to use temperature records instead of averages, and find out possible episodes of freeze-thaw or summer frost. But the temperature records were insufficient to build such data: insufficient amount of stations, missing months or even years, different periods covered according to the stations. The frost probability model could have partly compensated this lack, but it is so far available only for august.

4.3.Possible applications, limits and additional studies

4.3.1. Use of the thesis

The study proposed a selection of environmental variables to be investigated in priority for evaluating a potential planting site. They did not insure success; they provided a method for detecting risky sites.

This thesis was a preparatory work that allowed bringing out trails for important factors and express hypotheses on the way they impact young spruces.

Some results allowed quite direct applications since they were strongly statistically based, like the evaluation of exposure so high wind speeds or the evaluation of pedogenic and vegetal context in case of Brown Andosols. The first use should be a test of the diagnostic protocol on different planted areas in Iceland.

The rules described above could be turned into sampling protocol, to be completed with death rate sampling.

4.3.2. Limits and possible continuations

Some factors are undeniably missing, consequently the environment characterization was not exhaustive and so is probably the list of selected predictors. No hierarchy could be set either for respective importance of factors, even more that any attempt would be immediately put in question if other variables had to be added.

Some results would request further investigation. It would be necessary to find out if some presently selected predictors are only reflecting other predictors (altitude, distance to sea); more data is also needed to confirm some hypotheses (insufficiently represented soils or forest structure, inaccurate temperatures…).

The question of possible compensations couldn't be fully answered. It has been suggested that an unfavorable value for a given predictor can be balanced, improved by another variable, like for soil classes/vegetation class & cover or altitude/distance to sea. But many situations could not be studied due to the lack of observations, and no threshold could be defined for describing a "minimum" situation that allows satisfying survival.

The time dimension was also missing. Since most of diebacks occur when trees are juvenile, a satisfying site for juvenile growth is expected to be also satisfying for adult stage. However, some sites might be more exposed to lethal factors for grown up trees. For example insufficient settling of roots might be bearable for years but stop the growth of the tree at a given time or make it very sensitive to wind snap.

Conclusion

The present thesis is aimed at explaining the environmental causes for diebacks among Sitka and Lutz spruces. Ten variables were selected after a thorough description of the environmental factors that might influence diebacks. The statistical analysis of the probability of dieback, according to each predictor, allowed for identifying the nature of the correlation of positive, negative or neutral variables, and testing the hypotheses of the effect of the predictor. Even if some of the selected factors did not give significant results from statistical analyses, there was a strong trend towards their influence on survival.

The thesis provides clues for improved understanding of the causes of dieback of juvenile spruces and the choice of potential planting sites. The evaluation of a planting site should be led in three steps. First of all, check that the site does not show any if the limiting situations unfavorable wind or exposure context. Secondly, the synthesis of soil type and vegetation should allow qualifying the site of favorable or not. Best situations are likely to be land with lupine or tree cover. In that case, the Brown Andosols are quite favorable soils. Further research is needed to determine the relationship between vegetation and soil factors. The analysis indicates that altitude is positively correlated to survival while the distance to ocean is negatively correlated. Thirdly, curvature and canopy cover are considered as improving factors.

Since planting and afforestation are expensive, assessment site properties prior to planting is important and might improve survival. The results also open windows for more studies with specific sampling, and possibly under controlled environment.

These results only concern plantations of Sitka and Lutz spruce. One possible extension of the study is to include other tree species both conifers and broadleaves. On areas where the environmental conditions are unfavorable for spruce or planting in general, natural regeneration of birch might form lower birch woodlands in a longer time scale.

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Annexes: list of contents

Annex 1: Variable list and metadata

	Variable name	Description
Qualitative	Dirmf	Most frequent wind direction
	Dirmax	Direction of the wind having the highest speed
	AfforestationType	How the trees settled on the plot : planted/direct seelding
	AgeStructure	How many tree generations live on the plot
	AfforestationOn	Description of the land before plantation
	SoilPreparation	Description of the preparation of the soil before tree settlement
	SlopeDir	Direction of the slope on which to plot is located
	Topex>0class	Shelter indicator based on the sum of topex (50m) values, negative values being replaced by 0
	ForestSize	Size of the forest the plot belongs to
	ForestUsage	Purpose of the forest the plot belongs to
	SpeciessMixture	Description of the specy blend that has been planted : one species/several
	MeanHeightMature	Estimated mean height the population will reach when mature
	LandType	overview of the vegetal population
	Grazing	Is the forest opened for grazing
	VegetationClass	Description of vegetation (except trees already measured by the inventory)
	VegetationCover	% of soil covered by vegetation
	SurfaceClass	Description of the upper layer of the soil
	SoilDepth	Measure in cm of the soil depth
	SoilClass	Type of soil
	SoilBase	Description of the underneath layer
	Topex_dirmf	Extracted Topex value for the most frequent wind direction
	Topex_dirmax	Extracted Topex value for the direction of strongest wind
Quantitative	Sum topex Hor	sum of the 8 topex values taken to the horizon
	Sum Topex 50 relatif	sum of the 8 topex values taken at 50m
	Sum Topex 50 >0	sum of the 8 values taken at 50m when they are positive (negative have been replaced by 0)
	ForestSize	size of the forest in which the plot is located
	NeedleTreeCover	% of needle tree canopy cover in the total canopy cover
	CanCovMature	Canopy cover that the forest will reach when mature
	Altitude	Altitude (m) of the plot

	Augustfrost probability	Probability that temperatures goes under 0°C at least once in august (model based figure)
	meanT_year	mean annual temperature, calculated with all annual averages available from the most appropriate weather station
	nb living trees/plot	count of trees alive per plot, juvenile and adult
	living trees density/ha	density of trees alive per plot, juvenile and adult
	nb juvenile/plot	count of juvenile, alive or dead, per plot
	nb living juvenile/plot	count of juvenile alive per plot
	nb dead juvenile/plot	count of dead juvenile per plot
	living juvenile densities/ha	Density of iving juvenile only per plot
	Vmax(mf)	maximum windspeed in the most frequent wind direction
	Vmax(max)	maximum windspeed
	Distance to forest border	4 values: 1 per cardinal direction.
	Distance to sea	Shortest distance from the plot to the sea
	Curvature	Topographic indicator for surface shape; 3 values corresponding to 3 scales (60x60m, 120x120, 160x160)

Annex 2: Origin of the wind data

Origin of the base wind model

The Icelandic Meteorological Office is offering a free use of the Wind Atlas, a model recently build on the base of the Weather Research Forecast (WRF) model.

The need for quality mesoscale weather predictions led multiple research institutes to work together on forecast models. The Weather Research and Forecasting (WRF) model is one of these flexible tools meant to be used both for direct operational applications and also as a base for more advanced forecast models. The WRF model is a numerical weather prediction and atmospheric simulation system, maintained and supported as a community model to be used internationally and suitable for many applications: data-assimilation, analysis and climate-simulation, air quality modeling… (Nawri et al., 2012). Thus, the Icelandic Wind Atlas is an example of particular use of this WRF model.

The bases of the WRF model are mainly air temperature, wind speed, air pressure measurements; it also includes a ground elevation model. Records have been assimilated and analyzed by the WRF-Var System (Data assimilation) and the ARW Solver (analyzing system based on compressive, nonhydrostatic, moist Euler equations and map projections). The obtained model is then discretized, spatially and temporally, and values are spread on grids (Skamarock et al., 2008). A 3km grid-point spacing has been used in the wind power assessment project for Iceland: the Wind Atlas.

From the WRF model to the Wind Atlas

The aim of the Wind Atlas is assessing the wind energy potential for the entire island. The WRF results were too coarse; indeed, the project needed assessments in very limited region, such as a valley. Therefore, the Wind Atlas Analysis and Application Program (WAsP) developed by the Department of Wind nergy at the Technical University of Denmark has been used to improve the WRF mesoscale model (Nawri *et al.*, 2014). The input data are simulations with 3 km grid-point spacing produced by the WRF model.

The Wind Atlas has been built in two steps (Nawri *et al.*, 2014):

1. From simulated winds (WRF model output) : “upward” modeling to remove effects of surface type
   - ⇨ obtaining of a “generalized” regional wind climate model for the whole domain (“regional model” on the figure 15)
2. From the regional model: “downward” modeling to integrate the response of vertical wind shear to spatial differences in surface roughness
   - ⇨ obtaining of the wind climatology for specific locations (“Local model” on figure 15)

The averages and other coefficients are calculated from the approximation of wind speed distribution. In this model, the occurrence of wind speeds is approximated by a Weibull distribution, characterized by two parameters:

- A: the scale parameter, reflects the measure of wind intensity. A≥0; unit = m/s.
- k: the shape parameter, reflects the measure of wind speed variance. k≥1; nondim.

The relationship between wind speed (U), A and k is given by a density function:

$$f(U;A;k) = \frac{k}{A}\left(\frac{U}{A}\right)^{k-1} \exp\left[-\left(\frac{U}{A}\right)^{k}\right]$$

One example of graph is given in figure A. The different curves correspond to several wind directions. The maximum of this function is, for given A and k, the maximum wind speed that I am looking for. More precisely, two wind speeds are searched: the maximum, independently of its occurrence frequency, and also the maximum expected for the most frequent wind direction. Thus, both intensity and frequency are taken into account.

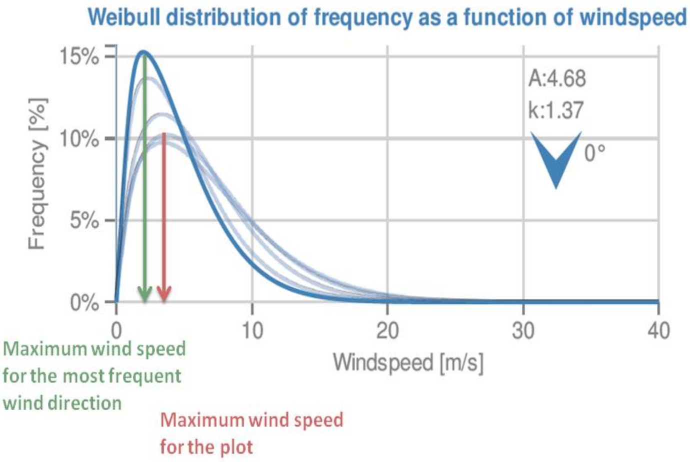

Figure A: Weibull distribution curve for a particular nest. source: Wind Atlas

Maximum wind speed calculation

I want to write the Weibull density function for each plot, in order to extract its maximum and therefore the maximum wind speed. I consequently need the values of its components. The Wind Atlas provides for altitudes ranging from 10 to 200m and on a 3km grid-point spacing:

- the frequency of wind for 12 wind directions (distributed as clack's graduations, from 0° (or 360) to 330) and 5 values of surface roughness.
- the Weibull A and k coefficients, also for 12 directions and 5 values of surface roughness.

From the data of the IFI, the surface roughness is calculated for each plot; the elevation model provides the altitude.

All these values are crossed in a report table available for all the grid nests. Each plot has therefore been related to its closest nest. The method is as follows and an example is provided in Table A:

1. Pick the surface roughness and altitude of the plot. In our example, the plot shows a surface roughness of 0.1 and the closest altitude is 25m.
2. In the corresponding table, pick the most frequent wind direction (in green, Table A) and the wind direction for the highest A coefficient (which reflects the highest wind speed, in red in Table A)
3. The valid coefficients for this plot are now known. The values of the function are calculated for wind speeds (U) ranging from 0 to 55m/s (since 55m/s is the record of speed ever measured in Iceland).
4. The maximum is picked and the corresponding wind speed is extracted (as illustrated on figure 16), both for the wind direction showing the highest wind speed and the most frequent wind direction.

Sector-wise Weibull distributions for surface roughness length 0.100 m

Height [m]	Parameter	0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°
10	Frequency [%]	4.4	33.0	12.0	6.0	5.2	8.1	8.1	8.4	6.9	3.4	2.3	2.3
10	Weibull A	3.280	4.550	4.330	4.460	3.800	5.310	5.320	4.670	4.180	3.560	3.240	3.020
10	Weibull k	1.570	2.411	1.918	1.601	1.492	1.783	1.791	1.726	1.740	1.708	1.763	1.404
10	Mean windspeed [m/s]	2.9	4.0	3.8	4.0	3.4	4.7	4.7	4.2	3.7	3.2	2.9	2.8
10	Power density [W/m^2]	40	65	69	97	68	140	140	99	70	45	32	38
25	Weibull A	4.150	5.690	5.210	5.470	4.590	6.400	6.330	5.700	4.920	4.380	4.060	3.640
25	Weibull k	1.625	2.675	1.992	1.693	1.600	1.897	1.785	1.798	1.766	1.763	1.861	1.449
25	Mean windspeed [m/s]	3.7	5.1	4.6	4.9	4.1	5.7	5.6	5.1	4.4	3.9	3.6	3.3
25	Power density [W/m^2]	76	119	116	164	106	226	236	171	113	80	59	63
50	Weibull A	5.490	7.230	6.410	6.970	5.440	7.690	7.910	7.040	6.140	5.450	5.230	4.540
50	Weibull k	1.762	2.867	2.098	1.838	1.689	2.042	1.879	1.877	1.919	1.846	2.139	1.528
50	Mean windspeed [m/s]	4.9	6.4	5.7	6.2	4.9	6.8	7.0	6.2	5.4	4.8	4.6	4.1
50	Power density [W/m^2]	157	236	204	304	162	362	432	305	197	144	109	111
100	Weibull A	6.750	8.760	7.620	8.300	7.130	9.530	9.660	8.540	7.910	6.400	6.380	5.580
100	Weibull k	1.765	2.694	2.196	1.978	1.868	2.172	2.094	1.918	2.025	1.881	2.038	1.647
100	Mean windspeed [m/s]	6.0	7.8	6.7	7.4	6.3	8.4	8.6	7.6	7.0	5.7	5.7	5.0
100	Power density [W/m^2]	291	434	329	471	319	651	701	531	398	229	207	182
200	Weibull A	7.630	10.510	9.650	8.600	7.760	11.130	11.250	9.780	9.370	7.980	6.790	5.980
200	Weibull k	1.718	2.398	2.550	1.739	1.653	2.236	2.197	1.819	1.891	1.872	1.899	1.507
200	Mean windspeed [m/s]	6.8	9.3	8.6	7.7	6.9	9.9	10.0	8.7	8.3	7.1	6.0	5.4
200	Power density [W/m^2]	436	806	599	614	486	1 011	1 059	850	713	446	270	260

Table A: report table for a given grid point, here for surface roughness 0.1.

Seen the origin of the data, these wind speeds might include on the one hand global topography such as large valleys or major mountains and on the other hand very local variations through surface roughness. But the presence of smaller relief is probably not taken into account. This is another interest of using topex, and especially the values corresponding to selected wind directions: it might have influence on the wind speed provided by the wind model, as summed up on figure 15.