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Climate change, uncertainty and the economic value of genetic diversity

a pilot study on methodologies

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"Genetic diversity is the best tool to counter environmental change and to hedge against uncertainty"

"Worse than uncertainty, perhaps, is the assurance that whatever the conditions at the start of the rotation, they will change before the end"

Quotes: Ledig & Kitzmiller, 1992
– when climate change was still just a possibility.

Preface

This working paper is the result of a project regarding methods for economic valuation of forest genetic diversity when facing the uncertainty of climate change.

The Authors, Copenhagen, October 2008.

Content

Summary

Forest genetic research has traditionally been aimed at improving the use value of forests related to wood production, including breeding and provenance trials with selection for general adaptation across a range of environmental conditions. Often, when production is the aim forest owners select a single or a few provenances recommended for specific localities based on results from tree improvement programmes. However, forest owners and forest genetic researchers are facing a new challenge, the uncertainty of climate changes. A range of effects of climate change on trees and forests have already been documented, such as changes in the patterns of forest pests and moving tree lines, and many more are anticipated in the future. Within the time span of a forest stand rotation climate change may alter the environmental conditions as well as the biotic factors in a specific site thereby rendering an unforeseen change in optimal species, provenance or clone. The challenge for the forest owner lies in coping with the uncertainty in climate change, whether it is at the species, provenance or clonal level. In a recent outbreak of Ash die-back, clonal variation in Danish seed orchards of European Ash (*Fraxinus excelsior* L.) was decisive as only a few clones proved to be healthy (Olrik et al. 2007). Likewise, genetic diversification, e.g. use of different clones, is a way to cope with the uncertainties of climate change.

The value of diversification is well known in economics, e.g. the value of risk reduction through diversification in a portfolio of assets on the stock market. However, the economic value of genetic diversity in forests goes beyond the risk reducing effects and includes, e.g. option values when several clones are mixed in the same forest stand. This report aims at exploring the principles of assessing the economic value of having several different clones of Norway spruce (*Picea abies* (L.) Karst.) either as separate stands or mixed in the same forest stand; this in order to hedge against the uncertain changes in environmental conditions induced by climate change.

Though we are looking at what may be perceived as a genetically quite narrow material (clones from only one specific species), we are able to demonstrate the potentially large gains from securing a reasonable level of genetic diversity. The gains investigated only relate to the production values for the forest owner, and do not include, e.g. the value of a decreased risk of total stand failure on account of forest genetic diversification. This also has large value for society as forests produce a number of non-marketed environmental services, e.g. recreational opportunities and avoided nutrient leaching, which are not provided if large forest tracts are lost due to stand failure caused by adverse climate change. Although these values are potentially vast, their quantification is not within the scope of the study, but they are commented upon in the report.

We simulate a possible climate change of a decrease of 0.15 °C per decade with a probability of 0.2 and an increase of 0.25 °C with a probability of 0.5, resulting in a maximum increase over a century of 2.5 °C. This is in accordance with climate change scenarios for Denmark based on future moderate to large green house gas emissions as modelled by DMI (2008) and IPCC (2007). The reaction to growth of temperature changes is estimated using a dynamic growth model (Johannsen,

unpublished), which contains a site rate constant that expresses the accumulated effects of the environment on tree growth. Based on data from a clonal trial (Karlsson et al. 2001) we estimate site rate constants for 14 different clones of Norway spruce, which when used in the model change according to the simulated temperature changes. Using a rotation period of 100 years, we simulate different treatment strategies: diversification, where we basically choose to have different clones on different areas; and dynamic reactive adaptation where at each decision point in time, the manager observes how the trees have grown and chooses to thin away the poorest performing ones. The latter is simulated both with uninformed and informed choice of clones. We illustrate six different management scenarios. Based on 2,000 simulations of climate change the following mean present values (PV), standard deviations, minimum and maximum present values are found, all in DKK:

Strategy	Scenarios	Mean PV	Std dev.	Min	Max
No diversification	Choosing at random one of the 14 possible clones	6,306	1,889	893	10,973
Diversification, clones in different stands	Choosing two specific clones with different degrees of reaction to climate change	5,024	1,227	1,598	7,617
Dynamic, reactive adaptation, mix of clones in the same stand	The same two specific clones	5,301	1,670	1,769	8,796
	Two randomly chosen clones	6,969	1,707	1,456	10,719
	An informed choice of the two best performing clones	7,830	1,434	3,105	10,721
	An informed choice of the three best performing clones	7,859	1,480	3,221	10,886

It is seen that diversification leads to a lower standard deviation and higher worst case outcome, but for the two specifically chosen clones also to a lower mean present value. Using dynamic, reactive adaptive management by having the same two clones in the same stand and thin according to the best performing clone, increases the mean PV. If we use the information on which clones perform best, and mix them, we obtain considerably higher present values and lower standard deviation. Thus, by using knowledge of the different clones' performance and adaptation possibilities, we are able to increase the expected value of Norway spruce production.

One further possibility, which we have described in the report but not modelled, is the possibility of forward-looking adaptive dynamic management, where the forest manager not only looks at past performance, but also takes expectations of the possible future changes into account. In this approach, it may be beneficial to keep poorer performing clones longer in order to take advantage of a shift in climate switching the performance of the species in opposite directions, i.e. making the poor clone superior. Again, it is a prerequisite that the clones are mixed in the same stand.

Suppose (boldly) that the clones analysed here represent in fact the genetic material available for growing Norway spruce in Denmark, and that the crude analyses of sensitivity to climate change etc. undertaken here are relevant and a reasonable guess at the true variation. Without this latter information, the forest owners may pick their plant material randomly among the clones. The result of this is the values obtained in the first line in the table above. However, if forest genetic research is able to provide enough information to arrive at a recommendation of at least to mix in each stand a set of two-four different clones, then the results from the fourth scenario show us that forest owners, who do this at random, will at least experience an increase in the present value of 650 DKK/ha and maybe as much as 1,000 DKK/ha – in timber values alone. Add to this the decrease in risk associated with the adaptive management and the diversification effect. If enough information is available to recommend the optimal clones to mix, the gains may be even larger. The sixth scenario shows us that forest owners who make informed selection of three clones to mix in the forest stand can obtain increases in the net present value of more than 1500 DKK/ha compared with the conventional one-clone forest. This increase is perhaps more expressive in percentage, equivalent to an increase of approximately 25 %. Again, the increase in expected value is also associated with an equally large percentage reduction of the risk, as well as a substantially higher net present value in the worst case scenario.

Norway spruce makes up around 20% of the Danish forest area, corresponding to some 90,000 ha. Crudely aggregating the potential gain across this area the gain is magnified to a present value of 135,000,000 DKK. Using the interest of 4% the corresponding annual value flow is 5,400,000 DKK. This is a very crude aggregation and by far a very conservative estimation of the potential gains from having forest genetic research and tree improvement programmes contribute to the preparation of Norway spruce forest for the forthcoming climate change.

Clonal forestry is relatively far away from practice in Denmark, also in the case of Norway spruce, and hence the specific numerical results here should be taken only as indicative. This, however, is not a serious limitation: The qualitative results obtained are much more general, e.g. the role of diversification and the principle of gains from mixing clones in adaptively managed stands. These results can in general be expected to be found also for other sets of clones, provenances or species.

The report is based on a limited empirical material, which stresses the need for qualified information from genetic research and tree improvement programmes as climate change is picking up speed and forest owners every day make decisions that will affect the stability, health and growth of forest many decades into the future. The decisions are made on information that was produced under a research and tree improvement paradigm focused on tree breeding for production under a known climate believed to be stable. Any new and improved information is greatly needed – even if it is not exact and only indicative.

Therefore, existing clone and provenance trials in forest genetic research and tree improvement programmes should be systematically investigated across as large climate gradients as permitted by the location of the trials. Such analysis should be able to bring about at least indicative information on the genotype response to

7

variation in the main climate and growth factors. Such information can subsequently be used in more thorough analyses along the steps outlined here, perhaps with a special focus on potential gains from mixing provenances on the same area. Tree improvement programmes should use the information produced to gradually adjust current recommendations concerning local and regional choices of planting material, and of course to adjust and diversify breeding strategies accordingly – as needed.

In the longer run, such research may go into more details along the lines discussed earlier. In particular, genetic research into sensitivity of different provenances and clones to potentially more frequent pest attacks, mild winters etc. may be relevant.

On a broader scale, ecological and economic research could aim to provide more information on the way forest ecosystem services and their value rely on the state and characteristics of the forest ecosystem and notably its stability. Such information will be needed for a reliable economic modelling of the consequences of climate change for the provision of such ecosystem services at landscape levels.

1. Introduction

Two decades ago global climate change was still only a possibility and few forest owners thought about the impact of a changed climate on newly established forest stands. Today, changes in the global climate are accelerating and the results are starting to show, e.g. according to Stroeve et al. (2007) the decline in summer ice extent on the North Pole is 30 years ahead of any climate model. While most attention in the news media is being directed at the melting ice caps, scientists in different fields are also finding evidence of increasing temperatures, e.g. trees and plants are moving their optimum elevation level upwards, the patterns of forest pests are changing and in many cases pest attacks are getting more severe, the reason believed to be climate change (Lenoir et al. 2008, Kurz et al. 2008).

Moving tree lines and changing pest patterns are just two effects of climate changes. Forests and trees will be affected in a myriad of ways but how and when is highly uncertain. The need to cope with uncertainty induced by climate change is especially important in forest management, where decisions are made based on long term considerations. Perhaps the most long-ranging decisions are those concerned with forest genetic resources and their diversity, because they will affect the state and flow of values of future tree generations. Therefore, such decisions should effectively incorporate the aspects of uncertainty related to climate change.

1.1 Genetic improvement

Forest genetic research has traditionally been aimed at improving the use value of forests related to wood production, e.g. development of forest trees with increased growth rates, better trunk form, increased wood quality and higher resistance to pests and diseases (Hannrup et al. 2004, Hansen & Kjær 1999, Savill & Kanowski 1993). The improvement programmes also include breeding and provenance trials with selection for general adaptation across a range of environmental conditions or selection for specific adaptation, i.e. selecting provenances or clones that are growing particularly well in a specific locality or environmental setting (Isik & Kleinschmit 2003, Matheson & Cotterill 1990). In Denmark, based on accumulated experiences and knowledge from a large number of provenance studies with many species it is known that selecting the wrong provenance can lead to total failure of the forest stand (Kjær et al., 2005). As a consequence, detailed recommendations on choice of seed sources exist in Denmark, as well as in many other countries, including guidelines limiting the transfer of seeds across strong environmental gradients (e.g. O'Neil & Yanchuk 2005b, Sorensen 1992). Many large scale tree improvement programmes cope with the genotype-environment interaction by breeding in multiple environmental zones with the objective to develop separate gene pools for different zones.

1.2 Genetic diversification

When production is the aim, forest owners tend to prefer the single provenance that has proven to be the best producer based on field testing in tree improvement programmes. However, climate change may alter the environmental conditions in a specific site within the time span of a rotation thereby rendering an unforeseen

change in optimal provenance. What was best in the past may not be superior in the future. The challenge for the forest owner lies in coping with the uncertainty in climate change. Diversification is one strategy to cope with uncertainty, which implies the use of several, genetically differentiated clones in order to avoid relying on a narrow genetic basis. For example, before a recent outbreak of Ash dieback in Denmark (expected to be associated with a new fungus), all European Ash (*Fraxinus excelsior* L.) clones in Danish seed orchards were assumed to be highly suitable for growing under Danish conditions. However, after the outbreak only a few clones proved healthy, and the inclusion of a fairly large number of clones in the seed sources thus turned out to be a wise strategy (Olrik et al. 2007). Likewise, Burdon (2001) mentions genetic diversity to cope with mutations and genetic shifts in pathogens. In a similar way genetic diversity may prove valuable when the biotic growing conditions are uncertain. Therefore, in the face of large and only partly predictable climatic changes, genetic diversity has been recommended as a way to secure adaptability (cf. e.g. Ledig & Kitzmiller, 1992; Kjær et al., 2005).

Such genetic diversification can be at species level, provenance level or even clone level and refers to maintaining genetic differences between individual trees in a given forest stand. A forest stand consisting of only a single clone will thus have zero genetic diversity as all the trees are genetically identical. A forest stand of multiple clones will have higher diversity depending on both the number of clones and any potential relationship between these clones. An important rationale for genetic diversification in forestry has always been the requirement for a planting material that can grow well under a variety of growth conditions. This requirement is due to the large environmental heterogeneity to be expected within and between nearby sites, and especially because seed sources need to be deployed within larger regions in order to be operational. In the face of expected climate change, this aspect has come much more in focus, because the coming growth conditions now remain quite uncertain at the time of stand establishment (Larsen, 1990, 1995). The general adaptability as well as production of a given clone over different growth conditions is often referred to as its *phenotypic plasticity*. High phenotypic plasticity indicates that a given clone can grow fine under quite different growth conditions, while low phenotypic plasticity refers to a clone with high sensitivity towards the growing conditions. The term can refer to the single clone, but also be applied on higher levels of aggregation: averages of families, provenances or specific planting materials. From a diversification point of view it is not the level of phenotypic plasticity *per se* that is important, but rather how different seed sources combine good general performance with high levels of plasticity (trees growing equally poor at all sites are not attractive). In the presence of high level of phenotypic plasticity, it may be a single clone that outperform all other clones at all sites. In this case genetic diversification would not reduce the genotype-environment interaction. However, with lower levels of plasticity it is likely that different genotypes are superior at different sites in which case increased diversification will lead to reduced plasticity and thereby genotype-environment interaction and the level of the planting material. The term '*reaction norm*' is applied to describe the response curve of a given genetic entity across the specified range of environmental conditions. This aspect of genetic diversification will be pursued in more details in the sections below.

At the species level, traditional forest management in Denmark has focused on selecting the single species that was expected to be the best value producer at a given site. As economic analysis has pointed to the economic superiority of Norway spruce (*Picea abies* (L.) Karst.) at a large range of sites, i.e. a high plasticity, it has become one of the most common tree species in Danish forests covering 19 % of the forested area. However, it is not a native species to Denmark and it is already at the limit of its climatic habitat. The climate in Denmark is too Atlantic compared to the natural distribution area of Norway spruce, and in certain years in recent decades the health of the species has decreased substantially (Larsen et al. 1993). This potentially makes it one of the more vulnerable tree species in Denmark given a change towards a warmer, drier and perhaps more windy climate. Predictions of the development of Norway spruce in a warmer climate induced by a doubling of the CO_2 concentrations show an increased productivity at the southern limit, but also a retraction of the range with natural regeneration far to the north (Sykes & Prentice 1995, Bradshaw et al. 2000). The health problems of Norway spruce associated with expected higher frequency of droughts and storms, as well as increased susceptibility to pest and pathogens, are part of the reasons why some researchers recommend that planting of Norway spruce in Denmark is reduced (Larsen 2008). However, Norway spruce still have some attributes which cause it to be preferable in some cases, such as easy and cheap stand establishment, high productivity of well-known roundwood products and a tree structure which allows extensive use of machinery in planting, thinning and harvest operations. At the same time Norway spruce is one of the species for which we have most genetic knowledge and experiments in Denmark and in other Scandinavian countries, and thus we may have at least some empirical basis for assessing adaptation possibilities for different genotypes of Norway spruce, and hence change the question from one excluding the species from Danish forestry to one of selecting the set of genotypes likely to perform best under potential climate change.

1.3 Valuation of genetic diversification in the face of climate change: A pilot study

The value of diversification is well known in economics, e.g. the value of risk reduction through diversification in e.g. a portfolio of assets on the stock market. The economic value of genetic diversity in forests in a similar way reduces the risk of economic loss from choosing a single or a few clones that later turn out to be poor performers at the given site or susceptible for new pest. However, genetic diversity in forests also provides additional option values that are beyond the risk reducing effects. A mixture of clones will thus provide option values when several clones are mixed in the same forest stand, leaving the forest manager time until the subsequent thinning to decide on which set of the applied clones should be maintained for rotation. This is an important aspect because climatic changes are expected to be manifested as trends over time, and therefore time is an important parameter.

In the present study we look at the value of diversification taking the issue of time into account. Based on empirical data from clonal trials with Norway spruce in Denmark and Sweden, this study aims at exploring the principles of assessing the economic value of having several different clones either as separate stands or

mixed in the same forest stand; this in order to hedge against the uncertain changes in environmental conditions induced by climate change.

Our study is limited to growth trait and we therefore calculate the economics of production value merely on these. As discussed above, this is likely to underestimate the true value of diversification, because resistance to new pests can become a major aspect in the future. Also, the study only covers a fairly narrow span of the potential diversification spectrum as we only look at increasing the number of clones from a single species. Mixing of species and distant populations could generate much higher level of diversification. Still, we are able to demonstrate that potentially large gains can be obtained from securing a reasonable level of genetic diversity.

In the following we will start by describing which climate scenarios are likely with the present knowledge on greenhouse gas emissions and subsequent climate change. Then we will discuss the impact on tree growth and forests. In section 4 we will describe three ways of dealing with uncertainty in management, seen from an economic perspective. The three ways are risk diversification, dynamic reactive adaptive management and dynamic forward-looking adaptive management. In sections 5 and 6 we develop a model to illustrate risk diversification and dynamic reactive adaptive management. The possibilities of dynamic forward-looking adaptive management are shortly described at the end of section 6. The results are discussed in section 7 and in section 8 we draw some perspectives on the role of tree improvement and breeding programmes vis-à-vis climate change. Furthermore, some recommendations for improvement of the model are given.

2. Climate scenarios for Denmark

While there is little doubt that the global climate is changing, there are great uncertainties as to when and to what degree the changes will occur. Although there are several theories concerning the reasons for climate change, e.g. the influence of cosmic rays on cloud formation and global climate (Svensmark & Calder 2007), there is wide consensus among scientists that increasing levels of greenhouse gases due to human activities and release of primarily methane and CO2 stored in the Earth's pedosphere is the dominating cause of global climate change (IPCC 2007, DMI 2008). The following overview of climate changes is based on reports by the Intergovernmental Panel on Climate Change (IPCC) and the Danish Meteorological Institute (DMI).

The IPCC works with four different groups of scenarios for future greenhouse gas emissions and subsequent climate changes. Green house gas emissions differ among scenarios as a result of different paths of global development, e.g. economic development, population growth etc. Common to all of them is a global temperature increase of 0.2°C per decade during the next two decades. Hereafter, temperature increases differ among scenarios. Among other common climatic changes are increases in droughts as well as floods, increased intensity and occurrence of extreme wind conditions both in the tropics and at higher latitudes, and increased precipitation in higher latitudes though with large seasonal variation.

The point of departure for the current work on climate changes in Denmark and Europe by DMI is the fourth assessment report on climate changes by the IPCC (2007). DMI has adopted two of the four groups of scenarios by the IPCC along with a scenario that imply maximum increase in temperature of 2 °C in Denmark. Ongoing work with DMI's regional climate model HIRLAM[1] is based on these scenarios. The three scenarios are summarised in Table 1.

Table 1: Description of the A2 and B2 emission scenarios by IPCC and the EU2C scenario.

Scenarios	Description of global development	Emissions
A2	Generally assumes a divided world with regionally oriented economic development. Continuously increasing population. Slow and fragmented technological changes and improvements of per capita income.	Large
B2	Also assumes a divided world, but more ecological friendly than A2. Continuously increasing population, but slower than in A2. Intermediate levels of economic growth. Moderate, but fragmented technological change.	Moderate
EU2C	Assumes that the EU-countries' goal of a global, anthropogenic temperature increase of maximum 2 °C compared to the pre-industrial period can be fulfilled.	Least

For each of the scenarios DMI has used the HIRLAM model to predict the climate in Denmark in the period 2071 - 2100 and compared this period with data observations from the period 1961 - 1990. Furthermore, as recommended by the IPCC

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[1] HIgh Resolution Limited Area Model.

10 different indicators for extreme climate have been reported. Comparisons of climate and selected extreme weather indicators are shown in Tables 2 and 3.

Table 2: Climatic changes in Denmark according to three scenarios based on a comparison of the periods 1961 – 1990 and 2071 – 2100. DMI (2006).

Climate scenarios	A2	B2	EU2C
Land			
Mean annual temperature	+3.1° C ±1.5° C	+2.2° C ±1.5° C	+1.4° C ±0.7° C
Annual precipitation	+ 9%	+ 8%	0%
Summer precipitation (JJA[1])	– 15%	– 7%	– 3%
Max daily precipitation (JJA)	+ 21%	+ 20%	+ 22%
Ocean			
Mean wind speed (DJF[2])	+ 4%	+ 2%	+ 1%
Max gale force (DJF)	+ 10%	+ 1%	+ 1%

1 June, July, August

2 December, January, February

Table 3: Chosen extreme indicators for the three climate scenarios. The table shows the expected differences between the periods 2071 – 2100 and 1961 – 1990. The last column shows mean values of two modelled predictions of today's weather. These values are not completely identical to, but in fair accordance with observations made in the period 1961 – 1990. DMI (2006).

Indicators	A2	B2	EU2C	Today
Number of days with frost	- 44	- 31	- 26	73
Length of growth period, days	+ 55	+ 39	+ 22	224
Longest heat wave, days	+ 9	+ 4	+ 4	5
Days with more than 10 mm precipitation	+ 3	+ 3	- 1	13
Strong precipitation events, % of precipitation above 95 percentile.	+ 5	+ 6	0	32

Though large variation exists between the three scenarios, some common features include higher mean annual temperature, less precipitation during summer, higher occurrence of heavy precipitation and higher mean and maximum wind speeds. For the A2 and B2 scenarios annual precipitation is expected. Generally, it is believed that A2 scenarios will lead to a climate which is found in central and southern France today, whereas B2 scenarios will result in a climate corresponding to northern France today.

While all scenarios in the IPCC and those collaborated on by DMI involve global warming, there is a force working against this trend. The thermoline circulation in the Atlantic Ocean, also called the meridional overturning circulation (MOC), is a flow of cold North Atlantic Deep Water towards the south which is matched by a warm northward surface flow. The MOC transports heat to the North Atlantic, which, when released, moderates the climate in north-western Europe. The MOC is predicted to slow down during the 21st century and thereby counteract a warming, though not enough to avoid a general warming (IPCC 2007). Though deemed *very unlikely* by the IPCC, should the MOC come to a complete stop the northern hemisphere would experience a cooling of 1-2° C on average. However,

within a period of 100 years the MOC would largely recover and circulation of cold and warm water would be re-established (Vellinga & Wood 2002).

The scenarios presented in this section are from 2006 and form part of the IPCC's fourth assessment report, and as such they are still among the latest predictions for Denmark. However, new observations are made continuously, climate models are improved, and new forecasts are produced with better predictions of both direction and scope of climate change. New data shows a continuous increase in greenhouse gases, mainly carbon dioxide and methane. The latter is increasing at a surprisingly high rate, perhaps due to positive feedback mechanisms[2] (NOAAA 2008). The values in Tables 2 and 3 may therefore be at the lower end of predictions, when the next IPCC report is released. Nonetheless, the values presented in this section form the base for the calculations in sections 5 and 6.

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[2] E.g. as the temperature rises in the northern regions methane is released from thawing tundra and sea beds, thereby contributing to further temperature increases.

3. Forest, trees and climate change

This section presents an overview of the known and expected impacts of climate change on trees and forests and their likely interaction with genetic diversity. The assessment of genotype reactions to climate change and the translation of these reactions into effects on productive functions of forest ecosystems is key information needed to assess the economic value of genetic diversity.

All commercially planted trees in Denmark have natural distribution areas that extend far beyond the Danish borders, and typical cover several eco-geographical regions. A prominent example is Scots pine (*Pinus sylvestris* L.), which in Europe is native of both Finland and Spain. However, it is also one of the species that exhibit the highest levels of genotype-environment interaction (at the provenance level) when planted in Denmark. The performance of a given Scots pine planting in Denmark is therefore highly dependent on the choice of the best seed source for the specific site (Larsen 1997). Similar results have been found for several other species in Denmark as well as world-wide, and as previously mentioned recommendations for selecting seed sources and seed transfer guidelines exists in many countries (see e.g. Eriksson et al. 1980, O'Neil & Yanchuk 2005b). This work reflects that genetic differentiation corresponding to local/ regional adaptation of trees is widely observed (or anticipated) as a common phenomenon in forest tree species. Variation according to climatic parameters is commonly reported to be decisive: variation in phenology thus often reflects a suitable fit to local photo- and thermo-periods ensuring appropriate timing of flushing, flowering, bud set and winter hardening. Climate changes may therefore be expected to challenge forest population of the majority of species at the majority of sites.

A general increase in production in Scandinavian forests may be anticipated due to warmer climate, though mainly in the northern parts (Beuker et al. 1996, Beuker 1994), due to increased CO_2 in the air, longer growth period for some species, increased nitrogen mineralisation and availability, which stimulates growth (Bergh et al. 1999). However, the extent to which Nordic forests can respond to such improved growth conditions will depend on the phenotypic plasticity of the applied species – and planting material within species. An important aspect of global warming in temperate and boreal forests is that new combination of photo-period and thermo-period will occur – the climate will get warmer while the day-length regimes will remain the same at a given site. Of obvious importance will be to what extent (and how much and how fast) species and forest populations will be able to adapt to the new climatic changes and thereby forming new adaptive patterns to replace the existing ones. In this context the level of genetic diversity is expected to play a major role in both a short and contemporary timeframe, because the expected response to natural selection is closely related to the levels and patterns of genetic diversity (Eriksson et al. 1993, Davis et al. 2005, Savolainen et al. 2007, Kremer 2007).

Increased number of severe storms (cf. Table 2) can lead to large losses in species prone to storm damage. Experiences from strong storms in Denmark have pointed toward large differences between species (Larsen 2008), most likely due to differences in root architecture. Genetic variation in basic root structure is poorly stu-

died, but in a study on pilot scale Nielsen (1992) observed variation between clones of Norway spruce and Sitka spruce in their root-top ratio and speculates that this could lead to differences in their likelihood to be damaged by storms. Root structure and architecture is expensive and difficult to measure on standing trees and therefore never included as standard in testing programmes. Therefore, a risk reduction strategy would *ceteris paribus* point towards diversification in terms of including more genetic diversity in the planting material.

The impact of new pathogens is difficult to predict, but may cause damages beyond the effect of reduced growth. Damages can occur both from new pests that invade the ecosystems as the climate becomes favourable, or from existing pests that become more aggressive. The latter is likely to happen because warmer climate can lead to a prolonged season where the pest can reproduce with the potential of additional generations during the growing season. This can result in an exponential increase in the population size of pests. The devastating effects of Montaine pine beetle (*Dendroctonus ponderosae* Hopkins) in Western North America is an example of a large scale outbreak that may be influenced by climate changes (Williams & Liebhold 2002, Kurtz et al. 2008), and studies on genetic variability have shown that important genetic variations in terms of susceptibility can be observed (Yanchuk et al.2008) indicating the importance of genetic diversity.

Besides increased population size of pests, the trees themselves may become more susceptible to pests due to increased periods with low rainfall during the growing season (cf. Table 3). Little is known regarding the three-way interaction between genetics, drought resistance and pest susceptibility, but the risk of increased damages from biotic factors also speaks in favour of maintaining diversity. In Denmark, clonal variation has been observed to be beneficial in the case of attacks from insects (aphids on *Picea sitchensis* (Bong) Carr., cf. Jensen et al. (1997) and wolly adelgid on *Abies nordmanniana* (Stev.) Spach., cf. Nielsen et al. (2002)) as well as fungi (die-back of *Fraxinus excelsior* L.; cf. Olrik et al. (2007)). Genetic variation in a given planting may be of crucial importance in order to reduce the risk of plantation failures due to insect and fungus attack because the biotic damagers have the advantage of being able to recombine in a large number of generations during the lifetime of a single tree.

At present, we know little about genetic variation in the ability of mature trees to handling situations with water tress. Substantial variation between provenances has been observed at the seedling level, e.g. Nielsen & Jørgensen (2003) found important differences in the response of European Beech (*Fagus sylvatica*, L.) provenances when exposed to different levels of water availability under nursery conditions. Similar results have been obtained in detailed studies of Norway spruce in Sweden, but it is difficult to infer results from nursery conditions to a mature tree setting. Indirect measures based on $\delta 13C$ isotopes have indicated that Water Use Efficiency (WUE) may vary between provenances and genotypes for some species reflecting adaptaptation of specific provenances to dry conditions (cf. e.g. Lauteri et al 2004), but the response of the tree is likely to also depend heavily on the root mass, architecture and vertical distribution. Given the difficulty in assessing expected response on water stress, a genetic diversification strategy may also in this respect be an important part of a risk reducing management approach.

4. Decision making under uncertainty, forest genetic diversity and climate change

Scientists have debated the likely effect of various climate changes on trees and more broadly forest ecosystems (Mohren et al. 1997). Much has been accomplished and discovered about various climate-tree interactions, and yet much remains to be known and revealed. In particular, the exact direction climate change will take in various regions all over the world simply remains to be seen. The expected climate change may occur quite swiftly compared to the length of a tree generation, not to mention the adaptive mechanisms of long-lived ecosystems like the forests, and the overall changes within a single tree generation can be substantial (O'Neill & Yanchuk 2005a).

Nevertheless, it will appear too slow for decision-makers to have any clear idea of its direction and the consequences for the forests they manage. Hence, decisions must inevitably be made in the face of great uncertainty. In economics, the issue of decision making under risk and uncertainty is of great interest. We will draw forward three aspects from the economic research on decision making under uncertainty, which can be used to illustrate important economic aspects of the management of forest genetic diversity, and which will be demonstrated in sections 5 and 6 using the available data on climate-genotype-production relations on Norway spruce.

4.1 Reducing risk through diversification – an economist's approach

The first aspect is that of risk and the disutility associated with risk for most individuals. Since the seminal work by von Neumann and Morgenstern (1953) it has been recognised that because people tend to be risk averse, risky returns are less desirable than certain returns, *ceteris paribus*. Climate change implies a greater uncertainty concerning the future returns to any forest investments, because it is unknown how climate change will affect the growth, health and stability of forest stands. Forest owners have the option to diversify against risk in their forest management, and forests genetic diversity could be one vehicle to secure such diversification – also with respect to climate change. As discussed above, we expect different species, different provenances or different clones to react differently to climate changes, at least to some extent, and we can therefore reduce the risk by spreading our use of species, provenances or clones, as appropriate and relevant. This opportunity arises, because the responses of the species, provenances or clones to a given shock are not perfectly correlated due to their variation in reaction norms. The principle is shown in Figure 1, which is typically used to illustrate that a diverse portfolio of assets that correlate less than perfect may reduce the uncertainty of an expected return.
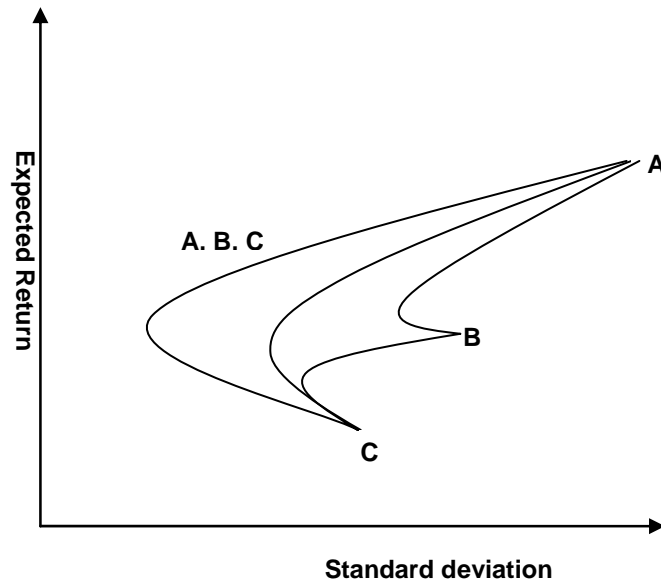
Figure 1: Illustrating how mixing genotypes A, B and C may result in reduced uncertainty (standard deviation) for given expected returns.

In most economic decisions, diversifying to reduce risk in returns comes at a cost in terms of lower expected returns. This may also be the case for the forest owner, but since the risk in this case may not be well-defined or known for the various choices he has, it is perhaps impossible to say, which choice of species is likely to reduce the expected returns. Apparently, diversification against climate change related risk may in principle not be much different from diversifying against roundwood price variations using, e.g. mixed-species forestry. Except that the risk is better described and known in the case of roundwood prices. The gain for the risk averse forest owner from risk diversification comes from a better risk-return relationship. If a forest owner considers the option to have a stand 100 % composed of the species B in Figure 1, he will in fact be able to pick a combination of species in the forest, e.g. a mixture of both A, B and C, which gives the same or a higher expected return at a strictly lower risk. Note that the consequence of this is to pick the right mix of, e.g. provenances and not to mix as many as possible. Genotypes that show a high correlation with the responses of other genotypes in the portfolio would add little new value, and in practice adding more genotypes comes at increasing cost.

The forest owner may be able to achieve the risk reduction by having say *n* species (or provenances/ genotypes) growing in *n* different homogenous stands in his forest. Some stands will cope and provide the forest owner with economic returns, whereas other stands may be less fortunate, develop poorly and perhaps even collapse. On average, the forest owner will in principle be just as well off with *n* pure stands as he would have been had he used *n* species in say 3*n* stands – i.e. smaller stands, but still monocultures. In fact, if there are returns to scale in establishing the stands, he may favour larger stands and hence the *n*-stand version. This is illustrated in Figure 2.

19

If climate change favours *either* the red or the green type but most likely *not both*, having both types in some mixture has value to the forest owner
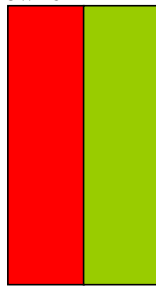
In terms of risk diversification, each of the two model forests here are perhaps the same to the forest owner. They have equal shares of the types.
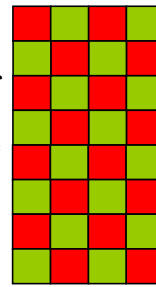
Figure 2: Implementing diversification. By diversifying his choice of tree species, provenances etc., the forest owner can reduce some of the risk climate change implies for him. Diversification does not mean mixing on every area. However, mixing may affect returns through economies of scale (negative or positive) – therefore the forest owner and society may prefer different degrees of mixing genotypes, as failure of one species on large land areas may cause a loss of positive externalities, social values which are not necessarily the concern of the forest owner.

For society, the choice of how to implement risk diversification may not be trivial, even if society as such is less concerned with risk in returns of the single forest owner than he is himself. The problem for society is that if climate change implies a risk of severe stability and health problems and potential collapse in larger forest areas, then these forest areas may also stop producing a number of the non-marketed environmental services of great value to society. An example from Denmark is the problems of serious nutrient leaching following large-scale wind throws in Norway spruce. The larger the area in question, the more likely negative impacts will be. Hence, society may prefer the forest owner to implement diversification in a much more elaborate way than optimal for him. The reason is that the social value function of the forest includes a number of elements likely to be of much less importance to the forest owner than to society, cf. again Figure 2.

An elaborate kind of risk diversification in plantation forestry could be the random planting of several species in each reforestation spot – resulting in a high degree of inter-specific forest genetic diversity in the stand. This kind of mixed-species forestry, however, is often impossible for silvicultural reasons. Very different species tend to develop very differently in their youth, and often such initially diverse stands quickly grow into more or less monoculture ones through inter-species competition in the young stand – in which case little or nothing have been achieved, but most likely at a high cost in terms of management and production lost. A different approach would be to plant stands of one species per stand, but ensure large levels of genetic diversity in each stand. Kjær et al. (1995) suggest deploying seed sources for long rotation species that maintain an effective population number of 20 or above. Assuming that different genotypes fits different climates (genotype-by-environmental interaction), such an approach will reduce risk in returns compared with picking more narrow genetic basis for the planting material, and will ensure that sufficient genetic variation is present for selection to work on. A low risk strategy could further be supported by selecting genotypes that perform well over a suite of different sites (little genotype-by-environment interaction). Use of genetically diverse, unimproved provenances may be an easier alternative. But, if improved planting material is available, such

a strategy will imply costs in terms of 'values forgone' in terms of productivity by not using sources based on selected trees. Different species can be planted at different sites matching the soil conditions, and diversifying the species choice.

What we have discussed so far is the potential of forest genetic diversity in reducing risk in a traditional portfolio selection way (Markowitz 1952). This way of coping with climate change risk is likely to be important at the individual owner or firm level, and in this specific case we argue that the way diversification is undertaken in forest management is likely to also influence the expected societal value of forests.

4.2 Dynamic, but reactive decision making under uncertainty

In the above, it is implicitly assumed that once we have decided upon some specific forest genetic diversity in or between our new forest stands, we wait for climate change to unfold itself and see which stands fail and which stands succeed. The planning mode is best described as anticipatory. The forest owner would make a loss on the stands that fail (as would society), relative to those who succeed. With this approach, the next decision point for the forest owner would be to salvage the poor performing stands (to reduce the loss of alternative production forgone) once he can recognise them and replace them with new stands of trees with different and perhaps better genotypes. His initial decision on the forest genetic diversity is an irreversible decision in an economic sense, because the initial costs of establishing the stand and the production lost on poor-performing types cannot be recovered.

However, if genotypes are mixed closely on any given area, then even if it is not known in advance how the different genotypes will react to climate change, whatever it be, the forest owner may benefit from observing change and reactions and react to these through thinning aimed at the individuals and hence genotypes in a stand, which performs the poorest. Thinning away the poor performing trees will result in the neighbouring trees taking over the released area and increase their own growth. Thus, growth potential is increased through thinnings.

This is a well-known effect already common in silvicultural practice, but with uncertain climate change and perhaps even with limited information on genotype-climate interaction, the economic potentials and gains from such reactive thinning actions will increase. The stylised Norway spruce example in sections 5 and 6 aims to show how such a reactive thinning approach in the face of uncertain climate change will in general increase average returns and reduce variation in returns from timber production in forest stands with closely and randomly mixed genotypes.

Climate change effects will occur only after some time. Societies must therefore support strategies which allow for an adaptive strategy over such long time horizons. For plantation forestry, it is important that forest genetic diversity is not reduced through widespread deployment of genetically narrow seed sources. Because we have imperfect knowledge of which species, provenances or genotypes will do well in the future, we need to have a variety of these growing

under a variety of conditions in order to bring about the new important knowledge on which to base future decisions on.

4.3 Dynamic, forward-looking decision making, adaptive management and real options

A final approach to decision making under uncertainty is the one associated with Bellmann's principle of optimality. It presupposes a deep insight into the probabilities of future events as well as state responses to these future events. Models to value real and financial assets under uncertainty have been developed since the early 1970'es. The field is highly developed with regard to models valuing various financial assets and derivates, but in particular over the last 15-20 years the field of real options has grown to provide a coherent approach to deal with real and natural resource type of assets.

When decisions are irreversible and there is uncertainty about the future value of some decision alternatives, delaying the irreversible decision includes an option value. This is the second important economic aspect we wish to discuss in relation to forest genetic diversity. Having the option to delay important irreversible decisions requires that we are able to design and implement flexible forest management strategies. Flexible strategies 'buy time'.

The option value was first identified by Arrow and Fisher (1974) and Henry (1974) in the cases of e.g. the irreversible development of a nature reserve, whose future value is known to be uncertain. Another example is the irreversible harvesting of an old growth forest of uncertain future value as a seed source: If you harvest the forest now, you get the value of the timber, but lose the potentially increasing value of the forest as a seed source. If you postpone the decision to harvest, you may learn that the value as a seed source increases perhaps above the timber value, and you can benefit from this increase. If the value as a seed source becomes inferior, you are still able to harvest the stand and get the timber value. This 'value of waiting' was later described in managerial economics by McDonald and Siegel (1986) and has developed into the field of real options analysis (Dixit and Pindyck 1994).

Similar values may be related to flexible forest management options arising from forest genetic diversity, in particular when facing uncertainty caused by climate change. For example, if we can defer the final decision of which species, provenance or clone we want to form the dominating and primary wood producer on a piece of land, we may learn more about the evolution of climate change and perhaps the effects on the various kind of trees. The simplest and crudest way of doing that is of course to simply defer, e.g. the planting of the new stand. This, however, may be impossible in the case of reforestation of forest land and certainly likely to be too costly if the land cannot be used for other purposes, while waiting. In the case of afforestation of agricultural land, it may be a reasonable option (Thorsen 1999).

Another approach to introduce flexibility into the forest management plan is to establish a stand with two or more species, provenances or clones, and then observe their growth development as well as the evolution of climate change and

22

its effect on the growth patterns of trees. Next, the forest owner may enter the young or medium-aged stand and through selective thinnings remove the trees, provenances or species which turned out to be ill-fitted to the climate change realised, and allow the better-fitted to make use of the space liberated. This is like the dynamic reactive approach, but now the forest owner will also take into account the climate change observed by updating his expectations concerning future climate change, e.g. if we in twenty years time observe that temperature has increased with 1°C already, then an overall increase of 2 °C and perhaps more seems more likely than we would assess it today. Of course, such an approach requires rotations of some time span or climate changes of some speed and magnitude to result in significant option values. Only one paper, Jacobsen and Thorsen (2003), exists that provide a deeper analysis of such a case. It would probably be right to argue that such species or genotype mixes will sometimes be impossible for silvicultural reasons, or at the very least potentially costly in terms of higher establishment and management costs. The gains in option values should exceed these additional costs – otherwise the approach is not advisable. An important finding in Jacobsen and Thorsen (2003) is that with increasing uncertainty about future climate change and hence relative performance of species, it becomes optimal even in a mixed stand to keep the currently underperforming species at higher stocking levels than otherwise optimal. This implies cost in terms of production foregone as this species takes up space the better performing species could have used. However, to a certain point this is outweighed by the value of having enough of the underperforming species around to be able to take advantage of a shift in climate switching the performance of the species in opposite directions.

This means that even when we know everything about the climate change-genotype interactions and have knowledge of future climate change probabilities, we may harvest additional value from mixing genotypes in the same stand. In addition to the above discussed benefits of removing in a reactive manner the less performing genotypes through thinnings, we gain new knowledge on climate change and genotype reactions. Additional value comes from foresight and knowledge about the possibility of currently underperforming genotypes turning out better in reaction to future climate change – and the value of this. The effect is to keep around for a longer time than otherwise these underperforming genotypes – hence to invest in a higher genetic diversity in all states of the world. The principle is illustrated in Figure 3.

Mixing genotypes on the same area may allow for selective and adaptive adjustments along the way. We effectively postpone the choice of dominating genotype. We keep underperforming genotypes in play longer if optimal, because future climate change may favour the underperforming species to the better performing.
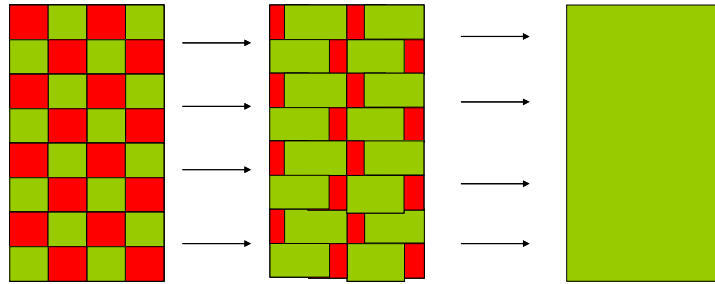

Figure 3: The option value of management flexibility. An illustration of the effects of forward dynamic looking behaviour associated with the values of real option and flexible management practice. Even if the species symbolised by the red colour is known to underperform at current and some, but not all, possible future climate states, it is kept around in significant amounts also in later stages. The value of this comes from the possibility that climate change will harm the species symbolised by the green colour, and benefit the red.

The resources within this pilot study did not allow us to fully develop this dynamic forward-looking decision process further in the present report. This will be done subsequently, as it is most likely of great value to be able to assess this extra potential gain of mixing species on an area when facing risk of climate change. In the next section we present the theoretical stochastic dynamic programming model we expect to use for evaluating this forest management strategy. However, to improve the understanding of the value of waiting, the option value, we develop and present here a simple example, see Figure 4.
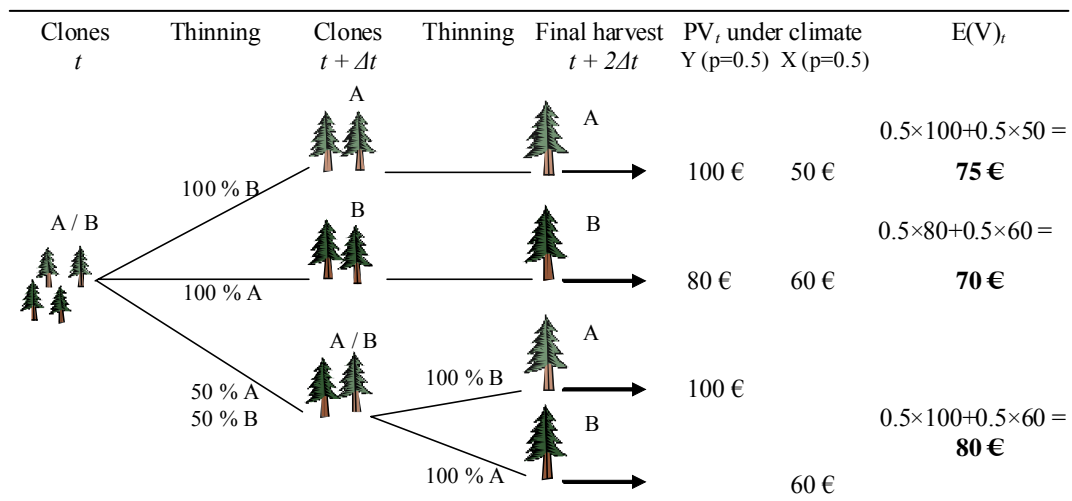
Figure 4: The economic gain from diversity and plurality of options. When clones A and B are both kept in the stand after the first thinning (time t + Δt) *the forest owner can postpone the decision on which clone to keep for the final harvest, meanwhile learning more about the future climate, which can go in either direction Y or X. PV$_t$ and E(V)$_t$ are present and expected value of the stand at time* t. *The value of waiting, also called the option value, is in this example 5 €.*

Suppose a forest owner has a stand consisting of two different clones A and B (provenances or species) in equal shares. Suppose that the forest owner believes that he faces two possible future climate states X and Y, each with equal probability 0.5. The stand now needs to be thinned to half the stem number in order to allow a proper development of the individual trees. Following the thinning a time period Δt elapses and a similar final thinning needs to be made – the remaining trees form the final stand to grow to maturity. However, after the time period Δt the forest owner will also learn the state of the future climate with certainty. All thinnings are assumed to have zero net value for simplicity, which means that the forest owner must make his thinning decision now based on his expectations of climate change and his insight into the value of the two clones under the different climates. Suppose that if climate X is realised, a pure clone A stand will represent a present value of 100 € at time $t + \Delta t$ and a pure stand of clone B will represent a present value of 80 €. Let the same values in case of climate type Y be 50 € and 60 € for clone A and B respectively. The situation is depicted in Figure 4. The questions the forest owner now needs to ask and answer for himself are: Should I remove clone A now? Or clone B? Or should I perhaps remove half of each, thereby postponing the decision until $t + \Delta t$? Evaluating these three decisions in terms of expected value is straightforward. Removing clone A now at time t results in a value of $E(B) = 0.5 \times 80 + 0.5 \times 60 = 70$ €, whereas removing clone B at time t results in $E(A) = 0.5 \times 100 + 0.5 \times 50 = 75$ €. Thus, if the forest owner insists to make the choice between the clones now, he will choose clone A and remove clone B. However, if he carefully evaluates the last option, where he will effectively keep enough of each clone in the stand to form a mature stand after the last thinning, he will learn that it has a value of $E(\max(A, B)) = 0.5 \times \max\{100; 80\} + 0.5 \times \max\{50; 60\} = 0.5 \times 100 + 0.5 \times 60 = 80$ €. Thus, the value of waiting and adjusting his thinning decision to keep his options open is $80 - 75 = 5$ €, the option value. It arises because by waiting and learning more about the future climate, he is able to make the best choice among the clones contingent on (more) firm knowledge and not just on expectations. In a real world example, there will of course be many more steps in time and more subtle thinning decisions to be made due to growth and price dynamics, but the general principle here will still be in play: When there is uncertainty about the future development, and different genotypes, clones, provenances or species are likely to react differently to different changes, there may be actual economic gains to be made from maintaining a reasonable level of diversity and hence plurality of options.

5. Developing a model for the analyses

In this section we describe the components of the model developed for assessing the economic value of genetic diversity for an example of Norway spruce clones. A model is developed which predicts the diameter growth, height and volume of a Norway spruce stand under uncertain climate changes. The stand development is thus dependent not only on thinning strategies and number of clones included in the forest stand, but also on stochastic changes of the climate during one rotation. Four approaches to forest management were described in section 4, of which the three first approaches are investigated using a model, which is based on a single-tree diameter growth model for Norway spruce in Denmark by Johannsen (unpublished), a volume function by Madsen & Heusèrr (1993) and a price function based on data on prices of Norway spruce from the Danish Forest Association.

5.1 Growth model description

The basis of the model is a dynamic diameter growth equation which predicts diameter growth for a given number of clones in a forest stand. As opposed to standard growth and yield tables, which are based on predefined thinning regimes, this model uses actual stand data to predict future growth. Annual diameter increment is predicted using equation (1), which consists of a site rate constant a, a competition component that is made up of a stand competition index and a tree competition index, and a size controlled growth factor that depends on the actual diameter of the tree. As trees grow in diameter, height growth is calculated using equation (2) (Johannsen, unpublished). In (1) and (2) the parameter estimates are given as determined by Johannsen, who based her work on nearly 300,000 measurements of Norway spruce trees in permanent experiments in Denmark. The superscripted parameter of 0.814 is a parameter for maximum diameter (0.814 m).

$$\Delta d / \Delta t = a \exp(-0.0319 D_g^{2} N / 100) \exp(-7.949 D_g / d) 2.161 d^{0.814} \exp(-0.046 d^2 / 10000) \quad (1)$$

$$h = \left(\frac{d}{0.673 (H_{100} - 13)^{-0.281} (9.940 D_g^{0,408} + d)} \right)^3 + 13 \quad (2)$$

In these equations, d is diameter in mm, a is the site rate constant, D_g is the quadratic mean diameter in mm, N is the number of trees in 100 per ha, h is height in dm and H_{100} is the height of the 100 tallest trees in m.

The site parameter a is a rate constant that describes the fitness of the tree to the specific site, i.e. a expresses the effects of the total environment on tree growth, e.g. climate, soil properties and topography. As used in the original context the site rate constant stays unchanged throughout the duration of the trees lifespan. In the case where climatic changes are taking place during a rotation and affect the overall effect of site on tree growth, the site rate constant is allowed to change and as such the effect of climate change is inherent in a. Establishing a genotype based change in a caused by climatic variation will allow us to capture and model the production effect of climate change.

A volume function by Madsen & Heusèrr (1993) is used to find merchantable volumes of each tree above stump and above a top diameter of 5 cm. The function is given by equation (3).

$$v_5 = \exp(-1.899967 + 1.586343x_1 + 1.146216x_2 + 1.75157x_3 - 2.358959x_4 + 1.048696x_5 - \tag{3}$$
$$0.018779x_6 - 0.015727x_7 + 0.061089x_8 + 0.001364w,$$
$$x_1 = \ln(d)$$
$$x_2 = \ln(h)$$
$$x_3 = \ln(1 + (b/d)^2(h-1,3)/h)$$
$$x_4 = \ln(1 + ((b/d)(h-1,3)/h)^{3/2})$$
$$x_5 = \ln(1 - (b/d)^4((h-1,3)/h)^2)$$
$$x_6 = \ln^2(D_g)$$
$$x_7 = \ln^2(H_g)$$
$$x_8 = \ln(age)$$
$$w = (1 - b^2/d^2)(1 - d/2)^2$$

where v_5 is the volume in m³, H_g is a stand parameter corresponding to D_g, b is the top diameter limit, while the remaining are as previously defined.

5.2 Roundwood price function

Equation (4) is a price function derived from an index of 2008-prices of different diameter classes, as stated by the Danish Forest Association (2008). The function is used to find the value of each tree based on diameter at breast height. Volume per tree and number of trees are used to find the total value of the stand.

$$P(d) = -0.009644d^3 + 0.602970d^2 - 3.877089d + 20.020489, \tag{4}$$

where P is the price in DKK per m³ of timber. This fitted polynomial is valid for diameters up to 52 cm.

5.3 Assumptions of climate changes

There is still much uncertainty regarding the effect of climate change on tree growth. Not only are the predicted climate changes uncertain as to whether temperature will increase or decrease in the medium to long run, but the effects of temperature changes on tree growth and tree health are also uncertain. If temperature increases, which is believed to be more likely than temperature decreases, the growth of Norway spruce in Denmark is expected to increase, but at the same time the health of the species is expected to decrease because of mild winters and the risk of stand failure due to windthrow and pest attacks are expected to increase. Due to the complexity and uncertainty of the accumulated effects of higher temperatures on growth of trees it is assumed that the total growth response to climate change is described by changes in the site rate variable a. The model could be expanded with a component that contains a risk of stand failure dependent on temperature. However, in the current version of the model it is assumed that tree

growth is positively affected by temperature increases. Furthermore, it is assumed that temperature is a proxy for climate changes and as such only temperature is included in the model as a variable.

As the site rate variable *a* is positively affected by higher temperatures, the uncertainty of climate change on tree growth is modelled as a change in *a* following a simple, but stochastic temperature change. During the rotation period of 100 years the model allows for a stochastic change in temperature every 10th year, which changes *a*. The temperature change is random, but based on the different climate change scenarios as described in section 2, the probabilities associated with temperature increases and decreases, respectively, are not symmetrical. The probability for a temperature increase and the amplitude of the increase are both larger than those associated with a temperature decrease (Table 1). The temperature change in one period is partly dependent on the temperature change in the previous period as expressed in equation (5):

$$T_{i+1} = T_i + \beta(\tau_{i-1}) + \tau_i, \qquad\qquad (5)$$

where T_i is total temperature change at time *i* (i.e. $T_0 = 0$), β is a constant between 0 and 1, and τ is a serially uncorrelated stochastic variable inducing the stochastic temperature change in each period. Here we use a fairly simple asymmetric trinomial distribution as described in Table 4. The dependency on past changes means that a temperature change is buffered (if the previous change was in the opposite direction), enhanced (if the previous change was in the same direction) or unaltered (if there was no change in the previous period). It is assumed that temperature changes are only observed (or reacted to) every ten years and that no changes occur during the first 10-year period. Changes in temperature leads to changes in the site rate variable as described in more detail in the following sections.

Table 4: Probabilities and amplitudes of temperature changes based on the climate scenarios

Temperature change	Probability	Amplitude/period
- decrease	0.2	0.15 °C
- increase	0.5	0.25 °C
- no changes	0.3	0 °C

5.4 Data on genotype-climate interaction

An experiment with clones of Norway spruce carried out by Karlsson et al. (2001) forms the data basis for the example. The objective of the clonal study was to assess the stability of clones within provenances across sites and involved 96 clones planted on 11 trial sites ranging from central Sweden to western Denmark, thereby representing a gradient of environments. For each clone height measurements were made 14 years after the seedlings were planted. No climatic data from the sites were readily available from the study but geographic coordinates made it possible to extract data on different climatic factors from FAO´s New_LocClim – Local climatic estimator (2005). As noted earlier temperature was chosen as a proxy for climate change, while other factors like precipitation and wind were disregarded. Temperature estimates were based on distance weighted averages of

observations from several weather stations and corrected for differences in altitude. The 11 sites cover an annual average temperature gradient of 2.35 °C and thereby resemble the maximum temperature increase expected under the B2 and EU2C scenarios.

The two sites with the lowest and highest temperatures, located at Västra Ryd and Knutstorp in Sweden, were chosen to represent the potential change in climate during a 100-year period. The two sites have an average temperature difference of 2.35 °C. Calculation of temperature dependent changes in the site rate constants was based on height measurements from these sites. The starting values of the site rate constants were based on measurements from a third site at Årdala in Sweden, which had an intermediate temperature level (Table 5).

Table 5: Source: FAO´s New_LocClim

Trial site	Annual avg. temp
Knutstorp, Sweden	7.78
Årdala, Sweden	6.14
Västra Ryd, Sweden	5.43

The height of trees on each sites as reported by Karlsson et al. (2001) was taken as a measure of their fitness to the environment of each site, including the temperature. Through a regression of clone tree height and the logarithm to temperature at each site, parameter estimates for the effect of temperature on height growth were obtained for all clones. Subsequently, 14 clones were selected. Six of the clones had the highest maximum parameter estimates of all clones, i.e. were influenced the most by temperature, six clones had the lowest estimates, i.e. were influenced the least by temperature, and two clones had intermediate estimates. This selection ensured a high level of variation of temperature responsiveness among clones.

5.5 Linking temperature induced productivity changes through the site rate constant

Each clone, i, grows differently on the three chosen sites and therefore each clone has a distinct site rate constant, a_i, and distinct responsiveness to temperature changes corresponding to their height at the three sites. As temperature changes so does a_i, and it does so differently for each clone. The responsiveness of a_i is estimated through a conversion of tree height to a_i at each of the two sites with extreme temperatures. The difference between a_i at the two sites relative to the difference in temperature yields a measure for changes in a_i given a change in temperature of one °C. In order to convert tree height into the site rate constant, it is necessary first to convert tree height to production class and then production class into site rate constant. The first conversion is made by inserting the measured height of each clone into a second order polynomial function based on tree height in production classes 10 to 20, corresponding to Carl Mar Møller's yield tables (Statens forstlige Forsøgsvæsen 1990).

$$PK(h) = 0.0846h^2 + 1.5815h + 8.0908,\qquad(6)$$

where h is height at age 13 years from seed and PK is production class.

The production class is subsequently converted into a site rate constant through equation (7), which is generated via two steps of problem solving. First, for each of the production classes 10, 12, 14, 16 and 20, equations (1) and (2) are solved for values of a_i that will fit tree height throughout the rotation to tree heights given by Carl Mar Møller for each of the five production classes. This results in an a for each production class. Subsequently, the function in (7) is estimated to obtain parameter estimates that minimise the difference in a found in (1) and (2) and (7) given production classes 10,…, 20.

$$a(PK) = -0.00026PK^3 + 0.013043PK^2 - 0.19192PK + 0.908074,\qquad(7)$$

where PK is the production class.

Using a simple linear regression of a_i (as implied by the heights of the 14 selected clones at each of the two selected sites) on temperatures, we obtain an estimate of the change in a_i given a change in temperature of one °C. Table 6 shows the responsiveness (da_i/dT) of each clone to changes in temperature, i.e. the climate change growth response.

Table 6: Height of each clone on the warmest and coolest trial site and related changes in a given a change in temperature of 1 °C

Clone	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Height,m Västra Ryd	3.06	2.37	2.13	2.10	2.51	2.81	2.77	2.56	2.60	3.31	3.33	2.64	2.81	2.27
Height,m Årdala	4.22	3.97	4.42	4.03	3.99	4.04	4.04	4.15	4.61	4.57	4.76	4.67	4.48	4.34
Height, m Knutstorp	5.84	5.19	6.27	5.25	6.06	4.48	5.64	5.31	5.88	7.00	6.27	6.90	6.25	7.09
$a_{i,\,start}$	0.112	0.098	0.123	0.101	0.099	0.102	0.102	0.108	0.134	0.132	0.143	0.138	0.127	0.118
da_i/dT	0.061	0.057	0.077	0.060	0.072	0.034	0.062	0.057	0.068	0.061	0.062	0.073	0.070	0.074

Following each observation of a change in temperature, the site rate constant for each clone is calculated as expressed in equation (8).

$$a_i = a_{i,\,start} + (da_i/dT) * T\qquad(8)$$

where T is total temperature change since establishment of the forest stand.

5.6 Economic models and estimates

The above growth model is combined into an economic model calculating the NPV of a given combination of clones and a given realisation of climate change paths. The model can be run with any number of clones, from a forest stand con-sisting of a single clone to a forest having only a single individual tree belonging to each clone. The analysis is undertaken in different steps of increasing com-

plexity, each corresponding to the approaches to forest management described in section 4. Three of these apply a Monte Carlo-type simulation approach, i.e. repeated random sampling, to assess the expected outcomes and their variances of given forest management approaches. The fourth step is the dynamic forward-looking adaptive management model, which was not fully completed at the time of finalising this report.

Step 1 of the analysis is made under the assumption that the forest stand in consideration consists of only one clone. This is the conventional forest management approach, where only one genotype (or provenance or species) is selected for reforestation following harvest. Usually, the selection is based on experience or knowledge of what is the best such choice. However, with uncertain climate change and a massive lack of research and insight into genotype specific responses to climate change, the choice of clones, provenances or species is made on a much less informed basis. Thus, we calculate the expected economic performance of each of the 14 clones, and the average of these would then correspond to the expected value of a random and uninformed choice among them.

The basic economic measure calculated is the expected net present value NPV[3] of the harvested volume from a forest (stand) of clone i over the rotation period T:

$$E(NPV_i) = \sum_{m=1}^{M} \frac{1}{M} \left[\sum_{t=0}^{TI-1} \frac{h_{imt} \times p(d_{imt})}{(1+\delta)^t} + \frac{H_{imTI} \times p(d_{imt})}{(1+\delta)^{TI}} \right]. \tag{9}$$

The discount rate is δ and the harvest at each time step t is given by h_t which in all the simulations follows a simple fixed rule: At each time step, 30% of the standing volume is harvested from below, i.e. the smallest trees (clones) are harvested first. The volume is sold at the net price p which is a function of the diameter of harvested volume. At time TI the remaining volume H_{TI} is harvested and sold. Note, that because the overall growth depends on the clone i, the passage of time t and in particular the stochastic evolution of climate changes in each simulation run m, the harvested volume and the prices are also stochastic from the point of view of the forest owner at time 0. In most of the simulations presented below we have $M = 2,000$.

Across all simulations we fix a number of parameters, e.g. the NPV is based on only one rotation, with a duration of $TI = 100$ years. During the rotation climate changes can occur every 10th year with the first observations of changes taking place in year 20. After 10 years of growth following the climate change the forest stand is thinned and the value of removed wood is recorded. At the end of the period TI remaining trees are removed and a net present value for the whole rotation including the thinnings is recorded. Table 7 shows the values, harvest rules and initial settings that are identical for all clones and stands. The results are quite sensitive to some of the parameters, e.g. the discount rate. In this report we will no go further into this issue. However, it should be mentioned that a smaller interest rate would result in substantially larger present values than those reported

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[3] In order to keep the model as simple as possible, establishment costs etc. are not shown separately in the model, but are inherent in the net prices.

in section 6, i.e. the smaller the interest the larger the absolute differences between the different steps.

Table 7: Initial characteristics of the forest at year 10 and common values used in the calculations

Element	Value
Discount rate, δ	0.04 annual discount rate
Thinning strategy, h$_{imt}$	30 % of volume every 10th year, from below
Rotation age, TI	100 years
Number of simulations, M	2,000
Tree diameter at year 10	40 mm
H100 at year 10	3.5 m

In step 2, we illustrate how having different clones in different stands in the forest can provide the forest owner with risk reducing options. Even without mixing the different clones in the individual stand, he will be able to pick the, for him optimal combination of expected returns and risk, according to his degree of risk aversion. To that end we estimate the variances of the expected net present value of 'single clone' stands:

$$VAR(NPV_i) = \hat{\sigma}_i^2 = \sum_{m=1}^{M}\left(PV_{im} - E(NPV_i)\right)^2\Big/M \qquad (9)$$

From this we get the estimated standard error σ_i of the expected NPV_i. In the cases where a forest consists of two different single clone stands in the proportions p of clone i and q of clone j, the variance of the combined forest is simulated in a similar way, taking into account the two clones' different reactions to climate change in each simulated climate change path of the M simulations.

Note, that the simple knowledge or recognition that different clones react differently to climate change is enough information or insight for the forest owner to start mixing clones across forest stands. However, to be able to optimise his choice of clones from a risk reduction point of view, he will need information on the likely performance (expected means, variances and co-variances) of the different clones (provenances or species), and the correlation of growth-climate change shocks across clones. Clones, which tend to show responses to observed climate changes that are not perfectly correlated with those of other clones, will offer options for risk reduction in a portfolio. Thus, already at this fairly low level of sophistication, quite some information obtained from genetic research and tree improvement programmes is needed. Estimating the correlation across clones of climate change response requires detailed data across climate gradients. The empirical data from Karlsson et al. (2001) allow a crude estimation of such climate change response correlations for each of the 14 clones. In the analyses below we will demonstrate the potential gain using a set of correlation coefficients from the data as well as two hypothetical correlation coefficients.

In step 3, we expand to model the dynamic, reactive adaptation forest management approach, where two or more clones are mixed in the same stand. In each simulated rotation the poorest performing individuals (clones) are removed through thinnings as climate change evolves and affect their growth patterns. This

means that per area unit, the best performing species under any climate change scenario will take up more of the land area than in the case where each clone is planted on a separate piece of land. As we shall see this results in drastic changes in the performance of the stands compared with the forest management strategies corresponding to step 1 and step 2. The basic economic performance measures remain those of equation (8) and (9), of course now with indices indicating the initial clonal mix of the stands. Thus, in this step of analyses, the forest owner makes use of further information in his decision, in the sense that he observes the climate change as it evolves, and the responses of the different clones. He then adapts his harvest decision to the obtained information.

Note however, that in all of the above steps, the thinning decision is undertaken reactively and quite mechanically (cf. Table 7). It is important to note that when it comes to the effect of uncertainty on harvest decisions, the 30% volume harvested in thinnings is *always* harvested 'from below'. Hence the forest owner will in all cases fully harvest the poorest performing clone before starting to harvest individuals from the next-poorest clone. However, at the time of thinning there could still be a possibility that climate change in the future may significantly change the performance ranking of the clones. In such cases, there may be a significant value associated with keeping at least some volume of the poorest performing clone(s) in the stand, and instead reduce the volume of the better performing clone(s). This concerns the way the distribution of the harvest across clones affects the expected future value of the stand given the updated expectations of the distribution of future climate changes. Such results have been documented in a theoretical study by Jacobsen and Thorsen (2003).

Thus, **the 4th step** in a full assessment of the value of genetic diversity would be a full stochastic dynamic programming model of forward-looking adaptive management behaviour. Such a model inherently solves the optimal distribution of harvested volume across the relevant number of clones, i.e. harvest policy, at *all* time steps and *all* possible future state combinations of climate change and wood volume given. It is easy to realise that the combinatorial effect of this implies that it may require immense computational power to perform the optimisation component of such a programme. The requirement grows fast with number of time steps applied, the number of clones (and hence volume states) involved and the possible number of future climate states. Work is currently ongoing on a simplified two clone model. In general, the problem for a two clone example can be formulated as:

$$W(v_{it}, v_{jt}, T_t) = \max_{h_{it}, h_{jt}} \left\{ h_{it} + h_{jt} + (1+\delta)^{-1} E(W(v_{it} - h_{it} + \Delta v_{it+1}, v_{jt} - h_{jt} + \Delta v_{jt+1}, T_t + \Delta T_{t+1})) \right\} \quad (10)$$

In equation (10) W is the expected value of the optimally managed stand, which depends on the current volumes v for each of the two clones i and j in the stand. As before T is temperature, h is harvest (thinning or final), δ is the discount rate and in the expectations operator E we see the expected value of the stand after another time period, i.e. after the growth and harvest related changes in volume v and the stochastic change in climate indicated by the change in T. The many possible states of v for the two clones and climate T over a period of 100 years in 10 steps of 10 years make the solution to this problem rather complicated computation-wise.

The solution to the model here will include the additional option value, as illustrated in section 4, obtained by being able to postpone in several steps the selection among the clones in the forest stand.

5.7 Limitations and assumptions

Before commencing calculations it is important to state the limitations of the study and the assumptions underlying the calculations. When natural processes are modelled and predicted a range of assumptions must be made in order to simplify the process.

Differences in height of clones between Knutstorp and Västra Ryd are assumed to be influenced by climate and site variation. In our model we link all the variation to variation in temperature. This is a simplification of the effect of site on tree growth, as other site factors, such as precipitation, soil and topography, are also important for differences in growth between sites. Furthermore, higher temperatures are not only expected to lead to higher growth rates, but also to a reduced health of Norway spruce because of mild winters. Due to the complexity and uncertainty of the accumulated effects of higher temperatures on tree growth, e.g. changes in pest attacks, wind throw etc., it is assumed that the total growth response is inherent in the rate constant a. However, our model only incorporates growth response effects (through a_i) at tree level, and hence it does not take into account changes in risks of total stand failure. As described in section 3 above, genetic diversification may provide additional flexibility and risk reduction due to variation between clones in reaction to new or existing pests and climatic extremes. Given the potential costs of plantation failures due to such effects, these effects not accounted for in the model may be of larger magnitude than the effect we include in our model. The rather crude incorporation of uncertainty and lacking firm knowledge of variation and co-variation across clones with different climate change types is of course also a severely limiting factor for the practical applicability of the concrete results presented below. Nevertheless, as we shall see, this pilot study has been able to illustrate the principles of assessing the economic value of genetic diversity.

The model does not take into account phenotypic variability among trees within the same clone, as would be expected in a real forest due to micro-climate variations etc. Instead, all trees of the same clone follow identical growth paths, which means that in scenarios where thinning is done from below trees from the poorest performing clone will always be removed first. In a real setting where the smallest trees are removed we would expect these trees to belong to more than one clone, because of the phenotypic variability of ramets from the same clone. Furthermore, as we look at an even-aged stand, the forest manager does not have the opportunity to replace poorly performing genotypes with better ones. The poorly performing genotypes are removed during normal thinning operations, which open up space for the remaining and better performing trees.

The study by Karlsson et al. (2001) concludes among other things that genotype-environment interaction increases with age. The data used for this example are from an assessment of the trees at age 14 years when the influence of environment on the phenotype is less pronounced than if data had involved trees of greater age. With data expanding over a longer period of time, more accurate and perhaps greater differences between clones would have been available.

6. Calculations and results

This section is divided into three parts, based on the three steps described above. The basic parameters are in each case as described in Table 7. Furthermore, we estimate minimum and maximum present values corresponding to the model's coolest and warmest scenarios.

6.1 Step 1 – A single clone forest stand

We estimated mean present values and standard deviations for each of the 14 clones grown separately; cf. eq. (8) and (9). These results along with minimum and maximum values are shown in Figure 5. The mean value across all clones is 6,235 DKK.
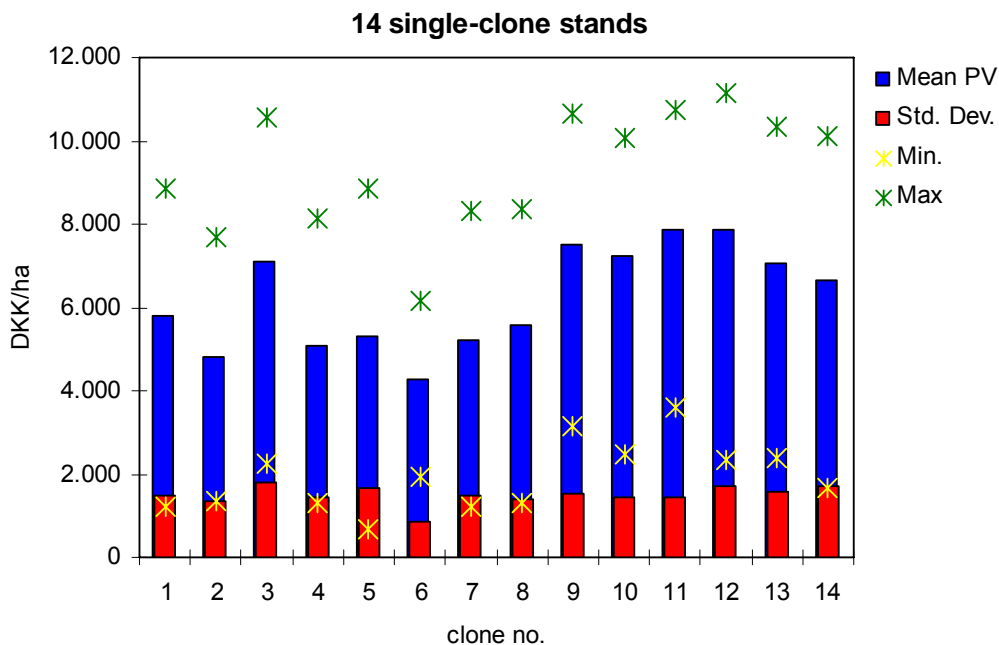

Figure 5: Economic performance measures; mean present value, standard deviation and minimum and minimum present values, for single clone stands under climate change. Based on 2,000 repetitions. Average mean present value across all 14 clones is 6,235 DKK/ha. Clone 12 has the highest mean present value of 7,864 DKK/ha.

It is seen that some clones (e.g. 3 or 5) are much more affected by climate change than others (e.g. 6), i.e. they exhibit different reaction norms in relation to the simulated changes. It is also seen that the worst outcome of an averagely poor performing clone (e.g. 6) may be better in worst case scenario than some of the averagely better clones i.e. those with larger standard deviations (e.g. 5 or 14). This reflects that some clones are more sensitive to changes than others, i.e. their optimal growth location is wider. Choosing a clone like clone 6 is probably only a reasonable choice, if the risk of adverse climate change is considered large or if the forest owner is extremely risk adverse. However, without such considerations and insights the same clone would most likely be excluded from the typical breeding programme due to its poor average performance. In fact it is dominated

by clones like, e.g. 11 which has a worst-case outcome almost as large as the mean performance of clone 6. With no knowledge on which to base the choice of clones, the forest owner may choose randomly among the 14 clones. This situation is depicted in Figure 6, which shows the expected present value and standard deviation of a randomly chosen clone.

Stand with one randomly chosen clone

PV = 6,306
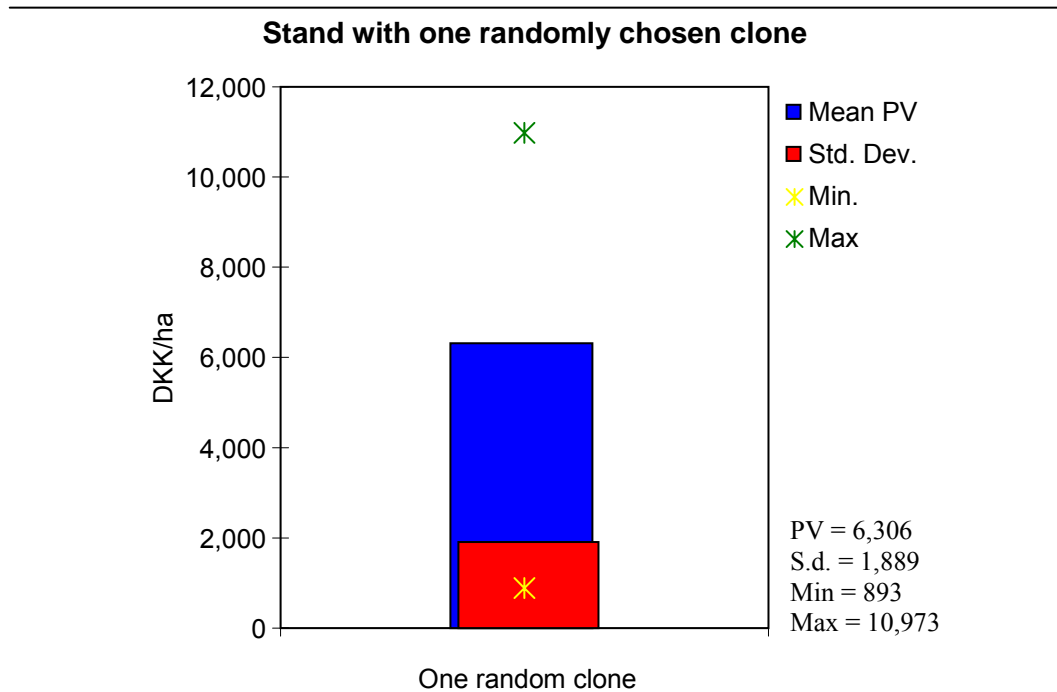S.d. = 1,889
Min = 893
Max = 10,973

Figure 6: Economic performance measures for a forest stand with one randomly chosen clone. Based on 2,000 repetitions. For each repetition one clone is randomly chosen among the 14 available clones.

6.2 Step 2 - Potentials for risk diversification

The second strategy is to diversify the risk by having two or more clones in separate stands. Figure 7 shows the expected present value for a stand consisting of different proportions of two clones, clones 5 and 6. As seen in Figures 5 and 7, clone 5 has a higher present value than clone 6, but also a higher standard deviation of the present value. It is highly likely that growth responses of these two clones to any sort of climate change will be highly correlated, e.g. that they will on average both grow faster under a warmer climate. It is, however, not obvious that this correlation will be perfect. Climate change comes as a complex of changes and it may be that not all changes affect the two clones in the same way. If correlation of responses across the clones is less than perfect, then utility and welfare gains from diversification among the clones can be made, as pointed out in section 4.

In our model here, we have a purely mechanical growth response to climate (here temperature) change, which is the crudely estimated mean responsiveness of *a*, cf. Table 6. It is positive for both (in fact all) clones and therefore we implicitly have a perfect correlation between the two clones in the basic model. A possible crude way of assessing the correlation between growth responses of the two clones is to estimate *a* for more sites along the climate (temperature) gradients and then esti-

36

mate the correlation coefficient between da_5/dT and da_6/dT. This has been done for all 14 clones based on data from the trial sites investigated by Karlsson et al. (2001), see Table 8.

In the growth model simulations the growth responses of clones 5 and 6 are perfectly correlated, so establishing a forest area with different proportions of the two clones in separate stands will result in the different expected present values and related standard deviations seen in Figure 7. We see a linear weighting of the means and variances.

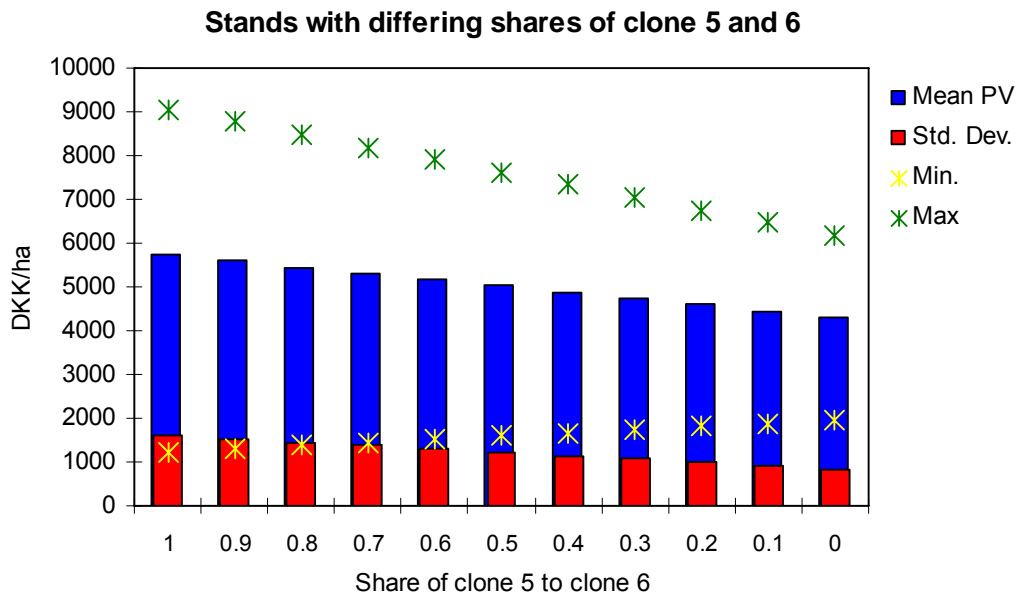**Stands with differing shares of clone 5 and 6**

Figure 7: Simulated average present values and standard deviation of having different proportions of a forest area allocated to each of two clones, clones 5 and 6. Note that the clones are kept in different stands. With equal shares of clones 5 and 6 the mean expected value is 5,024 DKK/ha and the standard deviation is 1,227 DKK. Based on 2,000 simulations.

With perfect correlation among the two clones, there is little room for risk diversification. In Figure 8, we have plotted the straight line of possible portfolio mixes of the two clones, with a 100% clone 6 resulting in risk-return combination represented by the lower end of the line and 100% clone 5 the upper end of the line. Only in the case where the forest owner has no other instruments (other types of investments) will there be a value for some forest owners with intermediate risk aversion to pick a mixture of the two clones on the line between those points. The less risk averse forest owner will instead go for the more risky but on average better performing clone 5, whereas the more risk averse forest owner will go for a pure clone 6 forest. In Figure 8 we have, however, also plotted (in dotted lines) the risk-return combination for portfolios in case the growth responses of these two clones are not perfectly correlated. We have shown the possible combination for a correlation of 0, 0.5 and 0.82, the latter being an approximation based on da/dT for clones 5 and 6 across multiple sites with different climates (Table 8). We see that in particular in case of low correlation, e.g. 0 or 0.5, there are gains to be made from diversification for the risk averse forest owner. In case of zero correlation, the risk averse forest owner, who would prefer a 100% clone 6 forest to a 100% clone 5 forest, would in fact be able to switch to a point on the 0-correlation curve here, with the exact same risk (around 840 DKK/ha in standard deviation)

but an expected return of 4,953 DKK/ha, a gain of 4,953 – 4,312 = 641 DKK/ha. This combination has an approx. 55/45 distribution of the two clones. The exact and optimal choice of combination will depend on the degree of risk aversion of the forest owner, but it is evident that significant gains can potentially be made in case one can identify clones with considerably less than perfectly correlated growth responses to climate change and mean performances that are not too different.
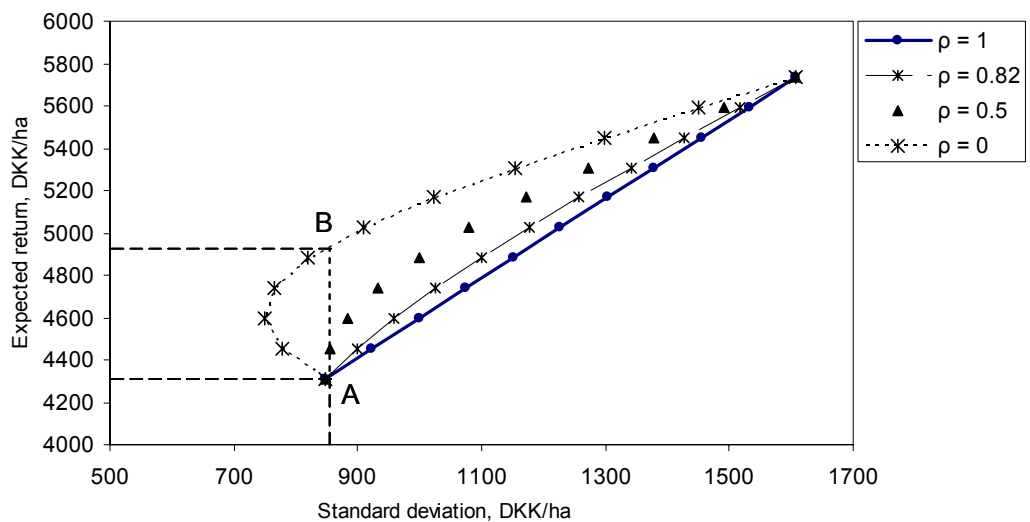

Figure 8: A mean-standard deviation graph that shows the trade-off between higher expected returns and the stability of the return. The four graphs are based on different levels of correlation between clones 5 and 6, from perfect correlation, ρ = 1, to zero correlation, ρ = 0. The correlation ρ = 0.82 from Table 8 is also shown. With zero correlation a risk averse forest owner can, without increasing the risk on his return, gain 641 DKK/ha by mixing the two species (point B) rather than choosing a pure clone 6 stand (point A). Based on Figure 7 data.

In practice, the forest owner may have little information on expected returns, standard deviations and in particular possible correlations among the clones or provenance. This means that risk diversification will essentially be made 'blind-folded', potentially at a cost much higher than the utility gains can justify. This is particularly so if many of the available clones or provenances have highly correlated growth responses to climate change. Table 8 shows a crude estimation of correlation coefficients between any two clones across the temperature gradient of the trial sites in the study by Karlsson et al. (2001). From the Table it can be seen that correlation coefficients are rather high between many of the clones. Only clone 3 shows a growth response that is negatively correlated with that of other clones.

Table 8: Correlation coefficients of da/dT between any pair of clones. The correlations vary from near perfect correlation, ρ = 1, to close to zero correlation. Based on data from Karlsson et al. (2001) and temperature gradients across various trial sites.

Clones	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	1													
2	0.73	1												
3	0.68	0.04	1											
4	0.98	0.78	0.56	1										
5	0.92	0.82	0.40	0.97	1									
6	0.59	0.90	-0.18	0.72	0.82	1								
7	0.88	0.97	0.30	0.89	0.89	0.81	1							
8	0.84	0.97	0.19	0.90	0.94	0.91	0.97	1						
9	0.86	0.96	0.22	0.92	0.94	0.91	0.97	1.00	1					
10	0.91	0.94	0.32	0.94	0.96	0.86	0.98	0.99	0.99	1				
11	0.54	0.87	-0.23	0.68	0.79	1.00	0.77	0.88	0.88	0.82	1			
12	0.99	0.81	0.57	0.99	0.96	0.70	0.92	0.91	0.92	0.96	0.66	1		
13	0.78	0.97	0.08	0.86	0.92	0.96	0.94	0.99	0.99	0.97	0.94	0.87	1	
14	0.69	0.97	0.36	0.71	0.74	0.80	0.95	0.91	0.90	0.89	0.76	0.77	0.89	1

Assuming the forest owner has access to information regarding the correlation of growth responses to climate change between the available clones, e.g. information such as Table 8, he may decide to use clones 3, 4 and 14, which have low and intermediate correlation coefficients, thereby ensuring a rather high level of diversification. The outcome is depicted in Figure 9, which shows a situation similar to the one in Figure 8. A less risk averse forest owner, who prefers clone 3 in a single clone forest, would be able to reduce the risk substantially (approx. 20%) at a relatively low cost in reduced expected value by also choosing clone 14, because of the low correlation coefficient between the two clones' growth responses. Further reductions in risk obtained by including clone 4 in the forest would come at a higher cost in reduced expected value. A risk averse forest owner would be in a win-win situation when increasing the number of clones from one to two and even more by a shift to all three clones. By shifting from a pure clone 4 stand to one with clones 3, 4 and 14 in a 30/50/20-distribution the lowest possible risk on the expected return is obtained, while the expected return is increased with 921 DKK/ha.
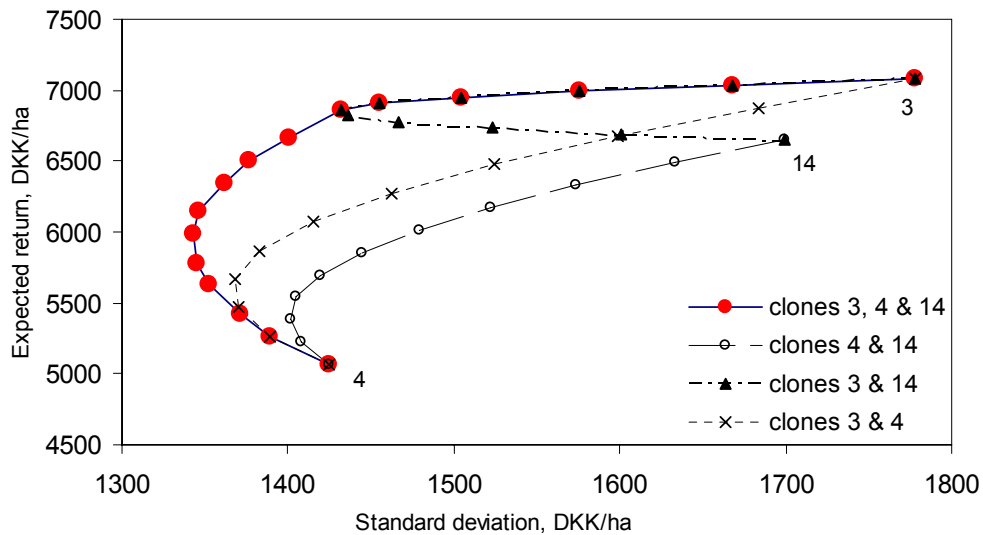
Figure 9: Reduced risk on outcome from a diverse portfolio of clones. In a forest consisting of clones 3, 4 and 14 grown on separate areas a risk averse forest owner gain a reduction in risk, though at a cost of a smaller expected present value compared with using only clones 3 and 14. Based on data from Table 8 and Figure 5.

6.3 Step 3 - Dynamic, reactive adaptation management

In step 3 of the analyses made here, we assume in our first analysis that two clones are mixed on the same area. Consequently, the manager can, once he has observed the actual growth over some period of time, adjust the mix of the two clones by choosing which one to remove partly or entirely through thinning. Space and resources liberated by thinning will be taken over by the remaining individuals in the stand. Figure 10 shows present values and standard deviations of forest stands with clone 5 alone, clone 6 alone, and a mix of the two clones on the same stand. Clone 5 is performing best on average, but climate changes may comparatively benefit clone 6 the most in case of a more adverse development. If such a climate development is observed, the mix allows the manager to let the thinning consist of clone 5 to a higher degree and hence favour clone 6. The effect of this option to adapt to the observed climate development is in particular visible on the minimum present value observed, while the average present value is more or less unchanged. The mean present value for a mixed forest stand is 5,301 DKK/ha, which is only marginally higher than for clone 5 alone (5,290 DKK/ha), but substantially higher than the average of clones 5 and 6. The standard deviation is also marginally lower compared with clone 5 alone, but more importantly: the minimum value is considerably increased. Thus, for these particular clones, mixing them in the stand reduces the potential losses associated with adverse climate developments. We note that in this example the effect of the mechanical and hence perfectly correlated response to climate (temperature) change is to reduce the estimated gains of reactive, adaptive management. With less than perfect correlation between the clones, we would most likely also have seen a higher expected present value for the mixing strategy.

Benefits of mixing clones

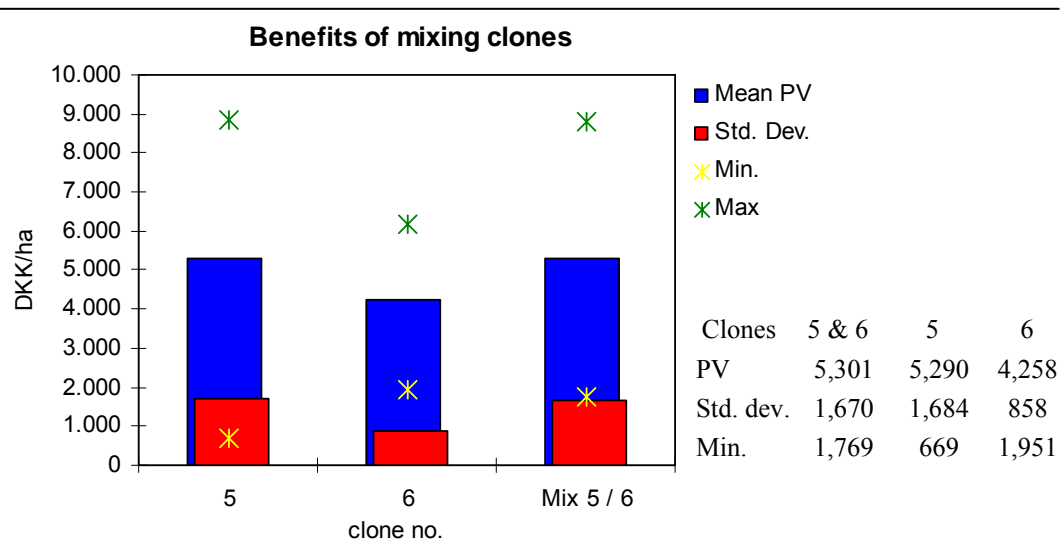| Clones	5 & 6	5	6
PV	5,301	5,290	4,258
Std. dev.	1,670	1,684	858
Min.	1,769	669	1,951

Figure 10: Dynamic reactive adaptation with two clones. Simulated average present values and standard deviation as well as min and max values for clone 5 alone, clone 6 alone and a mix of the two clones in the same stand. In the latter case it is possible to observe the changed climate and thin away the poorest performing clone. Clones 5 and 6 are based on Figure 5, while their mix is based on a simulation with 2,000 repetitions.

Less than perfect correlation is, however, not a prerequisite for seeing higher expected present values from mixing strategies and dynamic, reactive forest management. In Figure 11 we see the average result of a random mixing strategy for two clones across all the clones in the material. This is the average expected result, which would be expected if the forest owner had no knowledge of how different clones react to climate changes, but picked randomly across the 14 clones available. Compared with using only one randomly chosen clone (Figure 6), the mix of two clones and adaptive, reactive management results in both an improved expected present value (an increase of 663 DKK/ha), a reduced standard deviation (around 10 % reduction), and a higher minimum value (an increase of 563 DKK/ha). Only the maximum value is at the same level.
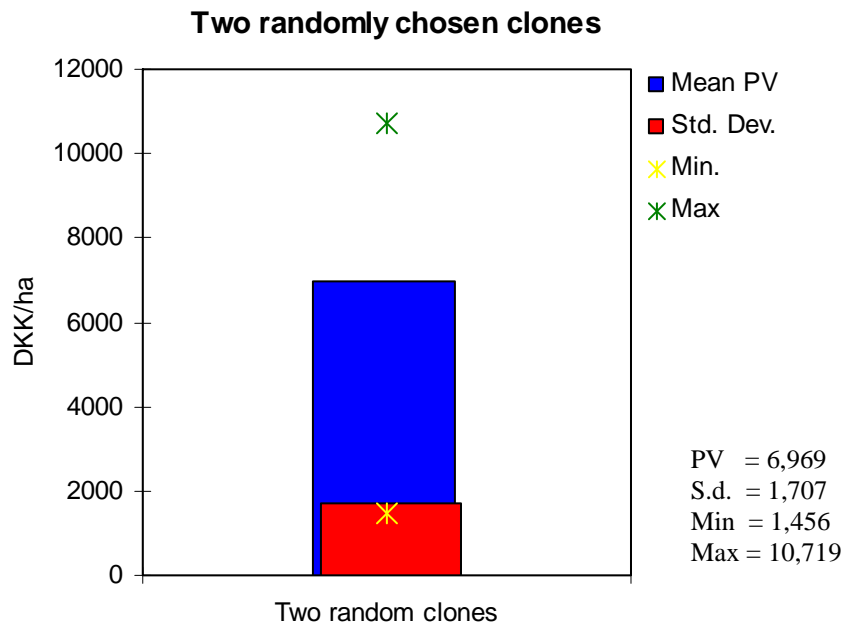
Two randomly chosen clones

Figure 11: Mean present value and standard deviation of a forest stand with two randomly chosen clones mixed in the stand. Based on 2,000 repetitions. For each repetition two clones are chosen randomly among the 14 available clones.

Thus, increasing the number of clones mixed in the stand from one to two on average is likely to improve the expected outcome and in fact also reduce the uncertainty of the outcome. In order to examine the effect of further increasing the number of clones, additional simulations were made for forest stands with 3 to 14 clones. The results are shown in Figure 12. The mean present value increases fast as we go from one to three clones, which also has the highest value (7,135 DKK/ha). With more than three clones the present value decreases slowly. The standard deviation generally decreases with increasing number of clones, but the largest decrease takes place when increasing the number of clones from one to three. Around 9 clones the standard deviation (1,409 DKK/ha) levels off for further increases in number of clones. Maximum present value is decreasing slowly with increasing number of clones and the highest maximum is thus found in the stand with only one clone (10,973 DKK/ha). This is expected based on the construction of the model as all simulations containing one or more of the better clones will under favourable climate development quickly adapt thinning regimes to favour these high performing clones. The minimum present value increases from 1 to 8 clones, where after the value is relatively even.
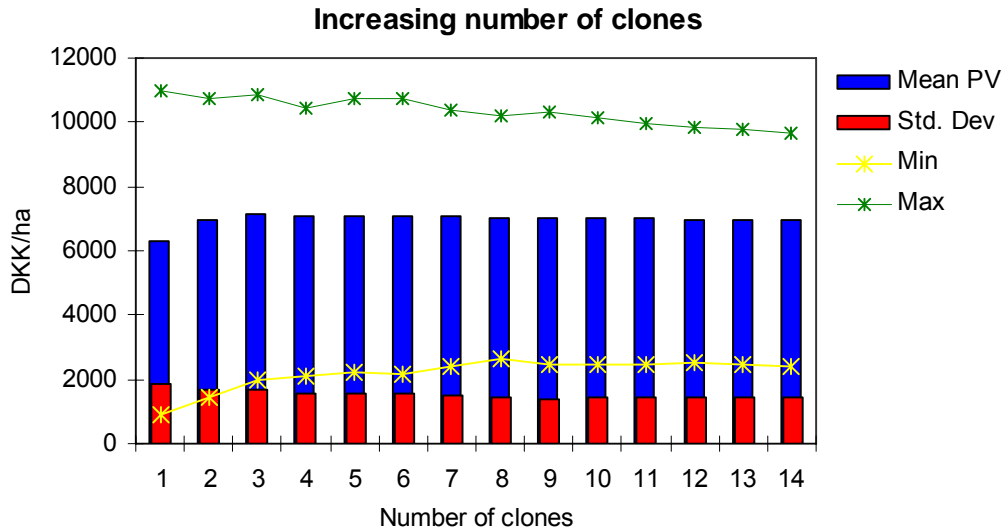
42

Increasing number of clones

Figure12: Dynamic, reactive adaptation with forest stands containing 1 to 14 clones. The clones are mixed in the same stand. Bars and lines show simulated mean present values, standard deviations, minimum and maximum present values. Values are based on 2,000 repetitions for each number of clones. For each repetition clones are randomly chosen among the 14 available and the same clone can not be chosen twice.

Now we assume that the forest owner has the information contained in Figure 5, i.e. climate change growth responses of all available clones, as well as information from trial sites showing that most of the benefits from mixing clones in the same stand take place when changing from the conventional single clone stand to a stand of two or three clones (Figure 12). The forest owner decides to establish two stands; one with clones 11 and 12, which have the highest expected present values of all clones, and one with clones 9, 11 and 12 for higher diversification. As seen in Figure 13 and Table 9 there is nearly no difference in mean present value and standard deviation between the two stands and only a small difference in minimum and maximum values, both in favour of the three-clone mix.
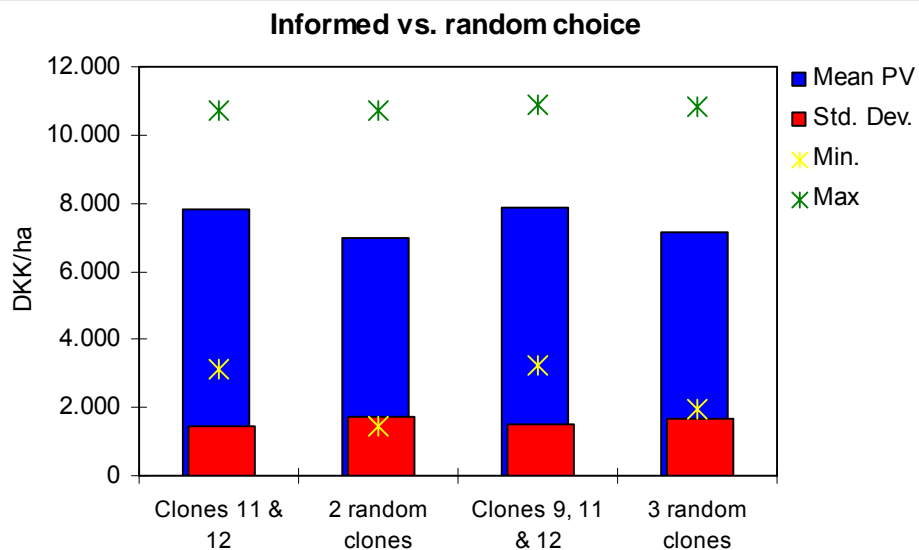

Informed vs. random choice

Figure 13: The value of information. An informed choice of three clones mixed in the stands. Clones are chosen based on knowledge of climate change growth response of each clone. Based on 4,000 repetitions.

43

What is more important than the difference between the two stands of known clones in Figure 13 is the value of the informed choice of clones compared to randomly chosen clones in case the information on growth responses is not available. The difference is illustrated figuratively in Figure 13 and numerically in Table 9. The shift from an uninformed choice of clones to an informed choice results in considerable improvements in mean present value, standard deviation and minimum present value, both in the case of a two-clone stand and a three-clone stand. Only the maximum present value is not affected considerably. As there is only a small difference between an informed choice of two and three clones, the largest gains when shifting from randomly chosen clones to an informed selection of clones are obtained in stands of two clones, cf. Table 9. When clones are chosen randomly, i.e. when no knowledge of climate change response is available, there is a larger gain of mixing more clones than when clones are selected based on information on their growth responses.

Table 9: The value of informed choice of clones. A comparison of mean, minimum and maximum present values and standard deviation between randomly chosen clones and specifically chosen clones. Based on Figure 13.

	2 clones			3 clones		
	11 & 12	Random	Difference	9, 11 & 12	Random	Difference
Mean PV	7,830	6,969	861	7,859	7,135	724
Std. Dev.	1,434	1,707	-273	1,480	1,655	-175
Min	3,105	1,456	1,649	3,221	1,968	1,253
Max	10,721	10,719	2	10,886	10,844	42

In a situation of uncertain changes in the climate the forest owner can increase his expected outcome and reduce uncertainty by diversifying the composition of clones, species etc. in the forest. Especially when clones are mixed in the stand and the forest owner adopts a dynamic, reactive approach to forest management the gains are substantial. According to the results shown in Figure 11 the largest gains are obtained when the number of clones is increased from one to two, and from two to three. Increasing the number of clones to 8 further increases the minimum present value and further reduces the uncertainty, but mean present value stays at the same level. With even more clones the gains in uncertainty reduction and minimum value are very modest and the expected present value is slowly starting to decrease. These results indicate that with the data used in this experiment, forest owners could benefit from mixing, even randomly about three clones in new forest stands. With more insights into the climate change growth responses of available clones and the response correlations across clones, an informed selection of a few clones further increases the expected present value of a mixed, clonal forest while also reducing the uncertainty of the outcome.

7. Concluding discussion

In this report we have identified a four step approach to analyse and evaluate the different potential economic gains from forest genetic diversity and not least the value of information on genotype specific growth responses to climate changes. Such information will always be derived from forest genetic research and field trials and put into practical use through tree breeding programmes designed to make different types of genetic material available to forest owners.

Within the time frame of this project we have been able to apply the first three of these steps to some empirical material on the growth of a limited set of Norway spruce clones across a climate gradient from mid Sweden to Denmark. Come climate change, this gradient could be relevant to perhaps the more northern parts of Scandinavia. The material is limited and we have resorted to modelling climate change as a change in temperature, and to model the growth response as the productivity response to a change in the temperature. Undoubtedly, researchers and professionals working with climate change as well as growth modelling will consider the approach fairly crude. Nevertheless, is has turned out feasible and furthermore it is a much more sophisticated approach to integrate these aspects into economic valuation measures than seen before in the literature. We will therefore begin this discussion by stressing the information and insights obtained and illustrating the potential overall economic value of genetic diversity and the value of information on genotype specific growth responses to climate changes. Following that we will elaborate on the limitations and in particular potentials for further development of the model and the approach. Section 8 provides some further perspectives with respect to future research in genetics, ecophysiology and biometrics.

7.1 The results of the three steps of analysis

In **step 1** of the analysis, we used Monte Carlo simulation methods to estimate the expected net present value and standard deviation of each of the clones in the empirical material – given the estimated growth responses to temperature changes, cf. Figure 5. We see that there is large variation in performance – some clones are quite sensitive to climate changes and others are more stable and show less variation in performance, be it good or bad. This information has a clear value.

Without any information about genotype specific responses to possible climate change, the forest owner will be left to pick randomly the genetic material for his forest from the joint distribution of the genetic material available. Letting the set of clones represent this material, one can assess the overall expected net present value of such a random and uninformed choice. The results are shown in Figure 6. The expected present value of such a strategy is 6,306 DKK/ha and the forest owner inherits both the minimum and the maximum observed outcomes from the full distribution. Consequently, the variance of these returns is quite large with a standard deviation of 1,889 DKK/ha.

Now, with the information available from Figure 5, the forest owner with a strategy to use only one clone would be able to pick that specific clone, which fits

his purpose best, i.e. the combination of expected return and risk that suits him. The potential gain of leaving the uninformed strategy and choosing instead, e.g. clone 11 in Figure 5 would be 7,864 – 6,306 = 1,558 DKK/ha in net present value, adjusted for the utility change from the risk in returns, which is 1,447 – 1,889 DKK/ha = -442, i.e. a reduced risk. Clearly, the aggregate value of information could be significant.

A strategy of choosing only one clone is, however, not necessarily optimal. This will be particularly true, if the growth responses to climate change are less than perfectly correlated across clones. In that case opportunities for risk diversification are significant. Therefore, in **step 2** of the analyses, we investigate the risk diversification effects of choosing combinations of two or more clones, to be established on separate stands in the forest.

In Figure 7, we show the expected returns, standard deviation and minimum and maximum values of having different proportions of two clones, 5 and 6, grown on separate stands in the forest, under the assumption that they are perfectly correlated in their growth responses to climate change. We see that due to the characteristics of these two clones, all intermediate mixes imply intermediate performance measures. Thus, increased expected returns come at the cost of increasing standard deviation, and no direct diversification effects are harvested. Nevertheless, in some real-world cases there may be only a few different provenances or clones available. Mixing them may enable the forest owner to get the expected return-risk relationship that fits his individual risk profile better than choosing either one or the other.

However, because climate change at any specific site will involve a complex of many factors changing, all information on growth responses to climate change is unlikely to be captured in the simple temperature dependent response function used here. Therefore, growth responses to observed temperature changes is likely to show less than perfect correlation, offering better options for risk diversification as shown in Figure 8. Using the empirical material on growth (height) responses across the temperature gradient of the sites in the material, we estimate a rough measure of the correlation in growth responses among the different clones (Table 8).

When three clones are chosen based on their correlation coefficients reductions in risk are obtained, though at the cost of reduced net present value in the example illustrated in Figure 9.

In Figures 8 and 9 we illustrate the potentials of risk diversification across two or more clones with less than perfectly correlated growth responses to temperature changes. It is evident that visible utility gains can be made, but the actual economic value of these will depend on the specific risk aversion of the forest owners. However, consider Figure 8 and suppose a forest owner is so risk averse that if he were to pick only clone, he would pick the clone with the lowest standard deviation. With significant risk diversification potential (e.g. a correlation of 0 or 0.5), he would be able to pick a mixture of the two clones, which has the same standard deviation but a larger expected return. The gain would be at least the difference in expected return, which in Figure 7 is 4,953 – 4,312 = 641 DKK/ha, but most

likely higher as he will also be able to shift his choice of combination to one with an expected return-risk combination of even larger value for him. Even higher gains can be obtained when shifting from one to three clones, as shown in Figure 9. Again, we see that if research in forest genetics and ecophysiology can provide such information, and tree breeding programmes subsequently provide the plant material, then significant welfare economic gains are to be expected.

In the two steps discussed so far, we have assumed that the forest owner applies a strategy where he essentially anticipates the climate change as it develops and takes the results as they come. His only coping strategies have been to pick either the single clone (step 1) or the combination of two or more clones (step 2), which fits his risk profile the best. In **step 3** we assume the forest owner realises that if he mixes more clones on the same area, then he will be able to react to climate change as it develops and use his thinning options to favour the clones better suited for the climate change experienced.

In Figure 10 we show first a small transparent example of this using again the illustrative clones 5 and 6. We see that mixing these two clones in a dynamic reactive adaptive management results in an expected present value almost as large as for the most risky of the two clones, but a lower variance and most notably a much higher value of the worst observed outcome. Thus, the adaptive management is also capable of reducing risk while maintaining returns even if the clones like in the present case have perfectly correlated responses to climate change.

This is further illustrated in Figure 11, where we have simulated the result of randomly picking two different clones for use in the same stand. We find that the gains from this strategy compared with randomly picking only one clone as in Figure 6 are quite large. We se that the expected present value increases by 10%: 6,969 – 6,306 = 663 DKK/ha and at the same time the risk decreases as the standard deviation of returns decreases by 1,889 – 1,707 = 182 DKK/ha and this is in particular due to the worst observed result increasing by 1,456 – 893 = 563 DKK/ha.

One may ask if further gains may be made by randomly mixing more clones in each stand. This is investigated in Figure 12, where we find that, given the empirical material and modelling approach, there are in fact further gains to be made from selecting more than two clones to plant in each stand. The gains, however, level out fairly much at about 3 to 4 clones, except for very risk averse forest owners, who may find the lower variance and in particular the higher worst possible outcome associated with even more clones in the stand of some value. These results suggest that significant gains can be made from reactive adaptive management of forest stands with two or more clones mixed – even if no information on the growth responses of these clones to climate change exists. However, in order to determine the optimal number of randomly picked clones, as in Figure 12, one would in fact have to make use of the information in Figure 5.

We see from the analyses in step 3 that a management strategy of mixing clones, even if random and without the information from Figure 5, can nevertheless result in significant gains in terms of increases in expected returns as well as decreases in risk. This is again an important policy result: *In the absence of good informa-*

tion on the growth response of different genotypes to climate change, much may be gained by mixing a reasonable set of genotypes in each stand and adjust their relative weights according to climate change as it develops and the growth responses are observed. The prerequisite for this is again a well functioning tree breeding programme with at least insight into variation between different genotypes at the current climate.

If the information in Figure 5 is assumed to be known by the forest owner, the next relevant question is if this information could not in fact be used to determine not only the optimal number of randomly chosen clones, but also which two-four specific clones it is in fact optimal to mix. This is investigated in Figure 13 and Table 9, where two and three clones, respectively, are chosen for a mixed forest stand based on their high mean present values in Figure 5, and compared with forest stands of randomly chosen clones. While there is not much to gain by shifting from a stand with the two best performing clones to one with the three best clones, the informed choice of two or three specific clones improve the overall economic performance considerably compared with the uninformed choice of two or three random clones. The gain is as high as 861 DKK/ha in expected return, reduced standard deviation of 273 DKK/ha and an increase of 1,649 DKK/ha in net present value in the worst case development. Again, the prerequisite for an informed selection of specific clones is a well functioning tree breeding programme with clonal trial sites that cover a large climatic gradient.

Further questions arise, e.g. if the thinning decisions made in the future should take into account not only the climate changes observed so far, but also the implications of these for the expected future climate changes and growth responses. Questions like this naturally lead us to the full dynamic, forward-looking adaptive management model, where more decision variables, e.g. also the strength of thinning is optimised freely. This is the model, which we have identified as **step 4** of the analysis. This model will further expand on the economic value of forest genetic diversity, but as it is much more demanding to develop and execute, this work cannot be finished within the limits of this report and project.

7.2 The model, its limitations and further development

In this report, we have suggested a general approach in four steps to assess the economic value of forest genetic diversity under varying management approaches and for different levels of information on the genotypes growth responses to climate changes. We have applied three of these four steps to a limited empirical material on Norway spruce clones growing at different sites in Denmark and Sweden. Clonal forestry is relatively far away from practice in Denmark, also in the case of Norway spruce, and hence the specific numerical results here should be taken only as indicative. This, however, is not a serious limitation: The qualitative results obtained are much more general, e.g. the role of diversification and the principle of gains from mixing clones in adaptively managed stands. These results can in general be expected to be found also for other sets of clones and of course also for sets of provenances or species.

Apart from this, there are of course numerous limitations. We have selected here a fairly limited empirical set of data and only subjected it to rather crude analyses

48

with respect to clone specific growth responses to climate change (in this case climate gradients), not to say a very crude analyses of the correlation of these growth responses between the clones. Undoubtedly, these parts of the model could be developed much further, and the benefits of doing this would be to reduce uncertainty connected with predicting the growth response of a clone to future climate changes. A further refinement of the model would be to include also the natural phenotypic variability among trees from the same clone, e.g. by drawing individual growth responses from a probability distribution rather than treating them as deterministic. To be able to fully benefit from such a more detailed modelling, one would of course need to be able to assign also joint probability distributions for future climate change in more factors than temperature.

This brings us to a second limitation of the crude approach developed in this report. For simplicity, we have chosen changes in one variable, temperature, to represent changes in the climate. This is of course a serious limitation as climate changes will very likely also cause changes in other important growth factors, e.g. precipitation and growth season. A more detailed modelling of these events and their likely joint probability function coupled with a more detailed model of growth responses to changes in such a broader set of factors will greatly increase the reliability of numerical simulation results. This credibility will come at a cost, because the many more variables will make it computationally much more demanding to apply, e.g. numerical optimisation methods to determine good forest management regimes and assess the economic value of genetic diversity.

Another limitation is the fact that we have focused our economic evaluation and risk modelling more or less entirely on the stand level. However, as we go beyond the stand level and consider the level of forests and forested landscapes new issues arise. Two of these issues are the wider economic value and functions of forests as such as well as risks that are not well modelled at single tree or single stand models.

Throughout this report, we have used economic gains as synonymous with private economic gains from timber production. We have assumed that prices of all outputs and inputs are exogenous to the possible differences in output and input quantities implied by the management strategies investigated. While the latter assumption is standard, and most likely not too important a limitation, the first is obviously a very narrow picture of the value of securing healthy and productive forest ecosystems in the future. Forests do not only produce marketable wood products, but also a range of services valuable to society, e.g. recreation, biodiversity protection, hunting and ground water protection. These activities and services comprise a large part of the values of Danish forests and incorporating them into the model would be a large benefit to the applicability of the model in a Danish forest context, however, also a vast task.

The variance in growth responses to climate change as modelled in this report may be perceived to include tree or stand specific issues like local health effects, drought or pest attacks. However, as stressed early on in the report, there are other kinds of risk that are large scale, e.g. risks of windthrow, large scale and long-term draught or large scale pest attacks. These risks may also change along with climate change, and their role is best evaluated in larger models, preferably

49

comprising whole forests. As climate change is expected to result in e.g. increased pest attacks among Norway spruce in Denmark and higher risks of windthrow, an obvious expansion of the model would be to include these risks not only at stand level, but also at forest level. There may be variations in the sensitivity of different clones, provenances etc. to some types of large scale risk, e.g. some forms of pest attacks. Such variations could be modelled and included in the economic assessment of the value of an optimal level of genetic diversity. Such expansion of the model would give an increased value to the possibility of adaptation to climate changes compared with the present version of the model.

Again, increasing the modelling scope from stand level and one type of climate change related uncertainty to forest and perhaps landscape level and several types of risk implies an increasing number of states and variables to track. This again hampers the chances for applying numerical optimisation methods for evaluating management strategies, and instead advanced numerical simulation studies may be performed.

8. Further perspectives

8.1 Implications for data needs

The above discussion on the model limitations and further developments already points towards the kind of data needed to be able to improve our knowledge of the economic value of genetic diversity, when facing the uncertainties inherent in the climate changes foreseen.

Clearly, a tremendous amount of research in meteorological research and climate modelling has been made the last couple of decades. Still, however, much uncertainty remains in particular with respect to other growth factors and regional effects around the world. This field of research is quite beyond the scope and topic of this report and the immediately related research fields. Therefore, we will not elaborate on this, but only stress the important effect of better knowledge about these issues will have for reaching the goals set in the report.

Moving closer to home and changing to a more immediate and practical perspective, the limited empirical material in this report in fact stresses the most obvious field for forest genetic research and tree improvement programmes to focus on. The need for any kind of qualified information is pertinent as climate change is picking up speed and forest owners every day make decision that will affect the stability, health and growth of forest many decades into the future. The decisions are made on information that was produced under a research and tree improvement paradigm focused on tree breeding for production under a known climate believed to be stable. Any new and improved information is greatly needed – even if it is not exact and only indicative.

Therefore, existing clone and provenance trials in forest genetic research and tree improvement programmes should be investigated systematically across as large climate gradients as permitted by the location of the trials. Such analysis should be able to bring about at least indicative information on the genotype response to variation in the main climate and growth factors. Such information can subsequently be used in more thorough analyses along the steps outlined here, perhaps with a special focus on potential gains from mixing provenances on the same area. Tree improvement programmes should use the information produced to gradually adjust current recommendations concerning local and regional choices of planting material, and of course to adjust and diversify breeding strategies accordingly – as needed.

In the longer run, such research may go into more details along the lines discussed earlier. In particular, genetic research into sensitivity of the different provenances and clones to potentially more frequent pest attacks, mild winters etc. may be relevant.

At a broader scale, ecologic and economic research could aim to provide more information on the way forest ecosystem services and their value rely on the state and characteristics of the forest ecosystem and notably its stability. Such information will be needed for a reliable economic modeling of the consequences of climate change for the provision of such ecosystem services at landscape levels.

8.2 A comment on genetic diversity in continuous cover forestry

In continuous cover forestry, where natural regeneration is dominating, other challenges may appear: What if the genetic material in these forests is already quite narrow? Will they be able to adapt themselves swiftly enough to survive under the future pressure of climate change? Or should forest management also here seek to introduce an increased variation through genetic enrichment plantings? 'Close-to-nature forestry' increases the role of the forest owner in terms of genetic management, because future tree generations are to a larger degree based on natural semination and less often on planted seedlings from seed sources managed 'outside the forest'. In Denmark for example, large scale planting of ash trees from a 2-clonal seed orchard has taken place during the last four decades. If these forest areas in the future will be regenerated naturally, the perhaps narrow genetic selection made will have long lasting effects in the forest. Genetic studies of the consequences of this are in progress, but they may be considered to introduce planting from more diverse seed sources at least in some close-to-nature driven forests in order to mitigate any effect of inbreeding, and to enhance the speed of and chances for the population to adapt to the unknown changes once they arise. Naturally regenerated forest also represents challenges from a genetic perspective (see e.g. Namkoong 1999) and these must also be considered when planning for sound genetic management of the forest. In any case, forest genetic research on species with long rotation ages should probably not focus only on bringing about increasingly specialised clones to be deployed at very specific planting sites. Rather, the tree improvement and deployment strategies for long rotation species should ensure that genetic variation is mobilised and maintained in the forests in order to facilitate response and adaptation, but also to buy time and flexibility to the forest owner. The general finding from our study – that genetic diversification is above the use of few clones – does not suggest abandoning forest genetic research and doing nothing in the field. Quite contrary, it requires development and implementation of genetically sound gene management programmes.

8.3 Potentials for valuing programmes for preservation of genetic diversity and tree improvement

Tree improvement programmes and the forest genetic research on which they build has traditionally been aimed at improving the use value of forests related to wood production, e.g. development of forest trees with increased growth rates, better trunk form, increased wood quality and higher resistance to pests and diseases (Hannrup et al. 2004, Hansen & Kjær 1999, Savill & Kanowski 1993). The improvement programmes also include breeding and provenance trials with selection for general adaptation across a range of environmental conditions or selection for specific adaptation, i.e. selecting provenances or clones that are growing specifically well in a specific locality or environmental setting (Isik & Kleinschmit 2003, Matheson & Cotterill 1990). The general goal being to recommend at each locality the planting material, clone or provenance best suited to the climate and growth conditions believed to prevail there. In these years, the tree improvement programmes and genetic research will increasingly also focus on providing knowledge, recommendations and seeds and planting material that takes into account the fact investigated in this report: That climate and growth conditions are likely no longer to be stable, but are in fact uncertain.

The values provided and sustained by tree improvement programmes are many and do not limit themselves to improved production of roundwood. They underpin and improve overall forest health and stability, which in turn secures the provision of a number of forest ecosystem services, many of which are not traded in the market place.

If tree improvement programmes and forest genetic research can provide information that helps forest owners in hedging the risks associated with the uncertainty of forthcoming climate change, then the value of this research and the tree improvement programmes will increase further. As we have documented in this report, the gains of applying the information on and the variation of the genetic material are likely to be quite significant at the stand level. We have documented gains from insight into the growth responses to climate change. These gains will arise both from the option to diversify risk by applying several clones at the forest level and from mixing different clones under a reactive, adaptive forest management regime.

We will conclude this report with a very crude illustration of the scale of values that we are looking at here. Suppose (boldly) that the clones analysed here represent in fact the genetic material available to growing Norway spruce in Denmark, and that the crude analyses of sensitivity to climate change etc. undertaken here are relevant and a reasonable guess at the true variation. Without this latter information, the forest owners may pick their plant material randomly among the clones. The result of this is the values obtained in Figure 5. However, if forest genetic research is able to provide enough information to arrive at a recommendation of at least to mix in each stands a set of two-four different clones (provided the tree improvement programmes can supply the material), then if forest owners do this at random, the results of Figures 11 and 12 show us that they will at least experience an increase in the net present value of the young stand of 650 DKK/ha and maybe as much as 1,000 DKK/ha – in timber values alone. Add to that the decrease in risk associated with the adaptive management and the diversification effect. If enough information is available to recommend the optimal clones to mix, the gains may be even larger. Figure 13 shows us that forest owners who make informed selection of three clones to mix in the forest stand can obtain increases in the net present value of more than 1,500 DKK/ha compared with the conventional one-clone forest. This increase is perhaps more expressive in percentage, equivalent to an increase of approximately 25 %. Again, the increase in expected value is also associated with an equally large percentage reduction of the risk as well as a substantially higher net present value in the worst case scenario. The gains refer to production alone. Inclusion of other stand damaging processes (insects, fungi, climatic extremes) would likely increase the gain estimates.

As we reported in the beginning of the report, Norway spruce makes up around 20% of the Danish forest area, corresponding to some 90,000 ha. Crudely aggregating the potential gain across this area the gain is magnified to a present value of 135,000,000 DKK. Using the interest of 4% the corresponding annual value flow is 5,400,000 DKK. This is a very crude aggregation and by far a very conservative estimation of the potential gains from having forest genetic research and tree improvement programmes contribute to the preparation of Norway spruce forest to the forthcoming climate change.

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