EUROPEAN FOREST GENETIC RESOURCES PROGRAMME

EUFORGEN

Approaches to the conservation of forest genetic resources

in Europe in the context of climate change

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European Forest Genetic Resources Programme (EUFORGEN) is an instrument of international cooperation promoting the conservation and appropriate use of forest genetic resources in Europe. It was established in 1994 to implement Strasbourg Resolution 2 adopted by the first Ministerial Conference of the FOREST EUROPE process, held in France in 1990. EUFORGEN also contributes to the implementation of other FOREST EUROPE commitments on forest genetic resources and relevant decisions of the Convention on Biological Diversity (CBD). Furthermore, EUFORGEN contributes to the implementation of regional-level strategic priorities of the Global Plan of Action for the Conservation, Sustainable Use and Development of Forest Genetic Resources (GPA-FGR), adopted by the FAO Conference in 2013. The Programme brings together experts from its member countries to exchange information and experiences, analyse relevant policies and practices, and develop science-based strategies, tools and methods for better management of forest genetic resources. Furthermore, EUFORGEN provides inputs, as needed, to European and global assessments and serves as a platform for developing and implementing European projects. EUFORGEN is funded by the member countries and its activities are mainly carried out through working groups and workshops. The EUFORGEN Steering Committee is composed of National Coordinators nominated by the member countries. The EUFORGEN Secretariat is hosted by Bioversity International. Further information on EUFORGEN can be found at www.euforgen.org.

Citation: Kelleher, C. T., de Vries, S.M.G., Baliuckas, V., Bozzano, M., Frýdl , J., Gonzalez Goicoechea, P., Ivankovic, M., Kandemir, G., Koskela, J., Kozioł, C., Liesebach, M., Rudow, A., Vietto, L., and Zhelev Stoyanov P. 2015. Approaches to the Conservation of Forest Genetic Resources in Europe in the Context of Climate Change. European Forest Genetic Resources Programme (EUFORGEN), Bioversity International, Rome, Italy. xiv+46 pp.

Layout: Ewa Hermanowicz
Cover photos: Michele Bozzano

ISBN 978-92-9255-032-5

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PREFACE

During the past two decades, the impacts of climate change on forests and the role of forests in mitigating climate change have been debated intensively. Globally, deforestation has contributed significantly to climate change by releasing carbon dioxide into the atmosphere and reducing the production of oxygen. Deforestation still continues in many parts of the world and a number of international initiatives have been developed to promote and implement sustainable forest management, especially in developing countries. In Europe, forests have been increasing both in terms of area and growing stock during the past 50 years. European forests have thus acted as a carbon sink as they have been recovering from the past centuries of deforestation and overharvesting.

In recent years, European policymakers have discussed various options for adaptation and mitigation to climate change and developed various policies to enhance the role of forests and the forest sector in mitigating the impacts of climate change. Most countries have incorporated climate change aspects into their national forest programmes and national action plans for biodiversity conservation. Several countries have also developed cross-sectoral national adaptation strategies to climate change. Unfortunately, these measures have mostly neglected the role of forest genetic resources in the adaptation of forests to climate change. Furthermore, although climate change is also considered as a threat to biodiversity conservation, most conservation efforts have focused on species and habitat diversity and paid little attention to genetic diversity, the fundamental basis of all biological diversity.

Within the framework of the European Forest Genetic Resources Programme (EUFORGEN), the implications of climate change for the conservation and use of forest genetic resources have been increasingly discussed during recent years. EUFORGEN was established in 1994 to coordinate pan-European collaboration on forest genetic resources as part of the FOREST EUROPE process (earlier the Ministerial Conference on the Protection of Forests in Europe). During Phase IV (2010-2014), EUFORGEN had three objectives, 1) promote appropriate use of forest genetic resources as part of sustainable forest management to facilitate adaptation of forests and forest management to climate change; 2) develop and promote pan-European genetic conservation strategies and improve guidelines for management of genetic conservation units and protected areas; and 3) collate, maintain and disseminate reliable information on forest genetic resources in Europe. EUFORGEN has brought together scientists, managers and policymakers to discuss various issues related to forest genetic resources and to develop pan-European approaches for better management of these resources.

The present report presents the findings and recommendations of the EUFORGEN working group on climate change and conservation of forest genetic resources. The report presents the current state of knowledge on the implications of climate change for conserving forest genetic resources and provides recommendations for further action. The working group met twice; the first meeting was hosted by Bioversity International in Maccarese, Italy on 18-20 June 2013 and the second one by the Centre for Genetic Resources in Wageningen, Netherlands on 4-6 February 2014. The Working Group provided an update to the EUFORGEN Steering Committee during its ninth meeting held in Tallinn, Estonia, on 3-5 December 2013. The draft report was presented to the EUFORGEN Steering Committee for review during its 10th meeting which was held in Edinburgh, United Kingdom on 16-18 June 2014. Comments from the Steering Committee were addressed in the final report.

CONTENTS

ACRONYMS USED IN THE TEXT

CO_2	carbon dioxide
EU	European Union
EUFGIS	European Information System on Forest Genetic Resources
EUFORGEN	European Forest Genetic Resources Programme
FGR	forest genetic resources
FAO	Food and Agriculture Organization of the United Nations
IPCC	Intergovernmental Panel on Climate Change
IUFRO	International Union of Forest Research Organizations
IUCN	International Union for Conservation of Nature
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change

EXECUTIVE SUMMARY

Over the past decades, European countries have taken significant steps in conserving the genetic resources of forest trees. However, they have rarely taken into account the implications of climate change for the conservation of forest genetic resources. Climate change poses unique conservation challenges that require specific responses. For these reasons, the EUFORGEN Steering Committee established a working group on climate change and the conservation of forest genetic resources. This report presents the conclusions of the working group.

In Europe, forests have been expanding in terms of area and timber stock over the past 50 years and subsequently they have acted as a carbon sink while they have been recovering from previous eras of deforestation. National adaptation strategies to climate change and other policies have been formulated in many European countries to harness the potential of forests and the forestry sector for mitigating climate change. However, the impacts of climate change on forests, and especially on their genetic diversity have not been given a proper consideration in these policies.

The working group made several recommendations for action. These focus on 1) establishing additional genetic conservation units specifically to respond to climate change, 2) enhancing cooperation among countries and enlarging the pan-European collaboration on the conservation of forest genetic resources, 3) the need for continued and expanded monitoring and sharing of data, including the development of decision tools and red lists, and 4) further research on aspects of assisted migration and on marginal and peripheral tree populations.

Climate change and forest genetic diversity

Global climate models predict an increase in average surface temperature for Europe, with winters becoming warmer in the north and summers in the south. The models also predict increases in winter precipitation in the north and decreases in the south, as well as decreases in summer precipitation in central and western Europe. Southern and western Europe are likely to experience warmer and dryer conditions with droughts starting earlier and lasting longer. Impacts will be most severe in the southern Iberian Peninsula, the Alps, the eastern Adriatic and southern Greece. In addition to these changes, the models also predict that extreme events will occur more often. While uncertainties remain, it can be concluded that the near future will see changes in the range of individual tree species, and that the species composition and the dynamics of forests will be affected.

From the point of view of conservation, the most important areas to focus on will be at the edge of species' ranges. While populations are migrating into areas that climate change has made more suitable, the leading edge is likely to suffer genetic narrowing because a few founder individuals, representing only a subset of the total genetic diversity, will be pioneers in new areas. At the same time the populations at the trailing edge are likely to experience fragmentation and a reduction in the number of individuals, with subsequent loss of genetic diversity.

Assessing and managing threats

It remains uncertain exactly how tree species and populations will respond to climate change. Nevertheless, it is important to attempt to assess the impacts of climate change on tree populations using a combination of intrinsic factors, such as population structure, regenerative capacity and dispersal ability, and extrinsic factors, including biotic threats like pests, pathogens and species competition and abiotic threats such as fire or changes in land use. The working group considered a wide range of potential threats and developed a preliminary decision cascade tool to aid the identification and management of those populations most in need of conservation. The proposed decision cascade tool appended to the report is a proof of concept and will need further development. Such a tool will be helpful in drawing up a red list of threatened tree species in Europe, which should focus on populations rather than species and which is urgently needed to guide future conservation.

The working group noted that many European tree species, especially those threatened in southern Europe, are also present in North Africa and the islands of Macaronesia. These populations are perhaps even more likely to be negatively affected by climate change, with little to no chance of colonisation from the south. For this reason, the working group recommends that for the purpose of conservation of forest genetic resources, the pan-European collaboration should include these areas. Collaboration should be initiated to include countries containing populations of relevant species outside of Europe. A larger geographic coverage of the regional collaboration on forest genetic resources would also be useful for developing a red list of threatened tree populations.

Conservation approaches

Many European countries currently have conservation strategies for forest genetic resources and efforts are under way to expand and strengthen these strategies. Current strategies, for example the EUFORGEN led pan-European network, do not always include populations that are under threat due to climate change. The report offers suggestions as to how to identify such units and recommends that these additional units be added to the European Information System on Forest Genetic Resources (EUFGIS) database, with an additional identifying field, so that information from them can be considered alongside all other conservation units in making strategic management decisions. There is also a possible role for assisted migration, especially for those species facing the most intense climate change. While there will clearly be problems to solve, assisted migration remains an important option to consider. Even with greater attention to the *in situ* conservation, there will still be a need for *ex situ* conservation. Collections of living trees, seeds, gametes and plant tissue may all be considered in different cases, and priorities assigned according to an agreed set of criteria. As with *in situ* conservation units, *ex situ* units should be monitored and be included and specifically identified in the EUFGIS database.

Research

The report deals primarily with questions of management, but in considering these questions, gaps in scientific knowledge became apparent. Little is known about the concrete effects of climate change on genetic diversity of tree populations. In addition, there is a lack of knowledge about assisted migration and how it might affect the genetic composition of a species and the species composition of an ecosystem. Marginal and peripheral tree populations are also poorly studied. These populations need to be identified, characterised and studied. More research results on these topics would help to improve conservation in the context of climate change and influence future policymaking.

INTRODUCTION

Climate change and its consequences for the Earth and human societies have been analysed and discussed at the international, regional and national levels for more than 20 years. In 1992, the Rio Earth Summit adopted the UN Framework Convention on Climate Change (UNFCCC) which was designed to stabilize greenhouse gas emissions at a level that would prevent dangerous changes in the global climate system. The UNFCCC entered into force in 1994 and a total of 195 countries have ratified it, although greenhouse gas emissions continue to increase. According to the Intergovernmental Panel on Climate Change (IPCC), the global average surface temperature (combined land and ocean temperatures) has increased by nearly 1°C during the period 1901 to 2012 (IPCC 2013). The recent IPCC report also notes that it is very likely that temperature will continue to increase throughout the 21st century in different parts of the world, including Europe. The latest projections indicate that summer temperature (June-August) will increase by 3°C to 4°C in most parts of Europe by 2081 to 2100, and even 4°C to 5°C in some places in the Mediterranean region (IPCC 2013). This will considerably alter the climatic conditions to which European forests are currently adapted.

The impacts of climate change on forests and biodiversity have been analysed by numerous modelling studies. The projected changes in climate are expected to shift and reduce the distribution range of major commercial tree species in Europe (e.g. Hanewinkel *et al.*, 2012). However, most modelling approaches have considered species as static and independent entities and overlooked the importance of genetic diversity and phenotypic plasticity in adaptation to climate change (e.g. Bellard *et al.*, 2012). Furthermore, studies on the impacts of climate change on biodiversity have largely focused on the species and ecosystem responses and neglected the role of genetic diversity (Bellard *et al.*, 2012). The incorporation of genetic diversity and phenotypic plasticity into species-distribution models has shown that the predicted decreases and/or changes in the distribution ranges of tree species due to climate change are likely to be smaller than previously estimated (Benito Garzón *et al.*, 2011).

Climate change will impact existing conservation networks or systems and will influence how new systems are designed. Conservation systems should be based on a dynamic and large-scale approach to ensure that the target species are able to adapt to climate change (Hannah 2010). In Europe, a pan-European network of genetic conservation units of forest trees is an example of such a conservation approach. Currently, this pan-European network consists of 3214 conservation units in 34 countries. The documentation of this network and the launch of the EUFGIS Portal[1] in 2010 were results of the earlier EUFORGEN work that had been carried out over several years.

In 2006, EUFORGEN and the International Union of Forest Research Organizations (IUFRO) organized a workshop on climate change and forest genetic diversity (see Koskela *et al*., 2007). The workshop noted that the impacts of climate change on forests will vary in different parts of Europe bringing both opportunities and threats. The workshop also stressed the key role that forest genetic resources play in maintaining the resilience of forests against the threats and in harnessing the opportunities. One of the workshop recommendations urged European policymakers and the forest sector to recognize the importance of forest genetic diversity in mitigating the negative effects of climate change on European forests by incorporating the management of this diversity into national forest programmes and other relevant policies, programmes and strategies (e.g. national adaptation strategies to climate change and national action plans for biodiversity conservation). Furthermore, the workshop recommended that the policymakers promote forest management practices which maintain evolutionary processes of forest trees and support natural regeneration of forests, especially in areas where long-term natural regeneration is self-sustainable despite climate change. During EUFORGEN Phase III (2005 to 2009), the Conifers, Scattered Broadleaves and Stand-forming Broadleaves Networks continued the discussion on the implications of climate change for the conservation of forest genetic resources while developing minimum requirements for the genetic conservation units of these groups of tree species. In addition, the Forest Management Network also discussed the impacts of climate change on the conservation and use of forest genetic resources. Building on this work, a EUFORGEN working group developed a pan-European genetic conservation strategy for forest trees in 2012-2013 (de Vries *et al*., 2015).

In 2012, the EUFORGEN Steering Committee decided to establish a working group to further review genetic conservation methods (both *in situ* and *ex situ*) in the context of climate change. The working group was tasked to develop recommendations for the management of the conservation units and the networks of the units, and to propose complementary conservation measures. More specifically, the Steering Committee requested the working group to:

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[1] http://portal.eufgis.org/

- Review relevant outputs of the previous Forest Management Network
- Review predictions of climate change and their consequences for conservation of FGR (e.g. abundance, composition and distribution of forest tree species and populations)
- Review findings on the most threatened tree species and populations
- Develop recommendations for management of genetic conservation units
- Develop complementary *ex situ* approaches
- Present an update
- Prepare a draft report

Furthermore, the Steering Committee advised that the working group should not only focus on the management of single units but also the pan-European network of genetic conservation units. The working group was also requested to address both *in situ* and *ex situ* conservation in climate change context, and analyse the level of duplication needed in conservation efforts. The working group was also asked to explore the idea of establishing conservation units outside the current distribution ranges of tree species. The following chapters of this report present in detail the findings and recommendations of the working group.

STATE OF KNOWLEDGE

Predictions of climate change

It is well documented that human activities have significantly affected global climate since the beginning of industrialisation which started around the 1750s. The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2013) echoed the finding of the fourth report (IPCC 2007a), according to which the concentration of atmospheric carbon dioxide (CO_2) has increased from 280 ppm in the pre-industrial era to 379 ppm in 2005. The highest rate of increase of CO_2 concentration was detected in the period from 1995 to 2005. This increase exceeded the natural range over the last 650,000 years (180 to 300 ppm) and is reported to be primarily a result of burning fossil fuels and changes in land use, such as increased urbanization and deforestation. The global methane concentration has also increased significantly from 715 ppb to 1,774 ppb in 2005. This again exceeds the natural range (320 to 790 ppb) and is considered to be due primarily to agricultural development. Increased CO_2 and methane concentrations have resulted in a marked greenhouse effect and global warming beyond that expected through purely natural processes. These increases and their impacts are being used to predict future changes in a variety of climatic variables. Using a variety of future emission scenarios the IPCC (2007a) has predicted temperature increases of about 0.2°C per decade and a minimum of 0.1°C per decade under a very optimistic scenario of emissions being maintained at the year 2000 levels.

Global climate models used in the IPCC Fourth Assessment Report (2007a) predicted an increase in average surface air temperature for Europe into the mid-21st century (2041-2070) (Roeckner *et al.*, 2003; Marsland *et al.*, 2003). The models predicted that warming during the winter period (December-February) will be greatest in north-eastern Europe (more than 3° C), while in the summer period (Jun-Aug),̌ the largest increase in surface air temperatures can be expected in southern Europe, (e.g. in the Iberian Peninsula) where temperatures could rise by up to 4° C during this period (Brankovic *et al.*, 2010).

The anticipated changes in winter precipitation patterns in Europe are expected to increase in areas north of 45 ° N latitude and decrease in areas south of 45 ° N latitude. For summer, the same models predict a reduction in precipitation in the temperate latitudes of central and western Europe. Warmer and drier conditions may cause prolonged droughts and extend the fire season with increased forest fire risk, particularly in Mediterranean countries where droughts will probably start earlier and last longer. Countries in central Europe will probably experience the same number of hot days as those currently occurring in southern Europe. The regions in Europe most affected are likely to be the southern Iberian Peninsula, the Alps, the eastern Adriatic and southern Greece (IPCC 2007a).

The negative effects of expected changes in average temperature and precipitation will be accentuated by the increase in frequency of extreme events. The speed of climate change is expected to be rapid, with the expectation of rearrangement of current global distribution of climatic conditions within this century (Loarie *et al*., 2009). Climate change and other global changes will greatly influence the forest ecosystem in Europe (IPCC 2007b).

General consequences of climate change for forests

It is important to note that, while climate change is occurring and measurable in terms of physical and biotic changes, there remains great uncertainty as to its magnitude and eventual impacts. Predictions based on current data and trends allow us to speculate on future events, but predictions, by their nature, contain an element of uncertainty. It is difficult to make accurate predictions in particular for extreme weather events, such as storms. That being said, based on the predictions for Europe, we can expect continued changes in species ranges, species composition and forest dynamics (e.g. EC 2008).

Forests generally occupy large areas and are populated by long-lived trees. Thus, climate change represents a particular set of challenges to the biology of forest trees. Within the lifetime of an individual tree the conditions could become up to 3°C warmer (based on a 150-year lifespan at an IPCC prediction of a 0.2°C decadal increase in global temperature). However, forest trees also have a particular adaptation capacity in comparison to other plants, such as annual herbs, that may help them to cope with climate change. Forest trees are known to demonstrate extensive plasticity in their response to climate change. This has been shown through changes in phenology, such as bud burst, in response to temperature (Menzel *et al*., 2006). Local adaptations are also evident within relatively short timescales (e.g. Jump *et al*., 2006; Savolainen *et al*., 2011).

Range shifts

Forest areas are expected to expand in the north and north-east but contract in the south (Kremer *et al*., 2012; Metzger *et al*., 2004; IPCC 2007b). Shifts in bioclimatic envelopes are predicted to change the distributions of species (Kremer *et al*., 2012). The loss in the south and gain in the north is both a challenge and an opportunity. It is likely that there will be extreme pressures on southern tree species and populations to adapt in order to survive. As tree species are long lived, extinction in the short-term (100 years) is unlikely (except in cases of rare species and those with restricted distributions and specialised habitats). However, there will be shifts in species' ranges and tree populations will have to adapt to new physical conditions. The northern expansion should occur through the spread of existing adaptations (e.g. temperate tree species moving into tundra as it warms). However, the southern tree populations will have to adapt to new conditions, such as unprecedented temperature increases and drought. In addition to range shifts at the extremes, altitudinal shifts are also expected. Models predict that alpine species are extremely sensitive to climate change (Schröter *et al*., 2005). A particular concern will also be the fragmentation of a species range into disjointed populations and this is predicted to occur more in the southern and marginal populations. Fragmented populations will also occur along with a northern expansion of populations. However, recolonization through fragmented populations was a feature of postglacial colonisation of many tree species (e.g. Lowe *et al*., 2006).

Species composition

As already illustrated from the changes in species ranges, species new to northern latitudes will give rise to new species compositions and communities. Drought in the Mediterranean region is likely to lead to changes in the abundance and distribution of a number of tree species in this region, such as cork oak (*Quercus suber*) and Aleppo pine (*Pinus halepensis*) (Schröter *et al*., 2005; Ruiz-Labourdette *et al*., 2013). In addition to the changes in species composition through replacement, there may be new opportunities for hybridisation of formerly isolated species. Hybridisation is common in deciduous oak species and, with changes in ranges, new species interactions will occur. This can have an economic effect if, for example, species restricted to the Mediterranean (such as *Quercus faginea* and *Q. fraineto*) move northwards and hybridize with the highly valuable temperate oaks (*Q. petraea* and *Q. robur*) (Valbuena-Carabaña *et al*. 2005; Kremer, 2010).

Competition and disease

In addition to abiotic conditions new biotic challenges, such as competition from other species and exposure to diseases, will negatively impact the survival of populations. It is suggested that forests of native conifers may be replaced by deciduous trees in western and central Europe (Maracchi *et al*., 2005; Koca *et al*., 2006). Along with the displacement of species, there will be an exposure to new diseases and pathogens. As a consequence of climate change, many species of phytophagous insects of northern temperate forests, including some of the most important forest pests, have also been observed to expand their range northward and upward, and this could affect the forest ecosystems through their activity (Battisti 2008). Moreover, changing climatic conditions can also influence the spread of infectious pathogens such as fungi and bacteria and add stress to forest trees making them more susceptible (Kliejunas, 2011).

Adaptation and changes in performance

With the loss and expansion of species range edges there will be a subsequent loss and potential expansion of locally adapted tree populations. The adaptability of populations can affect their performance. The productivity of forests in the Mediterranean region is closely related to precipitation patterns, and drought in particular can decrease productivity (Cotrufo *et al*., 2011). However, in contrast to the effects in southern populations, primary productivity and biomass will likely increase in northern populations due to longer growing seasons (IPCC, 2007). A review of the effects of climate change on primary productivity in forests globally shows a net increase in the primary productivity since the middle of the 20th century (Boisvenue and Running 2006). The impacts on wood production and wood quality remain uncertain, although experiments have shown changes in wood chemistry (increased starch compared to cellulose) and morphology (larger annual rings) in young birch due to elevated CO_2 (e.g., Kostiainen *et al*., 2006). Changes in tree-ring growth, which are likely due to the effects of climate change over the last 50-100 years, have been observed in recent decades in *Populus, Quercus, Pinus, Tsuga* and *Nyssa* in the eastern United States (Johnson and Abrams, 2009).

This is an area that needs further study, and is certainly of interest in terms of the economic use of forests. Another study comparing growth rates of multiple *Quercus* species in Britain showed species-specific responses, with southern European (non-native) oaks performing better than the native oaks (Sanders *et al*., 2014). This is of significance in terms of selecting future timber species but also in terms of species dynamics.

Climate change consequences for forest genetic resources

Forest genetic resources are fundamental to the diversity and adaptation of forest trees and their populations. FGR are crucial to maintaining the adaptive capacity in response to climate change. The consequences of climate change on FGR will be heavily dependent on the size and distribution of the current tree populations and indeed on the biology of the species. A widespread common species is less likely to be as susceptible to the impacts of climate change in comparison to a species that has a narrow distribution and small populations. The overall consequences are expected to be changes in allele frequencies and allele compositions as a result of altered forest dynamics. Changes are also predicted at the edges of distibution ranges and within the core areas of the ranges.

Despite the uncertain consequences of climate change on FGR, one likely outcome is an overall reduction in variation at least in the short-term. Novel variation via spontaneous mutation occurs continually in a population and is acted on by natural or artificial selection to generate a better-adapted progeny. However, studies to date show that the potential adaptation rate is much slower than the pace at which the climate is currently changing (Aitken *et al*., 2008) and that there is a prospect of an immediate reduction in our genetic resources in light of current climate change projections.

Although there is a degree of plasticity in trees, natural selection of favourable traits will occur throughout the range, but this is likely to be more intense at the range edges. This should be evident from changes in, for example, allele frequencies of phenology-related genes across clines. Data are currently limited on the effects of climate change on natural selection (Donnelly *et al*., 2012). A change in allele frequencies correlated with an altitudinal temperature gradient has been shown for *Fagus sylvatica* (Jump *et al*., 2006) and a growing number of studies are investigating changes due to climate change. The responses are going to be very different at the different parts of the range – the edges (northern/southern/marginal) and the core area.

In the north an important factor is the genetic landscape that is created from this expansion. Studies on the genetic impacts of ice ages have shown a variety of patterns and also point to the lack of a "one size fits all" approach (e.g. Lascoux *et al*., 2004). While current patterns of genetic structure are a result of dispersal after the last glacial maximum and in particular of dispersal into suitable territory that is unoccupied (Hewitt 2000), a considerably different pattern should be expected when species ranges shift into occupied habitats. At the northern edge of the range founder effects from stochastic dispersal events resulting in isolated populations are expected to influence FGR (Hampe and Petit, 2005). As more of the landscape is currently occupied by different habitats, the pattern is likely to continue in the form of a fragmented mosaic compared to the homogenisation and admixture that occurred following the last glacial maximum. Isolated populations can result in rapid adaptation to local conditions with a subsequent change in allele frequencies of the selected genes. Another element influencing and in some cases hindering adaptation in the northern populations is prevalence of pollen from southern populations dispersing northwards by prevailing winds. This can affect the fitness of the populations as the southern pollen is bringing genes adapted to different conditions, which may not suit the northern environment (Savolainen *et al*., 2007). However, in the long term this may be advantageous in adapting to a warming climate. In contrast, a species with limited seed dispersal will have a greater likelihood of local adaptation (Kremer *et al*., 2012).

At the southern edge, extinction and fragmentation of populations is predicted with the subsequent consequences of genetic drift and restricted genepools. Southern species will face increasing population fragmentation and reduction in population numbers. Populations in the south will face unprecedented warmer conditions and they possibly do not have the necessary adaptation potential to survive these changes (Aitken *et al*., 2008). Some of the southernmost populations are likely to become extinct, resulting in an overall reduction in FGR.

Within the core of the distribution the most likely outcome will be a change in the species composition through changes in forest dynamics with a possible reduction in genetic diversity.

Natural selection will of course be part of a dynamic process where current climatic envelopes of species are modified in the north and south, but this is a more long-term component of adaptation and indeed speciation.

Threatened tree species and populations

Threat occurs through three main processes: 1) direct elimination of individuals (e.g. overexploitation, grazing, pathogens, fire), 2) elimination of habitat (e.g. destruction, pollution, environmental change), 3) genetic impoverishment (e.g. by fragmentation, genetic drift) (e.g. Potter and Crane, 2010). Climate change can influence all three processes.

Assessment of threats

Just as predictions of climate change are uncertain (see pages 6-7), there is also great uncertainty concerning the biological response of tree species and their populations and the resultant impacts on FGR. To assess a threat a number of issues need to be taken into account. The IUCN uses population demographics and population ranges to assess the global threatened status of a species and this is also a useful model to apply on a regional basis (IUCN, 2012). Potter and Crane (2010) have proposed a risk assessment system that includes intrinsic and external factors. Intrinsic factors are demographic and ecological variables that are specific to the species itself (e.g. population structure and density, fragmentation, regenerative capacity, dispersal ability, habitat affinities and genetic variation). These intrinsic factors are generally known or can be estimated and can be used to assess adaptive potential or potential vulnerability. External factors (namely competition with other species, pest and pathogen threats and habitat pressures such as fire) are less easy to quantify and are therefore associated with a greater degree of uncertainty.

Adaptive potential

Threat to species or populations is a multifaceted phenomenon. There are two natural possibilities to avoid the threat of extinction of a species, when climate change is one of the main drivers:

adaptation and migration – both pollen and seed (e.g. Kremer 2007, Aitken *et al.,* 2008).

Adaptation responses comprise 1) plasticity (tolerance on the individual level), 2) epigenetic processes (from one generation to the next, e.g. Madlung, 2004) and 3) genetic variation (evolutionary divergence and natural selection at a population or species level). In trees genetic differentiation in adaptive traits is generally high. This indicates strong diversifying selection in the past (Savolainen *et al*., 2007; Alberto *et al*., 2013). Recent studies generally observe a high degree of plasticity for tree species as well as an element of epigenetic adaptive processes, mostly in relation to limiting factors such as drought tolerance and frost hardiness (Schueler *et al*. 2014) and also in relation to phenology (Menzel *et al*., 2006). Adaptation capacity on all levels (plasticity, epigenetics, and genetics) has the potential to influence species persistence. A major issue with regard to quantifying adaptive potential is the lack of data. In particular, the independence of neutral genetic variation and adaptive genetic variation (Holderegger *et al*., 2006) means that most of the available genetic data does not help to predict adaptative potential. The development of adaptive genetic markers coding for ecological traits (by, for example, genome scanning and phenotype/genotype association-studies) is ongoing (e.g. Holderegger *et al*., 2008; Manel *et al*., 2010; Kremer *et al*., 2011) but we do not yet have a comprehensive set of markers for predicting adaptive potential. In many cases the only option is to use landscape and habitat variability within a species/population range as a proxy indicator of adaptive potential. The adaptive responses of forest trees and ecosystems to environmental changes and erosion of biodiversity has been studied within the EVOLTREE Network of Excellence which was launched as a European initiative in April 2006. Candidate genes have been catalogued for phenological and drought-related traits in important tree families such as Salicaceae, Fagaceae and Pinaceae (Kremer *et al*., 2011).

Migration responses involve evading the threat through dispersal. Migration is dependent on the species capacity in terms of pollen and seed production or vegetative dispersal, the permeability of the landscape matrix to dispersal, and the availability of suitable habitat to colonise. While future migration away from temperature extremes in the south is generally assumed to be predominantly latitudinal, it can also involve an altitudinal component where vertical buffers such as mountains exist. In fact, without vertical buffers, migration needs to be much faster to evade the threats (Loarie *et al.*, 2009; Ordonez & Williams, 2013). On the other hand, low-frequency episodic events of long-distance dispersal can accelerate the populations’ migration responses (Alberto *et al.,* 2013b). In the particular case of species specialised to riverine habitats, such as black poplar (*Populus ni-*

gra), potential migration through natural dissemination of seeds to more suitable areas is restricted because of their limited capacity to migrate both in latitude and altitude along the constrained range of the riparian corridors (Villar *et al.*, 2010).

Predictions of ecological ranges from bioclimatic models show that a high proportion of the area within a potential distribution range of a species is not realised by the species due to the influence of community ecology (e.g. competition by established climax species and co-migrators, cooperation with seed vectors) (e.g. Savolainen *et al.*, 2007; Schueler *et al.,* 2014). In periods of environmental change all tree species are likely to suffer lags in performance. Thus, interspecific competition may be reduced, facilitating persistence under suboptimal conditions. Multi-species migration includes an immense variety of ecological interactions and thus leads to great uncertainty (Kremer 2007, Aitken *et al.,* 2008).

In general, rarity and low genetic variation are used as indicators of threat. However, threat processes can lead to genetic differentiation and thus local adaptation. An evolutionary perspective on species diversity shows that taxa are dynamic, not static. In some cases current divisions of subspecies and populations as distinct species will probably not match future reality (e.g. white oak species in Europe, Petit *et al.*, 2002).

Distribution of populations

Specific demographic and distribution patterns provide general indications for actual or potential threats. Differences in distributions will be a key factor in the susceptibility of a species to climate change. Therefore a rough estimation and classification of specific distribution types of populations is necessary. According to Frey (2003) populations can be: a) in the main distribution zone (mainly conjunct populations), b) part of a side distribution zone (mainly disjunct populations), or c) within the relict zone (outside of the current distribution range). These categories are separate to a species distribution and are particularly relevant when estimating impacts on tree populations or genetic conservation units. These distribution types are important in assessing threat, as a population within the main distribution zone (the core) will probably be less threatened than those on the periphery of a range.

Estimating specific threat types

The primary aim of the conservation approaches presented in this report is to maintain adaptive variation across the distribution range of forest trees in Europe. Thus we have to focus on those regions that will most likely be the most affected. These regions contain subpopulations which host important intraspecific genetic variation. The focus on marginal and peripheral tree populations is being highlighted in a current EU initiative (COST Action FP1202 *Strengthening con-*

servation: a key issue for adaptation of marginal/peripheral populations of forest trees to climate change in Europe (MaP-FGR)). A special interest lies on marginal populations at the rear edges of species distributions (Hampe and Petit, 2005). The IPCC (2007a) indicated that in Europe, the southern Iberian Peninsula, the Alps, the eastern Adriatic and southern Greece are those regions that will be most affected by climate change. The main threat in these areas is that of temperature increase and susceptibility to drought. It is these areas that maintain populations at the southern edge of the range of many species. Another important set of marginal populations is that of islands.

Based on the IUCN threatened status criteria of low population numbers, reduction in abundance and restricted distributions (IUCN, 2012), marginal tree populations of some widespread species should be considered threatened. Although the scale is different, the main threat type indicators and thresholds are similar for both threatened species and threatened populations. It is possible to assess a number of indicators for actual and future threats.

Indicators for general threats

Low genetic variation. Compared to herbaceous annuals and perennials, tree species tend to have higher neutral genetic diversity within populations, while genetic differentiation among populations is lower in more than 90% of tree species and correlates to high potential for long distance gene flow in trees (Hamrick, 2004; Alberto *et al.*, 2013b).

In contrast, the rare and endemic Spanish fir (*Abies pinsapo*) in Southern Spain and northern Morocco is already showing signs of decline in genetic variation (Liepelt *et al.*, 2010). Another example is the rare endemic Sicilian fir (*Abies nebrodensis*), which shows low levels of neutral genetic variation (Parducci *et al.*, 2001). Due to its close relation to the European silver fir (*Abies alba*), the remaining population of Sicilian fir has to be considered as a marginal population at the edge of the distribution range. A similar case is the Sicilian subpopulation of Turkey oak (*Quercus cerris* subsp. *gussonei*, locally interpreted as *Quercus gussonei*, Sala *et al.*, 2011).

Low or declining abundance. This is the principal IUCN criterion for threat because this is relatively easy to evaluate by demographic studies. Population thresholds for minimal viable populations and a decline in population over three generations or 100 years (for long living tree species) are taken into account (IUCN 2012).

Decline can consist of dieback of adult trees, such as drought-induced mortality events at the southern edges of distribution (e.g. Atlas cedar (*Cedrus atlantica*) dieback in Morocco and Algeria, or Scots pine (*Pinus sylvestris*) dieback in Turkey) as well as in arid inner alpine valleys of Switzerland (Allen *et al.*, 2010). Other causes of dieback can relate to introduced pathogens, e.g. cork oak (*Quercus suber*) decline by *Pythophtora tinctoria* infection in southern Spain (Gómez-Aparicio, 2013).

Lack of regenerative capacity and dispersal ability. Lack of regeneration can also lead to declines in abundance. Regeneration failure over time leads to unsustainable age structure in a stand and inevitably to abundance decline. At the southern edge of distribution regeneration failure due to drought can occur long before adult trees are affected (highly susceptible youth growth phases). Another cause can be overgrazing by red deer, as in the case of core populations of yew (*Taxus baccata*) and northern marginal populations of the service tree (*Sorbus domestica*) in Switzerland (Rudow, 2001), or cattle in the case of Italian maple (*Acer opalus* subsp. *granatense*) in southern Spain (Gómez-Aparicio *et al.*, 2005).

Seed set and dispersal ability are crucial to the survival of populations and species. These are both critically affected by pollinators and dispersers.

High degree of fragmentation. Fragmentation can increase vulnerability and genetic erosion. Based on the long-distance gene flow in many tree species (Kremer *et al.,* 2012), fragmentation effects start when distances between tree populations reach 50-100 km. Rare endemic species with limited distribution patterns often have a high level of fragmentation, such as Spanish fir (*Abies pinsapo*) with separation in different relict populations. Depending on the taxonomic interpretation of Trojan fir it is a single strongly isolated population (*Abies equi-trojani*) or a highly fragmented marginal population of Turkish fir (*Abies bornmuelleriana* subsp. *equi-trojani*) or even of Caucasian fir (*Abies nordmanniana* subsp. *equi-trojani*).

Indicators for threat triggered by climate change

High susceptibility to drought stress. There are numerous indications of increases in the frequency of extreme drought events in recent decades, and also of the high impact of drought on the decline of species and populations (e.g. Allen *et al.*, 2010; Choat *et al.*, 2012). The species which are most predisposed are those having marginal populations at the southern distribution edges (for example Atlas cedar in Morocco and Algeria or Scots pine in Central Anatolia, Turkey). There are several variables correlated with drought such as the aridity index, mean annual precipitation or maximum temperature. Moreover, extreme drought events are often accompanied and reinforced by disturbance regimes such as existing or new insect pests (gradation of bark beetles, processionary moths) or by wildfires (e.g. Allen *et al.,* 2010).

Migration impediments. Physical features of the landscape can act as barriers to potential migration routes along zonal gradients. The Mediterranean sea is a barrier for northward shifts of North African or island populations of Mediterranean species (e.g. *Cedrus atlantica* in Atlas mountains, *Cedrus libani* subsp. *brevifolia* or *Quercus alnifolia* in Cyprus) or for east-west-shifts from one coast/peninsula/islands to the other.

Another barrier type consists of large flat regions on continental plates for species or populations already using mountain ranges as vertical buffers adjacent or within these plains, e.g. the Castilla-La Mancha in Central Spain, the Central Anatolia in Turkey, the Pannonian basin in Hungary, and North-east European and Russian plains. Threat intensity increases if vertical buffers are exhausted (for example, *Larix decidua* and *Pinus cembra* in the Carpathians).

Limitation to azonal rare habitats. A species or population limited to rare azonal mountainous habitat can fragment and this can potentially lead to a threatened status (for example most boreal tree species in Central Europe, most deciduous tree species in the Mediterranean region). A different geology of mountain regions compared to the surrounding zones can have similar effects. Many examples of secondary species are known, e.g. tree species, which are found only on calcareous soils of mountain ranges, due to weak competitive capacity in other areas (e.g. *Pyrus pyraster* in the Jura mountain range, *Pinus heldreichii* in the Balkans).

Another limitation to rare azonal habitats is related to specializations in wetland sites. There are typical examples limited to moors (e.g. *Pinus mugo* subsp. *rotundata*) or to alluvial forest (e.g. *Ulmus laevis, Populus nigra, Alnus cordata* and *Platanus orientalis*). Even if azonal wetland habitats are less susceptible to drought pressure, migration is highly impeded, especially in moors and zones with highly fragmented alluvial forests due to intensive watershed management and river regulation (Barsoum and Hughes, 1998).

Ecological factors. A number of ecological factors can be associated with or exacerbated by climate change. Climate change has been implicated in the increase of invasive species, pathogens and diseases (e.g. Simberloff, 2000). With changes in climate there will be subsequent changes in species performance, thus leading to inter-species competition, not only with invasive alien species, but also with native species that are favoured, for example, by drier soils. Another particular case of ecological indicators will be the increased risk of fire in particular in southern region. This will favour those species that are adapted to fire – such as seed germination after a fire.

Overview of threatened species and populations

There is no red list focussing on threatened European tree species, much less a list including tree populations threatened by climate change. The IUCN World List of Threatened Trees (Oldfield *et al*., 1998) only provides fragmentary information concerning species in Europe. The European Red List of vascular plants (Bilz *et al*., 2011) focuses on plants listed in policy documents, crop wild relatives and aquatic plants. The lists from policy documents date to 1991 and earlier. Currently a limited number of tree species that are potentially vulnerable to climate change are ranked in the category 'endangered' (e.g. *Abies pinsapo, Cedrus atlantica*); most are still in the category 'least concern' (e.g. *Pinus sylvestris, Populus nigra, Alnus cordata, Pinus brutia, Pinus pinea, Platanus orientalis, Juniperus thurifera*) or 'not assessed yet' (e.g. *Ulmus laevis, Abies alba subs. nebrodensis, Liquidambar orientalis, Quercus alnifolia, Acer sempervirens*) (IUCN, 2014). An up-to-date overview of threatened and potentially threatened species and populations of European trees, including a focus on marginal populations and adjacent regions of Europe (Maghreb/North Africa, East Mediterranean/Near East, Caucasus/Alborz) is needed. This requires a systematic evaluation of all tree taxa across their distribution ranges. A preliminary list of threatened tree species and populations was developed during the preparation of this report. However, it is recommended that this preliminary list be further developed and finalized as a separate EUFORGEN activity in the future. Such a list can be developed using the criteria discussed in the section above.

It is also important to consider those tree species which form part of the isolated Macaronesian flora (*Laurisilva*) in the adjacent Atlantic islands. The *Laurisilvae* represent the last relicts of tertiary Mediterranean (Canary Islands, Madeira) or sub-Mediterranean (Azores) evergreen broadleaves forest flora (Schäfer 2003). The Macaronesian flora consists of many endemic species, which by nature of their isolation and fragmentation have to be considered as potentially threatened or threatened species (e.g. several *Laurus* and *Ilex* species, *Picconia excelsa, Ocotea foetens, Arbutus canariensis*).

Knowledge of measures and existing strategies

Background

Conservation of FGR faces several challenges, with climate change being the latest. There is an urgent need to strengthen efforts among European countries to conserve FGR, particularly those in marginal populations. Europe is a complex region where the distribution ranges of tree species extend across large geographical areas, with marked environmental variation. As biological distributions do not coincide with national boundaries, the regional cooperation among countries both in sustainable forest management and in FGR conservation is crucial.

Incorporating FGR into national and EU policies

National forest programmes are important policy tools, which can support the integration of FGR conservation into actions at the practical forest management level. National forest programmes are now in place in many European countries (Lefèvre, 2007; Rusanen *et al*., 2007; Hubert and Cottrell, 2007; Graudal *et al*., 1995; Behm *et al*., 1997; Tessier du Cros, 2001). Within many programmes the conservation focus is to maintain variability in adaptive traits (e.g. Graudal *et al*., 1995; Myking, 2002). Various conservation strategies have been revised based on the expected impacts of climate change but there is still much to be implemented in forest management practices. Forest managers are often unaware of the importance of using high-quality forest reproductive material and of the genetic consequences of management practices. The appropriate use of FGR could indeed support the resilience of forests, mitigate the risks and facilitate the adaptation of forests to climate change. In this regard, it would be worthwhile if conservation and use of FGR were incorporated into national adaptation strategies to climate change and national biodiversity action plans. National biodiversity action plans generally focus on conservation of biological diversity at species and landscape levels only, while a better connection between forest genetic conservation networks and other biodiversity objectives is needed (Lefèvre *et al*., 2013). The discussion on the integration of conservation and use of FGR as part of sustainable forest management into these policies and strategies is underway within EUFORGEN. In the face of climate change, the European Information System on Forest Genetic Resources (EUFGIS), launched in September 2010, has been created with the specific objective of supporting countries in these efforts. It could promote useful linkages between national FGR conservation programmes and biodiversity conservation efforts; it can also support linkages between applied conservation and research activities.

Strategies

In situ approaches

Conservation networks. In view of the predicted climate change, long-term conservation of forest genetic diversity provides the insurance for sustainable forest management. The heritable genetic variation and the intensity of selection play a critical role in the evolutionary response of species and populations to a changing environment. For this the first priority of a conservation strategy should be to maintain high levels of diversity within the genetic conservation units and species across Europe (Koskela *et al*., 2007). Within EUFORGEN, priority is given to a dynamic conservation of forest genetic resources *in situ* and *ex situ*. A pan-European network of selected genetic conservation units for various tree species has been created according to pan-European minimum requirements and data standards of these units (Koskela *et al*., 2013). The aim of this network is to conserve adaptive genetic diversity present across the range of European conditions in which each tree species occurs. Geo-referenced data on genetic conservation units based on 26 data standards at the unit level (geographical area) and 18 data standards at the population level (target tree species within a unit) has been documented into the EUFGIS database. As of May 2015 the network consisted of 3,214 units, with 4,061 populations of 100 tree species. The EUFGIS database has been shown to be particularly useful in identifying gaps in the conservation network, thus helping to create a more comprehensive set of units for genetic conservation.

The conserved adaptive diversity of forest trees throughout their distribution ranges will provide the raw material by which adaptation through natural selection will occur during climate change. Using the EUFGIS information system as a tool and a climatic zoning of Europe (Metzger *et al*., 2013) as a proxy for characterizing adaptive diversity conserved in the genetic conservation units across the continent, a core network of dynamic conservation units can be selected for different species according to their geographical distribution, their ecological characteristics and their vulnerability to climate change (see de Vries *et al*., 2015).

Monitoring. Continuous monitoring is an important element in a strategy to conserve FGR. In particular, recent EUFORGEN efforts to develop and undertake genetic monitoring could prove to be useful over time. Field inventories and continuous monitoring incorporating ecological and genetic data would provide a baseline to assess how well genetic diversity is actually conserved. This would show how well both adaptive and neutral genetic diversity is maintained through time, and would reveal changes in species composition, the occurrence of indicator species and competitors of target species and in turn give an indication of the consequences of management practices and/or environmental changes (Aravanopoulos, 2011). The data generated by monitoring could be stored in the EUFGIS portal and used to revise management plans.

***In situ* management.** Since there are threats to the integrity of FGR from a number of causes and given the uncertainty of climate predictions, a comprehensive spectrum of possible conservation strategies and management measures, should be considered in the context of climate change.

For most forest tree species, management plans for the conservation units allow silvicultural interventions directed towards the support of natural regeneration both in terms of quality and quantity of regenerating material. Applying given critical values for the number and density of seed trees, shortening of the regeneration time, regulating competition by other tree species and controlling invasive species should also be taken into consideration. A good level of genetic diversity and reduced consanguinity in the regenerated seedlings should be a management objective. Natural regeneration should be the preferred means but if this fails to occur, assisted regeneration can be carried out using local seed lots to maintain local phenotypic identity (Lefèvre, 2007).

Three different strategies have recently been proposed to enhance resilience of forest stands to climate change in central Europe (Bolte *et al*., 2009). This includes 1) 'Conservation of forest structures' by silvicultural intervention for older stands located in areas predicted to have low impacts from climate change; 2) 'active adaptation' by thinning, re-spacing and choice of alternative species are proposed for stands where the impacts are anticipated to be severe and 3) 'passive adaptation' for stands of low value (ecological and economic) that will rely on natural evolution facing the future climate shift. To help British forests to achieve higher levels of genetic diversity to accommodate climate change, another three potential strategies have been proposed using either natural regeneration or planting and each has a different mix of risks and benefits (Hubert and Cottrell, 2007): 1) maintaining genetic variation (higher initial diversity) and promoting natural regeneration by silvicultural interventions (tending, thinning, selectively removing poor quality individuals); 2) planting a mixture of provenances alongside the current population using the best climate predictions to guide the choice of provenances (using also a proportion of local stock might be useful as a safeguard); and 3) using assisted migration by planting a single provenance or species for locations that are predicted to experience high rates of climate change. This option will involve the transfer of genetic resources from populations under particular climate pressures into areas predicted to have future conditions equivalent to the extant conditions. For example, transferring drought-adapted populations from the south to increase the adaptability of populations in the north, which would otherwise have an increased susceptibility to drought in the future (O'Neill *et al*., 2008). This will be addressed in more detail in the recommendations section of this report.

In the case of restoration programmes an evolutionary perspective should be considered (Rice and Emery, 2003). The exclusive use of local material may not allow for a rapid adaptation to the predicted climate scenarios (Harris *et al*., 2006). However, to prevent introduction of invasive forest pathogens, restrictions on introductions should be developed. The introduction of new species can negatively impact native biodiversity (extinction of local tree species, mating among invasive and native species, loss of stability among the native population) (Chornesky and Randall, 2003; Cleeland and Mooney, 2001). Restoration and afforestation (ecological restoration) of degraded agricultural land has also been considered an important mitigation response to climate change. Afforestation and reforestation implemented for carbon sequestration to mitigate global warming under the Kyoto Protocol could likely result in plantations with limited genetic diversity or containing fast growing exotic species that could have further negative impact on biodiversity (Caparros and Jacquemont, 2003).

As a pre-emptive option in some cases, artificial *in situ* units can be created to serve as founder populations for new establishments, as in the case of riparian species (e.g. *Populus nigra*) (Rotach, 2001).

Ex situ *approaches*

Dynamic *ex situ*. Conservation of FGR is likely to become more complicated with rapidly changing climate. Therefore, actions for *ex situ* conservation will become increasingly important as a complement to, or substitute for, *in situ* conservation (St. Clair and Hove, 2011). Generally defined as planted forests established outside the original habitat of the genetic resources, *ex situ* conservation stands may be genetic resources of unknown genetic variability or characterized genetically by phenotypic traits or molecular markers. They tend to be expensive to establish and to maintain. Dynamic conservation can take place in *ex situ* stands when natural selection occurs at a site and when artificially planted trees (species, provenances, families) can be regenerated from seeds without much intervention (Amaral, 2004). If the original population is sufficiently sampled and the stand is large enough (minimum viable population size) (FAO, 1992), these stands could provide sources of reproductive material for commercial forestry. Although costly, multi-site stands can ensure further adaptations to a range of different environmental conditions and prevent unexpected losses of genetic material (Geburek and Turok, 2005).

Assisted migration consists of transferring species or populations from a vulnerable site to a new site that is predicted to be more suitable under future climate projections. Migration can comprise long-distance transfers into more favourable regions or indeed bolstering a threatened population with external genetic material. However, it can also include shorter, more incremental transfers, to support natural migration via the establishment of migration corridors and ‘stepping stones’. For example, isolated forest areas surrounded by agricultural land in the plains could be better connected through establishment of small stands or linear treelines/

hedgerows to link them and to facilitate more long distance gene flow. Provenance tests can be used to determine response curves of seed sources to different climates. Examples including those based on Norway spruce (*Picea abies*), loblolly pine (*Pinus taeda*) and other southern pine species, which showed reduced growth of between 5 and 10% compared to genetically adapted seed sources (Schmidtling, 1994). Assisted migration remains a controversial concept that evokes discussion within the conservation community (McLachlan *et al.*, 2007). In Europe, the scientific community agrees that for some species growing in areas that will experience most intense climate change, assisted migration offers a potentially cost effective strategy for climate-change mitigation, if used in addition to traditional conservation strategies and implementation of conservation genetics practices (Loss *et al.*, 2011a). Assisted migration or relocation is likely to be widely adopted as a response strategy but it has not been implemented yet through any policy measures (Loss *et al.*, 2011b). However, it will likely have many problems such as synecology (e.g. asynchrony or absence of specific pollinators, specific seed vectors, specific mycorrhiza) and maladaptation (e.g. frost hardiness problems in northward migration). Guidelines for provenance transfer and seed zones need to be adapted to account for northward migration of species and for possible assemblages in space and time (Hemery, 2007). In Canada, British Columbia is the first jurisdiction to have modified seed transfer guidelines specifically in response to climate change (Loss *et al.*, 2011a).

Static *ex situ*. Seed orchards, clone banks and clonal archives are examples of static *ex situ* conservation units, in that no changes will naturally occur in the genetic structure of the collection. These plantings are established with the sole purpose of preserving the genetic diversity of a valuable population, to safeguard endangered species that otherwise might be lost or to conserve/increase the genetic diversity of rare species of those with scattered distribution.

Collections of trees in arboreta or botanic gardens can also contribute to the maintenance of unique and rare genotypes of different tree species, despite the fact that in most cases these collections under-represent the within-species genetic variability due to the low numbers of individuals that are present (Hurka, 1994). Collections in botanic gardens, although limited, are also useful as research resources and also for propagation (e.g. Kay *et al.*, 2011).

For species in imminent danger of extinction or with declining populations, which fail to produce or whose seeds are recalcitrant, cryopreservation, vegetative propagation and *in vitro* culture offer the only safe and cost-effective techniques for their conservation, even if only a limited amount of genetic diversity can be preserved (Theilade *et al*., 2004). *In vitro* conservation can be effectively used only for collection and storage of particular genotypes of problematic species that are propagated vegetatively (Engelman, 1997).

Implications for conservation

The conservation initiatives outlined in this report are dependent on a number of logistical and technical issues.

The logistical issues are primarily those of resources – cost and capacity. As conservation of FGR is a cross-border initiative, it will involve collaboration of state bodies to bring about the effective conservation of species and particularly threatened populations into the future. The costs of assessing threats, ground-truthing of units, designating and managing units and continual future monitoring need to be addressed at national and pan-European levels. As outlined in this report the southern tree populations are those most under threat from climate change. However, the investment in conservation of these populations may be key to the species survival as a whole and beneficial beyond the current geography of these populations.

The technical issues are dependent on the biological reality of climate change and the response of tree populations and species. A matter of most obvious concern is the dynamic nature of the conservation efforts needed. Climate change and the response of biota to it are dynamic. For example, bioclimatic envelopes will change as the climate changes and species adapt. As a consequence, species distributions and the genetic compositions of the species will also change. Monitoring, in particular genetic monitoring, will be a key component of the conservation efforts. The dynamic nature of the change and response needs to be built into future approaches to conserve FGR in Europe and beyond. In terms of changes in genetic composition, it is important to know the different stakeholders' views of conservation. From a forest manager's perspective, the most appealing FGR benefit is that which gives rise to trees that produce good quality timber. However, from a purely conservation point of view, the adaptive capacity of a species takes priority over good quality timber. There is a potential bias and resultant change in allele frequencies depending on the selection rationale. Thus, a focus on the adaptive potential must be maintained when conserving the units. The dynamic situation should also be borne in mind when considering potential invasive species and diseases. This is also important when dealing with populations at the vanguard of the species distributions. These populations will colonize new areas and possibly disrupt existing habitats.

It should also be recognised that it may not be possible to save everything. For example, suitably sized populations are needed to maintain adaptive variation. However, this may not be possible in small relict populations that have been subjected to extreme drought. It will therefore be necessary to prioritise the units selected based on limited resources. The focus should be on marginal and in particular, rear-edge populations. Populations at the rear-end of species distributions, and species with distribution restricted to the southernmost areas could face extinction. Assisted migration or *ex situ* conservation units in appropriate areas may be the only possible option for dynamic conservation of such species and populations.

RECOMMENDATIONS FOR MANAGEMENT OF GENETIC CONSERVATION UNITS AND ESTABLISHMENT OF ADDITIONAL UNITS

Any conservation strategy directed towards reducing the negative impact of climate change should aim to reduce the risk of poor performance or mass mortality. The uncertain nature of climate change and the long generation intervals of forest trees put them at particular risk for maladaptation to climate change (St. Clair and Howe, 2007). Genetic diversity is critical for long-term forest sustainability as it provides the raw material for adaptation and natural selection. Forest managers might consider options that aim to maintain the existing genetic diversity in forest stands or, in such cases where it is particularly impoverished, even to increase it. To manage units effectively it is proposed to develop a decision cascade tool to guide forest managers to gauge suitable actions. An initial draft of such a tool is provided in Appendix 1. It is proposed to develop this through further EUFORGEN actions and to try and incorporate predictions based on current scientific knowledge.

Management of existing genetic conservation units

Genetic conservation units are populations considered to be particularly valuable for the management of forest seed sources and genetic diversity. These units have been identified in many countries, but only recently have they been combined into a European-wide network. The units included in the EU-FGIS database are selected on the basis of a set of minimum requirements that ensure populations are of sufficient size for inclusion in a conservation network (Koskela *et al.*, 2013). However, the rationale behind selecting conservation units must remain fluid and should be periodically assessed in the context of climate change. Bioclimatic regions across European countries will undergo contraction or expansion of their ranges. In particular, some will shift towards warmer and drier conditions. Because the current network of conservation units is based on bioclimatic regions, a revision of the network may be necessary in order to maintain the current design of one unit per bioclimatic region per country (as per the pan European core network, de Vries *et al.*, 2015.). The addition of units specifically threatened by climate change addresses this in the short term.

Genetic conservation units represent the most valuable set of forest stands, often containing remnants of the original autochthonous populations of forest trees. In line with the overall forest management goals for genetic conservation units, forest management should promote natural processes. Such approaches should make the most use of management techniques that mimic natural disturbances, including the maximal use of processes that induce, stimulate, and support genetic diversity. In cases where natural regeneration does not occur, then artificial regeneration with a local seed source should be used.

The following criteria should be used to aid a decision cascade which focuses on the maintenance of adaptive variation.

Monitoring of vitality and natural regeneration. Monitoring is essential to determine the level of change that is occurring. A set of parameters for assessing genetic risk has been suggested by Potter and Crane (2010). A modified version of the list of parameters is presented in Table 1. These parameters provide a useful framework in which to monitor change. They can be used to assess the progress of a population and can be used to determine levels of intervention, such as thinning for increased regeneration or removal of competing species. A scheme for genetic monitoring is already proposed by another EUFORGEN report (Aravanopoulos *et al*., 2015).

Promote active management in the units. After assessing the status of a population, the first option should be to maintain the population *in situ* where possible through active management. Forest management should compensate for the effect of a changing climate until proper migration strategies are defined.

Favour units that contain altitudinal and other ecological gradients. When selecting units for the conservation network, priority should be given to large units that contain significant altitudinal or ecological variation. A larger altitudinal variation increas-

Intrinsic factors Particular to the species/ population	**External factors Outside of the "control" of the species/population**	**Specific issues**
Population structure/density	Pest and pathogens	Endemism
Regenerative capacity	Competitive species	Conservation status
Dispersal ability (seed/pollen)	Invasive species	Marginal/ range-edge populations
Habitat affinities	Pollinators/dispersers	
Genetic variation		

Table 1. Parameters for assessing genetic risks (Potter & Crane, 2010, adapted)

es variability of environmental conditions and associated adaptive genetic diversity. If a unit spans multiple habitats, for example soil types, this is also more valuable than a more homogenous unit. For tree species with populations that are widely distributed but scattered, large units, involving small groups of populations are preferable. In contrast, for those rare species which only exist as small populations, conservation units can include a limited number of trees in the core zone, which often represents a sub-population that is available on the site.

Establishment of additional genetic conservation units

Selection of genetic conservation units for climate change vulnerability

The threats and uncertainties posed by climate change upon the conservation network make it necessary to incorporate several changes into the established criteria for the management of conservation units, which have been reviewed above. Among those modifications, some will involve changes in organization (e.g. to establish specific databases for conservation units aimed at mitigating climate-change effects, or whether to increase monitoring), while others may require analytical changes (e.g. to apply an environmental/ regional approach instead of the prevailing focus on the species networks), and others could be considered "experimental" due to uncertainties faced during the process. While applying such changes, it should be accepted that species/populations will be exposed to genetic changes that cannot be avoided (e.g., hybridizations after secondary contacts), that some losses of genetic diversity will be inevitable, and that the main objective of the conservation network is the conservation of forest genetic resources, as opposed to the conservation of the units *per se*. A review of the existing conservation network shows that once they have been completed by the countries involved, a good coverage of the genetic resources from the most important tree species in Europe is attained (de Vries *et al.,* 2015). However, the pan-European core network has not been specifically designed to combat the risks to FGR associated with climate change and further actions are needed if we want the core network to retain large parts of the species genetic diversity in the near future (up to 2075 to 2100). Most urgently, we should address the following:

Select additional units to represent marginal tree populations

National authorities should pay particular attention to marginal populations, as they may contain specific adaptations to environments that lie at the limits of the biological envelopes of each particular tree species. Southern marginal populations at the bioclimatic limits of the species distributions face unprecedented changes and will most likely become extinct without intervention (Aitken *et al*., 2008).

Add units of newly established or migrated tree populations

Long-distance dispersal events have a large influence in the genetic make-up of new populations colonizing the northern limits of the species distribution areas (LeCorre and Kremer, 2012). These rare events create islands of related individuals with reduced genetic diversity, which will greatly contribute to colonizing more northerly territories. There is a risk of accumulating deleterious mutations in these populations (e.g. Peischl *et al.*, 2013), thus supplementing these populations with additional genetic material could help to overcome a potential genetic bottleneck.

Allow additional units to be added to the core network of conservation units

The utility of new conservation units specifically selected to address climate change will be greater if they are integrated within the existing core network. However, some kind of flag (new database field) may be necessary in order to track such populations for any future strategy. This flagging would be important to identify the reasons why these units were chosen. A periodic revision of the country X zones core units will be necessary to adapt to future changes (see de Vries *et al.*, 2015).

Core units versus additional units

The additional units can be added as subsets of the core network. The concept and criteria of the core network will need to be modified for the additional units in response to needs due to climate change. Either a relaxing of the criteria or a modification to allow for particular conservation status may need to be included. Traceability of such relaxed conditions might prove useful for future strategies. Thus the network could be composed of:

Core Units. Populations of autochthonous origin, located within the main distribution range, in typical environments.

Marginal Units. Populations of autochthonous origin, located at the periphery of the distribution range, in potentially atypical environments. These units could incorporate both single population and meta-population approaches in order to maintain (or increase) their adaptive potential.

Migrated Units. Populations of non-autochthonous origin, located within the future predicted distribution envelope of the species, typically the result of assisted migration.

Monitor the additional units

Monitoring of the marginal and additional units may require additional efforts by country authorities. For southernmost populations, the detection of early signs of decline might be vital if silvicultural regimes are intended to have any significant contributions to populations' adaptation. Furthermore, biotic interactions could pose additional risks to genetic resources, even for those populations that are well within the climate envelopes (for example, if there is a lag between the migration of pests and trees as a consequence of shorter generation times). For northernmost marginal populations, the detection of colonizing events may provide early clues into the most appropriate environments for future colonization.

Exploring regional approaches to the conservation of FGR

Instead of the species-focused networks in place, a regional approach could be applied for some species, in particular species complexes or taxonomically uncertain groups, such as *Pinus halepensis* or white oaks of the Mediterranean basin.

Taxonomic issues

It is important to note that species are not static entities and that, for example, hybridisation can lead to speciation. The case of oaks in southern Europe illustrates the potential for hybridisation and formation of species. Hybridisation in certain systems could be assessed if additional units are chosen in "hybrid zones".

Species that are favoured by climate change

In spite of threats to FGR, climate change will favour the spread of some species (e.g. *Quercus ilex* will likely increase its distribution range in countries such as France). Even for such species, the rear-end and relict populations should receive special attention in order to avoid losses of valuable FGR. As mentioned above, the front end will lose genetic diversity at least during the initial phases of expansion. However, there is the possibility that populations from different glacial refugia could merge in some areas, creating new genetic diversity through mixing of allopatric populations. In turn, this could create segregation of adaptive traits leading to increased adaptation to climate change. It is in such areas of genotypic merging that the establishment of new conservation units might be most profitable.

Review of scientific advances

The recommendations and methods in this report need to be updated as appropriate. A review of scientific advances with a focus on the potential impact of climate change on conservation of FGR should be implemented in the future. Such a review should facilitate communication between scientists and managers for an early incorporation of new findings into the conservation policies.

RECOMMENDATIONS FOR COMPLEMENTARY *EX SITU* APPROACHES

In some cases it will not be possible to maintain *in situ* units as the conditions will change too much to allow a tree population to survive. In addition, some populations may hold particular variants or adaptive potential that need to be maintained. In these cases, *ex situ* conservation measures will be necessary. As mentioned previously, the decision cascade tool (Appendix 1) should help managers to determine when *ex situ* approaches are most necessary.

Ex situ conservation is defined here as "the conservation of components of biological diversity outside their natural habitats" (see article 2 of the Convention on Biological Diversity). *Ex situ* collections include whole plant collections, zygotes, gametes and somatic tissue. Of course there are fundamental differences between whole plant collections, such as seed orchards and collections such as cryopreserved seeds or embryos. The preferred option is to maintain a dynamic situation, one in which natural processes, such as gene flow and natural selection, are taking place. Static *ex situ* measures are those that instead of promoting a dynamic situation hold the material in stasis – such as cryopreservation of tissues.

Prioritization of tree species and establishment of *ex situ* populations

Prioritization

In order to optimize conservation efforts, the prioritization of species and the coordination of conservation measures on a pan-European level are necessary. The prioritization of species must consider 1) necessity of conservation according to the importance of species (e.g. ecological and economical values), 2) urgency of conservation according to the types and intensities of threat (as described earlier), and 3) feasibility according to the expected costs and impacts of measures in relation to the available budgets.

Ex situ measures are often closely related to the urgency of action. Having an overview of (potentially) threatened species and populations of European trees would allow earlier intervention for *ex situ* measures. Such a systematic and taxonomically synchronized "Red List" of threatened European tree species and populations has to be established and maintained on a long-term basis. Suggestions have been made within this report as to the criteria for establishing a red list – those related to IUCN criteria and also some specific to impacts predicted based on climate change. During the preparation of this report the authors found that a concurrent initiative is in place as part of the COST Action FP1202 to prepare a list of marginal populations under threat. Adjacent regions of Europe have to be taken into account, most of all North Africa, Near East and the Caucasus. These regions at the southern edge of the Mediterranean climatic zone are most sensitive to species distribution shifts triggered by climate warming. If they lose their current tree species they will be exposed to desertification, because there are no alternative more southerly tree species available to migrate northwards.

Establishment of *ex situ* populations

As most tree species have high adaptive potential (see section 'Adaptive potential' on page 11) this feature is important to consider and harness in the context of *ex situ* conservation measures. Therefore all measures dealing with artificial regeneration, i.e. most of the *ex situ* measures, but also assisted regeneration in *in situ* conservation units, must ensure that maximal variability of the original population is captured by 1) using appropriate seed collection strategies and 2) establishing optimally sized *ex situ* populations.

1) Seed collection strategies: best practice in seed harvest takes into account and fulfils minimum requirements concerning a) population size, b) number of mother trees, c) maximum spatial and ecological distance of mother trees, d) number of harvest years. Seed collection protocols should aim to capture maximal genetic diversity in artificial regeneration in order to optimise the potential for genetic and epigenetic adaptation.

2) *Ex situ* population size: the presence of a large number of regenerating individuals is crucial in order to provide the best opportunity for natural selection processes to operate.

If possible, *ex situ* conservation units should be established with at least 5,000 seedlings/saplings collected from populations that contain at least 500 adult individuals. Such *ex situ* conservation units should be based on seed collected across at least two seasons from at least 50 spatially separated mother trees growing across the range of ecological conditions within the site (Skrøppa, 2005). For scattered, rare and endangered species that have populations with low numbers of trees these minimum standards may have to be reduced. Alternatively, joining of fragmented subpopulations with neighbouring subpopulations in *ex situ* units could be considered in order to achieve minimal viable population thresholds.

As a general precaution on establishing units, the risk of introducing pests and pathogens should also be considered. Since prevention and early detection are the most cost effective strategies, phytosanitary measures (post-entry quarantines and border controls for biosafety) should be taken seriously to safeguard biodiversity (Clarke, 2008).

Dynamic *ex situ* conservation

Dynamic *ex situ* conservation involves the establishment of populations outside their natural habitats with the focus on facilitating and maintaining natural regeneration in the population. In some cases it will not be possible to maintain populations at their current location and so assisted migration may be the only option for dynamic conservation (Thomas, 2011). Assisted migration can involve human-mediated movement of a population via the introduction of a provenance or species into a new region or of facilitating natural migration. Within the context of this report, assisted migration discussions will focus on movement of a population beyond that which is expected to occur under short-term natural circumstances. The focus is also on maintaining genetic diversity within European tree species rather than introduced commercially important species.

Assisted migration is considered by some authors as a potentially important climate change adaptation strategy (Millar *et al.*, 2007; Campbell *et al.*, 2009), but should only be seen as a complementary measure or as a last resort because genecology information is still lacking for most of the forest tree species (Eskelin *et al.*, 2011) and the implications of this practice are uncertain and bring with it associated risks and impacts.

In order to minimise unforeseeable implications, the establishment of *ex situ* conservation units originating from assisted migration should be performed in gradual steps over relatively short geographical and ecological distances. These distances should not exceed a maximum threshold equivalent to the change expected within the next 20-30 years, or within 25% of one rotation time (e.g. O'Neill, 2013; Wang *et al.*, 2010a and 2010b). Existing provenance trials in Europe could be studied to build a consensus of the potential suitability of assisted migration in various cases (e.g. Alberto *et al.*, 2013b). Depending on the goal of the transfer, pure stands of introduced material can be set up where a single unit is threatened and needs to be conserved, while mixed stands of introduced and local material can be established to encourage the natural processes in other cases.

It is recommended to establish at least two *ex situ* units for each valuable conservation unit since the greatest effort is in collection and growing of reproductive material and the risk of losing one population can be high. Once a unit is duplicated, natural processes are still ongoing in the original unit, and these should be safeguarded and monitored.

The use of static concepts such as seed zones and provenance regions will need to be reviewed to ensure that managers have access to sufficient genetic variation in their planting stock. As forest reproductive material may need to be moved across national boundaries for planting purposes seed transfer standards may require modification in response to climate change to ensure that plantations have the potential to adapt to future environmental conditions.

Static *ex situ* conservation measures

For some species the preferred dynamic conservation approach will not be possible and in these cases, the only alternative is to maintain the species in stasis in a seed bank or gene bank (e.g. cryopreservation). In general, the earlier the intervention, the more effective it is and in most cases also the more economical. Parallel to the preservation of individuals in stasis, other static *ex situ* conservation measures should be taken, such as preservation of individuals in botanic gardens, artificial populations in seed orchards and genotype collections or *circa situm* conservation in cultural land and settlement areas (e.g. Dawson *et al.*, 2013).

Adequate monitoring

Future *ex situ* conservation units have to be included in the monitoring system in order to assess their development and viability under the conditions at the chosen sites. It is suggested to have a particular “flag” in the EUFGIS database to identify *ex situ* units. Particular focus should be placed on the genetic monitoring of the migration units. *Ex situ* dynamic units will give valuable data on future performance of species.

RECOMMENDATIONS FOR RESEARCH

It is vital to increase the current scientific understanding regarding the impacts and adaptability of tree species and populations to climate change. Although the recommendations in this report primarily deal with management issues, it is important to highlight some research gaps. Little is known about the impacts of climate change on genetic diversity, with only a few studies to date showing concrete effects. Aside from individual species and plant community responses to environmental changes, two particular areas are highlighted in this report.

Firstly, there is the lack of knowledge surrounding assisted migration and its potential impacts on genetic composition and species composition. One obvious source of data is the significant amount of provenance trials that have been conducted throughout Europe. These can be used to assess potential responses of species to large scale movement. Through further research we can better estimate impacts or future responses.

The second area highlighted in this report is that of marginal and peripheral populations. These populations need to be identified and characterised to enable predictions of future threatened regions. Research should be carried out to determine response and impacts within these marginal populations. Various types of marginality, including altitudinal marginality, are particularly important in populations within the core distribution of a species range.

CONCLUSIONS AND OVERALL RECOMMENDATIONS

Conclusions

Genetic diversity of forest trees in Europe is likely to be reduced as a result of climate change. This review shows that marginal populations in southern areas are particularly at risk. The most likely threats are drought and increased temperature in southern Europe. Climatic changes are likely to result in altered species ranges and species composition. The species biology will determine to some extent the level of impact of climate change on the populations; for example, species with large populations and broad geographic ranges are expected to be less affected than those with small populations and limited geographic ranges.

The consensus is that the current pan-European network was not specifically designed to conserve FGR under climate change. Thus, additional measures will be needed to conserve those FGR that are most threatened, e.g. small marginal populations living under extreme climatic conditions. A number of approaches were reviewed, but a key point is that there is very little empirical data available. Thus, best practice can only be based on predictions and estimates.

Recommendations

European countries should continue populating the EUFGIS database in order to identify gaps in regions and species.

- Add additional units to EUFGIS specifically flagged as FGR for climate change units. A particular focus should be placed on marginal populations and particularly those with known limitations in terms of ecological plasticity or genetic diversity.
- A resolution from FOREST EUROPE is needed regarding the movement of the material between countries for conservation purposes.
- The area covered by pan-European collaboration on FGR should be enlarged to include, for example, Macronesian areas and other areas with high endemism. These areas harbour high levels of endemism and unique genotypes.
- Collaboration with North African countries should be sought on common species. It is likely that common species will currently exist under more “advanced” climatic conditions in North Africa in comparison to Europe.

- A decision cascade tool should be further developed and used in the future. The tool presented within this report is an exemplar rather than a finished product. This could be progressed in the form of a particular EUFORGEN initiative.
- The development of species and population/region red lists should be considered as a EUFORGEN initiative. A number of examples are given within this report, but this needs to be more comprehensively reviewed and used as a continual work-in-progress. Part of this is being undertaken by the COST Action FP1202.
- More research is needed to assess the potential effects and impacts of assisted migration. Existing provenance trials can be used as a starting point, but further research is necessary to understand the potential adaptation of trees to future climate change scenarios.
- Research is also needed to assess the impacts of climate change on marginal and peripheral populations, in particular in relation to their adaptability.

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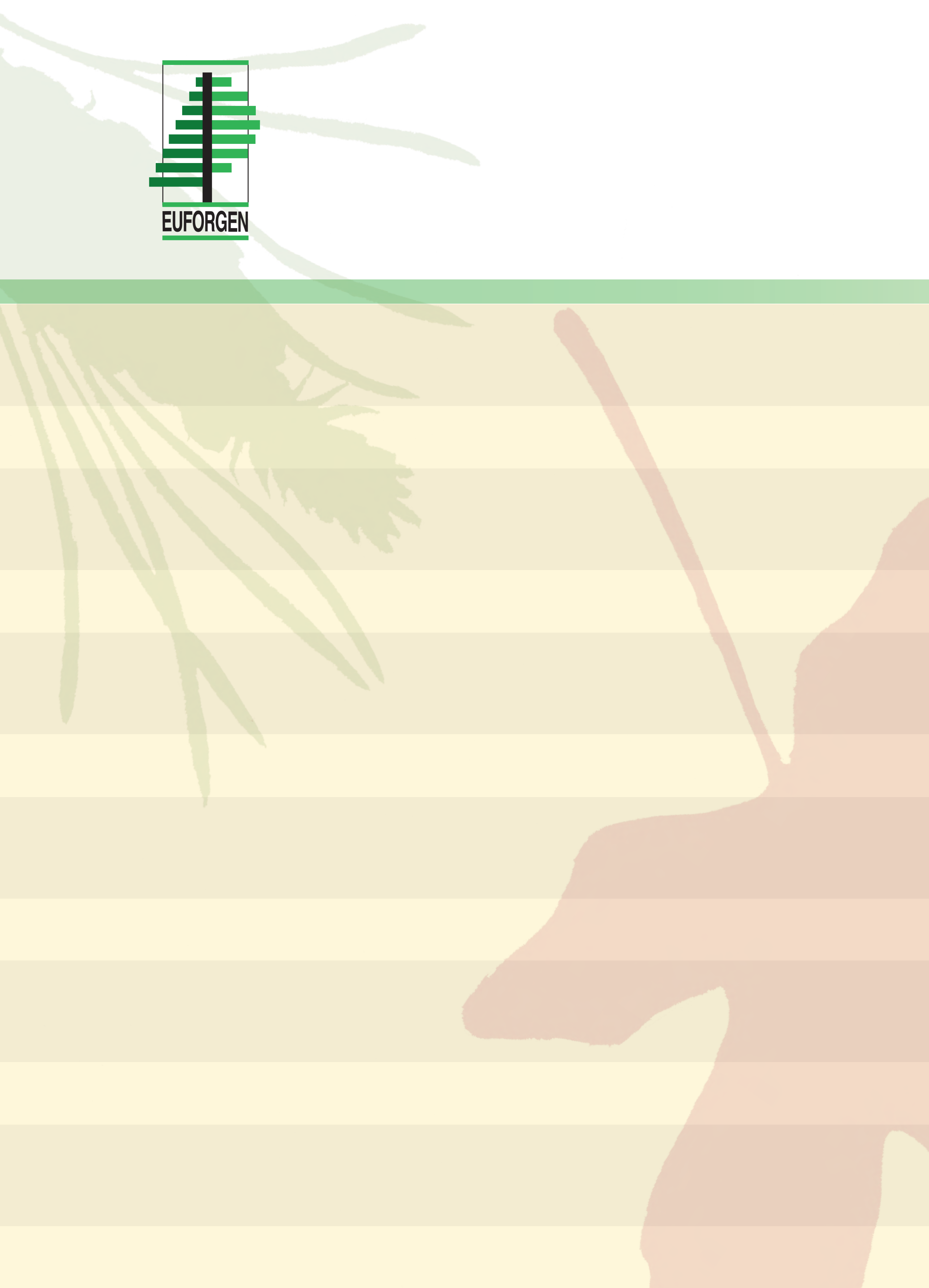
APPENDIX 1

POTENTIAL DECISION CASCADE FOR GENE CONSERVATION UNDER CLIMATE CHANGE: MEASURES, INDICATORS (vers.1.2: Rough draft to give an idea of the recommended decision cascade, detailed indicators for measures have to be elaborated)

o = obligatory indicator (AND); xx/yy/zz = alternative indicators (OR); >%/>>%/>>>%= level of population decline %

Level/ Step	**Measures**	**Indicators**											
		Relevant forest genetic resource (national data)	Conservation unit minimum requirements (EUFGIS, Koskela *et al* 2013)	Criteria for core network (de Vries *et al* 2015)	Criteria for conservation unit genetic monitoring (Aravanopoulos *et al* 2015)	Criteria for complementary genetic monitoring of the units (this report)	Relatve number of reproducing trees declining (% per 10 years)	Absolute number of reproducing trees declining under < minimum requirement	Specific pest, invasive neophyte	Lack of regeneration over > 10 years	Migration barriers, exhausted vertical buffers	High probability for genetic drift	Danger of extinction
0 general													
	prevention from habitat destruction (or rehabilitation)	o											
	restriction against introduction of pest, invasive neophyte etc.	o											
1. *in situ* conservation in genetic conservation units													
	unit establishment	o											
	EUFGIS record		o										
	unit demographic monitoring		o										
	unit included in core network			o									
	unit target of genetic monitoring				x	x							
2. *in situ* silvicultural measures in genetic conservation units													
	regulation of competition or pathogenes		o				>%	y	y				
	artificial regeneration		o							o			
3. *in situ* replacement/reorganisation of genetic conservation units													
	replacement by existing equivalent unit within country x zone		o	o			>> %	y	y	o			
	duplication of unit within surroundings/habitat		o	o			>> %	y	y	o			
	recombining duplicates of similar/near unit within surroundings/habitat		o	o			>>> %	y	y	o		o	
4. *ex situ* assisted migration of genetic conservation units													
	duplication of unit in direction of expected change (2x)			x		x	>>> %	y	y	o	z	z	
	recombining duplicates of unit in direction of expected change (2x)			x		x	>>> %	y	y	o		o	
5. *ex situ* preservation in field													
	genotype collections in conservation orchards, botanical garden networks			x		x		o		o		o	
6. *ex situ* preservation in stasis													
	seed bank, cryoconservation, in vitro conservation			x		x		o		o		o	o



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