A National Forest Tree Gene Conservation Strategy and Action Plan for Ireland

Colin T. Kelleher[a*]

Abstract

Forest Genetic Resources (FGR) are the basis on which the health of future forests are dependent. It is genetic diversity that enables trees to adapt to conditions and optimise their performance to succeed. A lack of diversity increases the vulnerability of a population or species to changing conditions and pathogens, while a greater diversity is a potential buffer against biotic and abiotic change. This paper undertook a review of international practice in FGR conservation and proposes a strategy to implement in an Irish context. Dynamic *in situ* conservation has been adopted as the best practice for the conservation of FGR in most cases. The dynamic approach is often referred to as a “near-nature” approach and the focus is to maintain adaptive potential in natural or semi-natural populations. A network or group of sites is also considered best practice in FGR conservation. This has been implemented in the EUFORGEN pan-European conservation network. Selection of the individual populations or sites to include in the network is dependent on the availability of data. The selection criteria are addressed in the strategy proposed. In order to conserve genetic variation, it is important to be able to assess the actual or potential level of this variation. Where data is lacking, proxies such as climatic conditions can be used. A table of actions for the implementation for the strategy is presented.

Keywords: *Forest Genetic Resources; FGR; Conservation; Genetic characterisation.*

Introduction

Background

Gene conservation involves the maintenance and development of genetic resources. The FAO 2014 report *The State of the World’s Forest Genetic Resources* defines Forest Genetic Resources (FGR) as “the heritable materials maintained within and among tree and other woody plant species that are of actual or potential economic, environmental, scientific or societal value. FGR are essential for the adaptation and evolutionary processes of forests and trees as well as for improving their productivity.” The key components of this definition are that the material is heritable – i.e. that it can be transferred through generations and that the resources are of current or potential value. FGR are the basic ingredients of adaptation. It is genetic diversity that enables

[a] DBN Herbarium and Plant Molecular Laboratory, National Botanic Gardens of Ireland, Glasnevin, Dublin 9.
[*] Corresponding author: colin.kelleher@opw.ie

trees to adapt to conditions and optimise their performance to succeed. A lack of diversity increases the vulnerability of a population or species to changing conditions and pathogens, while a greater diversity is a potential buffer against biotic or abiotic change, such as climate change (Alfaro et al. 2014).

Native or semi-natural forests are a limited resource in Ireland (e.g. see Perrin et al. 2008) and also throughout most of Europe. This is a result of historical over-exploitation and lack of adequate conservation. Semi-natural forests in Ireland are also highly fragmented, with very few large forest areas. This fragmentation can affect the genetic resources within the forest (Ratnam et al. 2014). A study of Irish and European alder populations showed evidence of genetic "bottlenecking" in the populations, which coincides with periods of large-scale deforestation (Cubry et al. 2015). Thus, there is an urgency to characterise and conserve the remaining areas and to support the expansion of semi-natural forest cover and the conservation of FGR.

The strategy presented here deals with conservation of a broad base of genetic resources. A conservation strategy should be cognisant of the needs of the commercial sector, but should not be a breeding programme for elite trees. Elite phenotypes will not necessarily be useful to future change and so a diversity of genes needs to be conserved. This strategy focuses on native tree species (Table 1) with the goal of securing forest genetic resources for future conservation and to create a baseline from which to guide future tree improvement. The native status of some species is still in question, such as *Populus nigra* L.*,* *Populus tremula* L. and *Pinus sylvestris* L., although recent work suggests a restricted population of native *P. sylvestris* may have survived (Roche 2019).

The first question to ask of a conservation strategy is "What do we want to conserve?" Ideally we would conserve everything to have a complete set of indigenous genetic resources. However, this is not possible due to resource constraints and so the strategy will focus on the adaptive potential of species. Thus, the primary aim of the conservation strategy presented here is to conserve the adaptive potential within natural or semi-natural populations. Adaptive potential is the capacity for trees to survive now and into the future and it is essential to enabling species adapt to climate change. This type of conservation strategy is a common approach utilised in other European countries (Graudal et al. 1995, Trivedi et al. 2019) and on a pan-European scale (Koskela et al. 2013, de Vries et al. 2015). This paper reviews the literature on FGR conservation approaches and presents a strategy for potential use in Ireland.

Many initiatives have been undertaken to assess forest genetic resources in Ireland and there are a number of programmes ongoing. Two main reports have provided a valuable synopsis of the current state and potential directions for FGR conservation. Cahalane et al. (2007) prepared an outline strategy to develop and sustain Ireland's FGR. A later report provided an update on the baseline information on the FGR resources available in Ireland (COFORD 2012). The 2012 report was incorporated into a larger report by the FAO on the State of the World's Forest Genetic Resources (FAO 2014). The FAO report summarised the global information on FGR and highlighted that worldwide knowledge on FGR is generally inadequate. While some species such as oak (e.g. *Quercus petraea* (Matt.) Liebl. and *Q. robur* L.) are well characterised others are not covered at all. Although the FAO report takes a global perspective, it also mirrors the situation in Ireland. Very few species have been adequately surveyed and fewer still have been actively conserved. The current paper aims to build on previous studies and propose a FGR conservation strategy in addition to providing a framework in which to implement it. In particular, the impacts of climate change have become increasingly urgent. Irish populations are facing into climate scenarios that may result in a deficiency of winter chilling necessary for bud burst, thus leading to asynchrony of growth. Increased prevalence of pest and diseases are also likely with climate change.

Review of international forest gene conservation strategies

Gene conservation strategies are a relatively new initiative, in particular for tree species, as domestication is still a relatively recent undertaking for most trees. Selection of target phenotypes (such as larger fruit) from genepools has been a common theme since the beginning of agriculture. However, the awareness of genetic resources and the methodical conservation of genetic resources has only been highlighted following increased intensification of agriculture and an increased need for higher yields (e.g. Gepts 2006). In Europe, the increased awareness of the importance of maintaining and preserving biological diversity brought about the establishment of the Natura 2000 network. This EU-wide network of nature protection areas was established under the 1992 EU Habitats Directive (Council Directive 92/43/EEC). Since then the importance of genetic diversity as the core of biodiversity has been emphasised, particularly following increased technological advances in measurement of genetic diversity. The Convention on Biological Diversity (CBD) came out of the "Earth Summit" in Rio in 1992. This convention put a focus on biological diversity and genetic resources and increased the awareness to conserve natural resources. Incorporated within the CBD, the Global Strategy for Plant Conservation provides a framework in which to conserve genetic resources of crops and their wild relatives.

An increased awareness of the potential of genetic resources has led to the development of conservation strategies to maintain and enhance these resources. In general, the objective of gene conservation strategies for forest trees is to maintain the adaptive or evolutionary potential of the populations being considered. In short, the aim is to safeguard future adaptability. When designing a conservation strategy there are a number of common themes in the literature relating to the selection and location of the conservation populations. Rotach (2005) provides a summary of steps to develop a conservation programme and this involves establishing objectives, setting priorities, selection of material to conserve and setting up monitoring. Objectives need to be established regarding the purpose of the conservation network. An initial consideration is whether the conservation populations should be *in situ* or *ex situ*. Following this, information is gathered in order to enable selection of the appropriate species and populations. Finally, a management plan should be prepared and a monitoring programme put in place.

The longevity of trees is a unique feature of their biology that needs to be taken into account when considering conservation of FGR. Based on a simplistic model of the current IPCC predictions of a 0.2 °C decadal increase in global temperatures, an individual tree could be exposed to an increase of 3 °C over a lifespan of 150 years (Kelleher et al. 2015). This is not as much of a concern for annual plants and crops as they can adapt and move more quickly, but for long-lived species, it could have dramatic impacts (Aitken et al. 2008).

In situ versus ex situ conservation

In situ methods of conservation are those that conserve species or populations at their original site. *Ex situ* populations are defined as forests established outside the original habitat of the genetic resource. In general, the most cost-effective and potentially the most practical approach for forest trees is that of *in situ* conservation (FAO et al. 2004). The cost of establishing *ex situ* populations can be prohibitive, but *ex situ* conservation may be particularly useful for conserving relict or rare and threatened populations (e.g. Vander Mijnsbrugge et al. 2005). *In situ* approaches also have an advantage of potentially using a single site for multiple species. *Ex situ* approaches are often static, in that genetic resources do not have the potential to evolve. Examples include living specimens such as clonal orchards or individual trees in arboreta and botanic gardens or preserved material such as those in cryogenic storage.

A consensus favouring "dynamic" or "near-nature" gene conservation for forest trees is evident from the literature (e.g. Eriksson et al. 1993, Kelleher 2018). The dynamic approach facilitates evolutionary processes and generation turnover, including regeneration. While the dynamic approach can be undertaken with *ex situ* populations, it is amuch more common method for *in situ* conservation. An example of the dynamic approach is the EUFORGEN (European Forest Genetic Resources Programme) initiative in which information on forest tree populations from many European partners has been collated into a GIS database – the EUFGIS (European Information System on Forest Genetic Resources) database (Lefèvre et al. 2013). A minimum set of requirements was established for incorporation of units (populations) into the EUFGIS system, thus creating a network of high conservation potential (Koskela et al. 2013). This database includes details of over 3,600 FGR conservation units in Europe, including a number of Irish populations. The EUFGIS database, through the support of EUFORGEN, allows for populations to be mapped and monitored over time. This is a key tool in conservation and monitoring of FGR in Europe and is being harnessed to develop action plans for FGR conservation in many European countries such as in the UK (Trivedi et al. 2019).

Related to the question of *in situ* versus *ex situ* are the concepts of assisted migration and assisted gene flow. These are human mediated activities, assisted migration being the mass movement of a species or population from a vulnerable site to a more suitable site (*ex situ*), while assisted gene flow is the use of pre-adapted genotypes and genes to adapt *in situ* populations to future climate change. These have the potential to mitigate maladaptation to climate change (Aitken and Whitlock 2013). The potential importance of assisted migration and assisted gene flow in adaptation to the impacts of climate change is also stressed by the Intergovernmental Panel on Climate Change report (IPCC 2014). However, the utility of assisted migration and the inherent risks need to be fully explored before it is adopted as a conservation measure.

Selecting species and populations

Selecting species

Selecting the species to conserve depends on multiple factors and the overall objective of the FGR conservation strategy. In regions with large tree floras (such as tropical regions), the species selection is much more relevant due to the large numbers of species. However, in temperate regions where the number of species in the flora is limited, then all species tend to be selected. The species selection and conservation implementation can be prioritised based on, for example, economic importance or on rarity. Rarity or threatened status can be assessed using criteria similar to those used by the International Union for Conservation of Nature (IUCN) to estimate threatened status, such as population demographics and population ranges (IUCN 2012). An initiative in New Brunswick, Canada prioritised species based on their rarity and then created a strategy for each species (Loo 2003). Graudal et al. (1995) selected all native tree and shrub species for inclusion in a Danish conservation programme.

Adaptive traits

It is important to note that current populations are not necessarily optimal or maximally fit in terms of their survival. Species and populations are fluid and are continuously changing. While the lifespan of a single tree varies from tens to hundreds of years, that of a population can be thousands (such as those that have developed since the retreat of ice-sheets following the last glacial maximum in Europe), and the lifespan of a species can be millions of years. What is useful for survival now may not be so in future. For this reason it is important to select multiple populations to conserve. Eriksson et al. (1993) suggest many small populations are preferable to one big population.

To conserve FGR, ideally the whole range of adaptive variation of a species should be selected. For example, variation in growth, form, wood composition, phenology, drought/waterlogging tolerance, disease and herbivory tolerance etc. Selection based on phenotypes is the current practice used in selecting elite trees for improvement programmes. However, while improvement programmes often involve selections based on form and wood quality, this is not suitable for adaptive potential. Information on adaptive traits is rarely available unless extensive provenance trials have been performed on all species. Selecting populations can be a difficult task, in particular as little is known about the genetic composition of most populations. In the absence of knowledge on adaptive traits, substitute proxies can be used.

Selection using molecular characterisation

Molecular markers can be used as proxies for adaptive traits, in particular where the genes governing the expression of a trait are known and targeted. However, often this is not known and so neutral molecular markers are used. Neutral molecular markers are developed from regions of the genome that are assumed to be under no selective pressure. They are prone to random drift and thus accumulation of mutations tends to be greater than in regions that are under selective pressure (Holderegger et al. 2006). Thus, while they do not show variation for adaptive traits they are extremely useful for assessing population history and tracking demographic changes (Kirk and Freeland 2011). Neutral molecular markers are routinely used to assess levels of diversity and to determine provenance, such as deciphering post-glacial migration histories of trees - for example, extensive studies have been undertaken for European trees by Petit et al. (2003). Molecular markers can be used to determine allelic richness and uniqueness of a population, thus aiding in selecting a suitable range of populations (Petit et al. 1998). As molecular techniques have developed the use of molecular markers has become a standard initial step in characterising the genetic composition of populations (Rajora and Mosseler 2001, Nybom et al. 2014). Further development of molecular markers targeting adaptive traits such as bud burst (Alberto et al. 2013) is enabling direct measures of genetic diversity within adaptively significant genes. Molecular markers are also being investigated as potential indicators of phenotypes as phenotypic characterisation is often expensive and time consuming. A study on *Picea sitchensis* (Bong.) Carr. utilised genetic variation to develop sampling strategies to capture the genetic diversity in its native range in British Columbia, Canada (Gapare et al. 2008). This study showed very little genetic structure within core populations, while peripheral populations were much more highly differentiated. These results highlight the levels of genetic heterogeneity across a range and also stress the importance of taking account of peripheral and marginal populations when conserving FGR (Fady et al. 2016).

Proxies of adaptive variation - climate

When little is known about adaptive variation or genetic variation, other proxies can be utilised. An approach to create a pan-European network of conservation units using climate as a proxy was proposed and utilised for a set of target species as part of a EUFORGEN initiative (de Vries et al. 2015). This took advantage of the data stored in EUFGIS to analyse the potential for establishing a network of conservation units. The core network units were selected using climate as a proxy of adaptive potential. The EUFGIS units were overlaid on a detailed environmental map of Europe (Metzger et al. 2005, Metzger et al. 2013) to determine coverage of the units and one unit per climatic zone per country was selected. All EUFGIS units would potentially be suitable for conservation purposes due to the minimum requirements for inclusion (Koskela et al. 2013). Graudal et al. (1995) also used climate and ecological conditions as a proxy in the selection of units to develop a network of conservation stands for forest tree species in Denmark and a similar approach was proposed in Flanders (Vander Mijnsbrugge et al. 2005). Climate proxies can also be used to identify species and populations on the periphery of a biogeographic range or climatic type (Fady et al. 2016, Hampe and Petit 2005).

Proxies of adaptive variation - ecology

Life history or biological traits, such as geographic range, pollination and dispersal dynamics including clonal growth will affect the conservation of genetic resources. Conserving meta-populations that have no possibility of gene transfer due to restricted gene flow could increase levels of inbreeding. Use of life history traits was undertaken for forest trees in Norway in order to classify genetic resources as viable or vulnerable (Myking 2002). Graudal et al. (1995) also used the biology and distribution of each species. However, this is dependent on reliable ecological and life history data being available for each species.

Management and monitoring

Management of conservation units should aim to reduce the risk of poor performance and mortality and should facilitate and promote natural regeneration. The dynamic conservation approach discussed in this paper emphasises a system with minimal intervention. However, where necessary, such as in cases where natural regeneration is not occurring, active intervention should be undertaken (Koskela et al. 2013). Examples include cutting out invasive and out-competing species, selective thinning, and propagation.

Management of a stand can significantly affect the genetic structure of populations (Ratnam et al. 2014). Ratnam et al. (2014) review evidence from boreal, temperate and tropical forests and while many studies do not show any significant negative impacts, fragmentation and clear-cut felling were shown to reduce the overall diversity in the populations. The extent of the impacts depend on the demographics of a population and the biology of the species. Knowledge of the biology of a species is key to effective management practices. Thus, management plans need to be developed to keep populations at favourable conditions for continued regeneration (see Rotach 2005).

A key element in the management must be periodic monitoring (de Vries et al. 2015, Kelleher et al. 2015). A baseline of demographic information needs to be established to enable monitoring. Monitoring is of particular importance in light of climate change to assess, for example, changes in demographics and regeneration within a target species, threats due to pest and disease, and competition with other species or the invasion of alien species. Indeed, Aravanopoulos et al. (2015) have suggested periodic genetic monitoring should be part of the overall monitoring of the pan-European conservation network. Genetic monitoring can be used to provide indicators of change over time (Graudal et al. 2014).

Promoting awareness of the importance of FGR

To have support for FGR conservation, an important element in many strategies is to increase the level of awareness and understanding about the potential of FGR. Loo (2003) noted that this was especially important for species or populations on private sites, where the land owner needed encouragement to allow a conservation programme to be implemented. Geburek and Konrad (2008) list the lack of public awareness as a major hindrance to the implementation of FGR conservation. They argue that forests are seen by the public as self-sustaining and so not needing input. The conservation of a single organism is far easier to portray than the genes within a forest. The promotion of FGR can be undertaken using demonstration plots to show the importance of species and provenance selection.

Current status in Ireland

The current status and capabilities for FGR conservation in Ireland have been previously reviewed in Cahalane et al. (2007) and the COFORD National Consultative Committee on Forest Genetic Resources report (2012). In short, Ireland is well positioned in terms of capabilities and knowledge to undertake a comprehensive FGR conservation programme. A national committee has been established under the COFORD council to steer and advise on the conservation of FGR in Ireland. A point emphasised in both the Cahalane et al. (2007) and the COFORD (2012) report is the need to maintain and increase capacity in the FGR sector, both in terms of funding and human resources. This is also recognised by the government report on forest research – FORI (DAFM 2014).

Review of knowledge and capabilities on forest genetic resources in Ireland

FGR conservation is recognised as a critical issue in maintaining a viable improvement programme and in safeguarding forests for the future. In order to allow for a conservation programme the following elements are crucial; human capacity, infrastructural capacity, knowledge and funding. In terms of human capacity, there is FGR expertise in government and higher education institutions and in private and state companies. The infrastructural capacity was reviewed by Cahalane et al. (2007) and the core set of facilities include; a National Tree Seed Centre (Coillte), seed testing facilities (DAFM), field trials, a database of provenance and field trial results in NATFOREX (www.natforex.ie), nurseries, plantations, provenance and species demonstration plots, research facilities in state laboratories (e.g. Teagasc and the National Botanic Gardens, including a National Forest Tree DNA Bank), and research facilities in Universities and Institutes of Technology.

A review has also been made of institutions involved in the use and conservation of FGR in Ireland (COFORD 2012). These can be summarised under the headings of regulation, research and collections. The institutions responsible for regulation are government bodies within the Department of Agriculture, Food and the Marine (Forest Service) and within the Department of Culture, Heritage and the Gaeltacht (the National Parks and Wildlife Service). Those involved in research include academic institutions and government bodies such as Teagasc and the National Botanic Gardens. Collections of genetic resources are either state owned or under private ownership. State-owned resources include natural, semi-natural and planted collections, and research collections. Plantations of native trees and forests are also maintained by NGOs, such as the Woodlands of Ireland.

Some of Ireland's native species have designated seed stands, which are used for propagating putatively native material. Depending on the source and history of the seed stand, these may be suitable as FGR conservation units. Approximately seven of the native tree species have significant seed stands (Cahalane et al. 2007, COFORD 2012).

Assessment of ecological and climatic envelopes for native species

Species Distribution Models (SDMs) correlate extant species distributions with climatic and environmental variables to determine a bioclimatic envelope (a range of conditions in which a species grows). This can be used to assess future changes in distribution ranges when models of climate change are simulated. A study assessing the impact of climate change on biodiversity in Ireland utilised SDMs to assess the changes in distribution of protected species and habitats (Coll et al. 2012). The study used species occurrence data along with climatic and topographical data at each location to develop a model of the species distribution or the bioclimatic envelope. This type of approach should be undertaken for all native tree species to provide assessments of current conditions and future impacts due to climate change. Another modelling approach involving the use of SDMs and data from common garden experiments could help refine potential performance by incorporating phenotypic plasticity into the assessment (Benito Garzón et al. 2019). Additional data, for example, soil type or ecological traits such as Ellenberg values could also be used to increase the accuracy of the bioclimatic envelope models. A combination of both climatic and ecological suitability has been utilised in the CLIMADAPT tool, which is a decision support tool for foresters in selecting suitable species for particular areas (Ray et al. 2009). The CLIMADAPT tool assesses current and future predicted site suitability for native species including; alder, ash, aspen, downy birch, pedunculate oak, Scots pine, sessile oak and silver birch.

The EUFORGEN pan-European conservation network utilised a climate approach to select populations which encompassed all geographical and climatic areas in Europe (de Vries et al. 2015). Some Irish conservation units were included in this network (Figure 1). Based on the climate models used, Ireland contains one major climatic zone (cool and moist), with other zones being more restricted to higher altitude areas. This agrees with the current seed zone treatment for Ireland, as it is considered just one seed zone or region of provenance.

In addition to ecological and climatic preferences, biological traits are important to take into account when conserving a population. Myking (2002) and Graudal (1995) utilise life history traits to assess vulnerability of a species or population. For example, dispersal ability and pollination biology are important in the context of population fragmentation. Irish forests, like many other European forests, are highly fragmented. Fragmentation can significantly impact the dispersal and genepool of insect pollinated trees, and also has been shown to increase inbreeding even in wind pollinated trees (Jump and Penuelas 2006). While the majority of pollen flow tends to be localised, it is dependent on the size of populations and can disperse kilometres away from the source (Bacles and Ennos 2008, Gallagher et al. 2013). Habitat preferences are also important for selecting suitable sites and facilitating forest expansion or regeneration. Another issue to take into account is whether the species is dioecious. If so, then sex ratios need to be considered and monitored. A list of some relevant biological traits for native trees is presented in Table 1. These traits can aid in decisions around the establishment of FGR populations and conservation networks.

Gaps needing further attention

<u>Funding and human resources</u>

In order to implement a FGR strategy, it is vital to have staff allocated to the tasks. The implementation of conservation strategies is often hampered by the availability of the necessary resources (e.g. Schmeller et al. 2014). Ample expertise is available to undertake the tasks laid out in Table 2 below but specific effort needs to be allocated

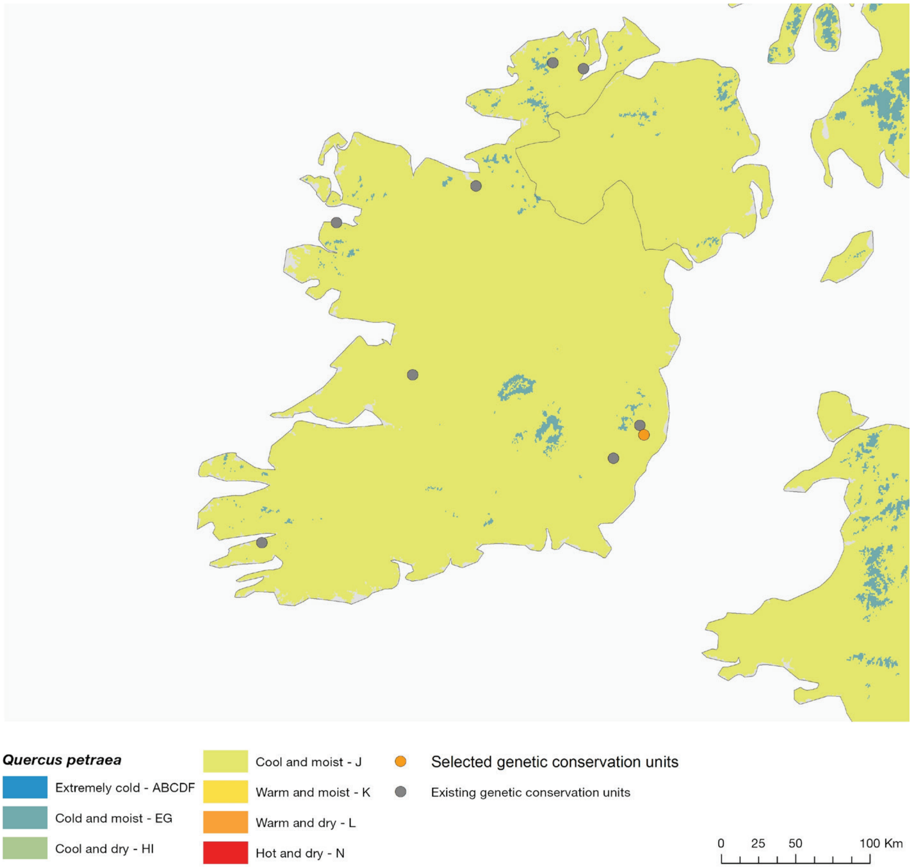

Figure 1: *A map of Ireland showing simplified climatic zones based on Metzger (2005, 2013). EUFGIS genetic conservation units for Quercus petraea are illustrated. Ireland only consists of two zones, cool and moist and cold and moist. The selected site is in the pan-European network. Map courtesy of Michele Bozzano, Bioversity, EUFORGEN secretariat.*

to the tasks. In addition to devoting staff time, it will also be important to allocate funding for further research and completion of assessments, e.g. for GIS analyses and for molecular characterization of populations. Sustaining and developing our FGR capacity needs investment now to secure these resources for the future. Support for updating and creating inventories of genetic resources is one of the actions in the National Biodiversity Plan (Government of Ireland, 2011).

Molecular characterization of FGR

There is increasing emphasis on the use of molecular markers for genetic characterization, breeding, and monitoring. Where available, molecular markers can be used in the selection of which populations of wild species to conserve (Petit et al. 1998). This approach is

Table 1: *A list of tree species to target for FGR conservation with some relevant biological information. Native status as in Webb et al. (1996).*

Species	Common name	Sex	Pollen dispersal	Seed dispersal	Clonal	Distribution
Alnus glutinosa (L.) Gaertn.	Black alder	Monoecious - separate catkins	Wind	Wind	No	Riparian/water
Arbutus unedo L.	Strawberry tree	Monoecious	Insect	Gravity/animal	No	Restricted
Betula pendula Roth	Silver birch	Monoecious - separate catkins	Wind	Wind	No	Widespread
Betula pubescens Ehrh.	Downy birch	Monoecious - separate catkins	Wind	Wind	No	Widespread
Corylus avellana L.	Hazel	Monoecious - separate catkins	Wind	Gravity/animal	No	Widespread
Fraxinus excelsior L	Ash	Dioecious plants and flowers	Wind	Wind	No	Widespread
Ilex aquifolium L.	Holly	Dioecious plants	Insect	Gravity/animal	No	Widespread
Malus sylvestris (L.) Mill.	Crab apple	Monoecious	Insect	Gravity/animal	No	Scattered
Pinus sylvestris L.[a]	Scots pine	Monoecious – separate catkins	Wind	Gravity	No	Widespread
Populus nigra L.[a]	Black poplar	Monoecious - separate catkins	Wind	Wind	Yes	Riparian/water
Populus tremula L.[a]	Aspen	Monoecious - separate catkins	Wind	Wind	Yes	Riparian/water
Prunus avium L.	Wild cherry	Monoecious	Insect	Gravity/animal	Yes	Scattered
Prunus padus L.	Bird cherry	Monoecious	Insect	Gravity/animal	No	Scattered
Quercus petraea (Matt.) Liebl.	Sessile oak	Monoecious - separate catkins	Wind	Gravity/animal	No	Widespread
Quercus robur L.	Pedunculate oak	Monoecious - separate catkins	Wind	Gravity/animal	No	Widespread
Salix alba L.[b]	White willow	Monoecious - separate catkins	Insect/wind	Wind	Yes	Riparian/water
Salix caprea L.	Goat willow	Monoecious – separate catkins	Insect/wind	Wind	No	Scattered
Salix cinerea L.	Sally	Monoecious - separate catkins	Insect/wind	Wind	Yes	Scattered
Salix fragilis L.[b]	Crack willow	Monoecious - separate catkins	Insect/wind	Wind	Yes	Scattered
Salix triandra L.	Almond willow	Monoecious - separate catkins	Insect/wind	Wind	Yes	Riparian/water
Salix viminalis L.	Osier	Monoecious - separate catkins	Insect/wind	Wind/water	Yes	Widespread
Sambucus nigra L.	Elder	Monoecious	Insect	Gravity/animal	No	Widespread
Sorbus aria Crantz[b]	Whitebeam	Monoecious	Insect	Gravity/animal	Apomictic	Scattered
Sorbus aucuparia L.	Rowan	Monoecious	Insect	Gravity/animal	Apomictic	Widespread
Sorbus hibernica	Irish whitebeam	Monoecious	Insect	Gravity/animal	Apomictic	Endemic species
Taxus baccata	Yew	Dioecious plants	Wind	Gravity/animal	Yes	Scattered
Ulmus glabra	Wych elm	Monoecious	Wind	Wind	No	Scattered

[a] Native status uncertain.
[b] Introduced.

Table 2: *Table of actions for implementation of an FGR strategy. The order of the tasks might vary depending on the information available.*

Task	Details
Establish an advisory committee to guide the strategy	An advisory committee already exists in the form of the COFORD Council and a specialist working group on FGR.
Involve stakeholders and increase awareness	In particular, NPWS and Forest Service, who are the main holders of FGR.
Set objectives and targets	Set objectives if they are other than to maintain a broad base of FGR.
Select species	Select species based on objectives.
Biological assessment	Assess bioclimatic envelopes and level of threat.
Genetic assessment	Where available utilise genetic data to categorise populations.
Genetic characterisation	Genetically characterise populations, where data is needed.
Select populations	Utilise criteria presented in this strategy to select suitable populations.
Assess populations	Assess the status of the populations being selected to provide a baseline for monitoring and assess threats.
Create management plans	Create these for each species and population.
Set monitoring protocols	Decide on parameters and the frequency of monitoring and the level of monitoring needed.

promoted in the EUFORGEN pan-European strategy for genetic conservation of forest trees (de Vries et al. 2015). Molecular markers can be used to determine and delimit provenance and assess genetic diversity in populations (García et al. 2018, Nybom et al. 2014). Molecular markers have been used extensively to study population dynamics of trees in Europe (Petit et al. 2002, Petit et al. 2003) and have been used to place Irish populations of oak (Kelleher et al. 2005, Kelleher et al. 2004a, Kelleher et al. 2010, Lowe et al. 2005) and Alder (Cubry et al. 2015) in a European context.

To date there has been a limited number of molecular genetic studies undertaken on native Irish trees. Studies characterizing Irish populations include those on *Alnus glutinosa* (L.) Gaertn. (Cubry et al. 2015), *Fraxinus excelsior* L. (Heuertz et al. 2004), *Populus nigra* L. (Keary et al. 2005), *Quercus petraea* and *Q. robur* (Kelleher et al. 2005, Kelleher et al. 2004a), *Salix caprea* L. (Perdereau et al. 2014) and *Sorbus hibernica* E.F.Warb. (Cowan et al. 2008). Other, as yet unpublished, studies have been undertaken on *Pinus sylvestris* and *Betula* spp. The results from these studies can help in selecting populations to include in a gene conservation network. To take the example of the alder study (Cubry et al. 2015), the molecular characterisation from this study revealed two distinct alder lineages in Ireland, one originating from the south – either from the Iberian Peninsula or the Bay of Biscay, and another from the east – possibly from the Carpathian Mountains. These distinct lineages were not previously known about before the molecular analysis, but this information can now be used to guide selection of representative populations to conserve based on their distinct post-glacial colonisation histories.

Threat assessments - climate change and invasive species

Climate change will impact our forests and subsequently their genetic resources. In some areas climate change may result in increased growth and more suitable climates for growing trees. For example, *Quercus ilex* L. is benefiting by increasing its range northwards (Delzon et al. 2013). However, this may result in reduced timber quality in species due to more rapid growth. There are a lot of uncertainties regarding the impacts of and adaptation to climate change in trees, in particular for extreme weather events. From an Irish perspective more knowledge is needed regarding the potential impacts and the use of empirical data should help guide future provenance and species selection (Black et al. 2010). For example, a reduction in the number of frost days can affect bud burst (Chuine et al. 2010). This is an important consideration for the mild temperate climate in Ireland. Reactions to lack of chilling temperatures can be species specific and two native species (*Betula pubescens* Ehrh. and *Populus tremula*) were shown experimentally to delay bud burst due to lack of chilling (Pletsers et al. 2015). However, these responses need to be assessed in other species. Provenance trials and species tests need to be continually updated to respond to climate change. The source material for provenance trials needs to have a large genetic base in order to enable future fitness.

Forest resilience and the capacity of trees to withstand biotic and abiotic pressures is dependent on biodiversity, so it is vital to maintain biodiversity including genetic diversity to increase the possibility of survival into the future (Thompson et al. 2009).

The threat of invasive species is made more urgent with climate change. The most notable example of an invasive species in Ireland is that of *Rhododendron ponticum* L. in oak woods. The removal and treatment of invasive species such as *R. ponticum* is costly and more invasive species are predicted with climatic changes. Monitoring of invasive species in woodlands needs to be improved and maintained.

Gaps in capacity for FGR conservation

One notable gap in capacity in an Irish context is cryopreservation. Cryopreservation is particularly useful for rare and threatened populations or species in which *in situ* preservation of individuals is impossible. There is no urgency for this type of a facility for FGR in Ireland as no tree species are listed in the current Flora Protection Order (Flora (Protection) Order, S.I. No. 356/2015). However, it is something to develop in time to keep in line with best international practice (Theilade et al. 2004).

A strategy for Ireland

The suggestions in this paper need to be agreed through consensus of multiple stakeholders. A suitable instrument to undertake this is the Department of Agriculture, Food and the Marine COFORD Council or a dedicated FGR advisory committee as suggested by Cahalane et al. (2007) and COFORD (2012). To create a solid basis for the proposed strategy and to secure its implementation, relevant stakeholders should include forestry professionals from the commercial sector (public and private), the research sector, and interested government and non-government organisations at all levels of forestry. The proposal below focuses on the development of a national network of sites for FGR conservation. This is analogous to the pan-European network, which has been partially implemented across EUFORGEN partners (de Vries et al. 2015).

Define objectives and set targets

Objectives and targets need to be set for each species. These will vary depending on the current utility of a species. For species that are currently in improvement programmes (e.g. alder and birch) or are currently commercially used, the objectives will be more than maintaining genetic diversity. For these species, the improvement programmes will form a part of the objectives and targets, in particular they can supplement *in situ* conservation with *ex situ* collections. For most species the objective should be to maintain the adaptive potential of the species within Ireland. This can be done by selecting populations that represent the range of genetic diversity within the country. Ideally, this should also be done on an island-wide basis, to include both Northern Ireland and the Republic of Ireland. As Ireland is considered a single seed zone, and our tree species tend to grow in a limited set of climatic zones (e.g. Figure 1), the level of climatic coverage will be reduced. Replication of one site per species per province (where available) should be a minimum target. Some species will have more limited distributions and will not be present in each province, e.g. *Salix phylicifolia* L. is restricted to a small number of sites in Sligo and Leitrim.

An optimistic aim would be to have the programme outlined below implemented by 2021 so as to coincide with the end of the current National Biodiversity Plan. This strategy also aligns with Target 9 of the Global Strategy for Plant Conservation, which aims to conserve genetic diversity of crops and wild relatives (GSPC 2012).

Species selection
From a forestry perspective, the commercial species should be prioritised for action. Some species have already been prioritised as commercially important by Cahalane et al. (2007). Based on commercial utility, the availability of molecular data and the existence of seed stands, a conservation programme for the following species should be undertaken first; alder (*Alnus glutinosa*), ash (*Fraxinus excelsior*), birch (*Betula pendula* and *B. pubescens*), oak (*Quercus petraea* and *Q. robur*), Scots pine (*Pinus sylvestris*) and yew (*Taxus baccata* L.). In the case of ash, there is also scope to screen for genotypes tolerant to ash dieback (Harper et al. 2016). Much of the work has already been undertaken for oak and this can be used as a model case to guide the other species initiatives. For example, sites have been selected and entered into the EUFGIS database for oak. There is also a significant amount of genetic data available for oak populations in Ireland (Kelleher et al. 2005, Kelleher et al. 2004a, Kelleher et al. 2004b, Lowe et al. 2005). If the EUFGIS database is adopted as a step in the process, then the focus needs to be placed on selecting the sites for inclusion.

Selecting populations for a network
To select populations or units a set of criteria similar to those of other reports can be used (De Vries et al. 2015, Koskela et al. 2013). Selection should be based on prioritizing *in situ* sites and selecting sites based on size of the unit, including the number of reproducing trees (more trees being better), public ownership in preference to private ownership and a preference for sites with information from genetic studies or provenance tests. In addition, intervention in the form of thinning, removal of invasive species and collection of seed should be allowed provided it aligns with the conservation objectives of the overall site.

One option is to create units within current natural reserves or Natura 2000 sites. This will need cooperation and consultation with the National Parks and Wildlife Service (NPWS), in particular to agree management plans as the objectives of conservation and FGR conservation may differ.

In order to select units it will be necessary to undertake a GIS exercise to cross reference multiple data sources, such as species distribution data, National Forest Inventory data, climatic and soils data. Species distribution data are available from multiple sources, including the National Biodiversity Data Centre[1], the Botanical Society of Britain and Ireland[2] and the National Parks and Wildlife Service[3]. A large-scale project by Perrin et al. (2008) has gathered data specific to native

[1] Available at http://maps.biodiversityireland.ie/#.
[2] Available at http://bsbidb.org.uk/maps/.
[3] Available at http://www.npws.ie/maps-and-data.

woodland. This project provides excellent baseline data on species composition and soil for each location surveyed and has incorporated this into an MS Access and ArcGIS database.

In addition to selecting populations on a climatic and geographical basis, there may be populations in Ireland that are particularly unique in a broader biogeographic context. This is seen as a national responsibility in FGR conservation (Schmeller et al. 2014). For example, Ireland contains populations of *Arbutus unedo* L. at the northern edge of the species range in the south west of Ireland. These may be particularly useful in selecting future trees for more northerly climates and will be of interest to other European countries, such as Spain and Portugal, who both contain large populations of *Arbutus unedo*. The tea-leaved willow (*Salix phylicifolia*) is found at the southern end of its distribution in Ireland. This species is also likely to have unique genotypes compared to populations in the core of its range.

Management plans

Management plans need to focus on maintaining the FGR of the targeted species, but sites can and often will contain multiple target species. For many populations a baseline of information will already be available, in particular for those designated seed stands or for populations already input into the EUFGIS database (Lefèvre et al. 2013). The baseline information should include the following: details of the site, such as location coordinates, area, ownership; the target species; demographics of the population; additional information such as genetic characterisation; interventions allowed; responsible authorities; budget and human resources (see Rotach (2005) for further details).

Monitoring

The monitoring protocol can be built into the management plan. Monitoring is undertaken to assess the conservation status of the unit over time and to insure that favourable conditions are maintained for FGR conservation, for example, the maintenance of natural regeneration (Koskela et al. 2013). The frequency of monitoring will depend on the species, but a guideline of 5- to 10-year cycles of monitoring has been indicated by EUFORGEN for the pan-European network. Monitoring needs to take account of indicators or evidence of natural regeneration, changes in species composition, influx or spread of invasive species, diseases and pests.

Monitoring of the overall progress of FGR and changes in international practices needs to be reviewed regularly to keep pace with best practice. There has been an increased focus on the potential for genetic monitoring and indicators have been developed to track changes in genetic diversity over time (Fussi et al. 2016, Graudal et al. 2014).

Climate change preparedness and threats due to invasive species

While climate change predictions and impacts remain uncertain, current predictions for Ireland suggest a warmer and wetter climate in the future (e.g. Christensen et al. 2011). Results from phenological gardens running more than 30 years have shown changes in phenology in the form of bud burst in trees in Ireland (Donnelly et al. 2006). This change results in a longer growing season, which in turn can lead to increased growth. However, if our climate becomes milder the lack of sufficiently cold winters can also affect bud burst. Although the interaction of temperature and photoperiod is complex and variable depending on the species, a lack of sufficient chilling can inhibit phenological responses such as bud burst (Körner and Basler 2010). It has already been noted that inadequate chilling has been shown experimentally to slow the progress of bud burst for birch and aspen (Pletsers et al. 2015). This can have subsequent implications on the length of a growing season. On the contrary, disruption of bud burst could also lead to late frost damage where it occurs asynchronously with weather patterns.

An increase in rare extreme events such as storms is also expected with climate change. Thus wind throw will likely become a greater issue and particularly for Ireland as it is so exposed to the Atlantic.

Most of the reporting and commentary on climate change and forestry is negative. However, an important positive point is that forestry is a mitigating factor for climate change, due to carbon sequestration (e.g. Bonan 2008). This has been noted for afforestation schemes in the case of Irish forestry (Hendrick and Black 2009).

Although not completely dependent on climate change, increases in the spread of invasive species, pests and diseases are likely in future. Monitoring of invasive species, both native and alien, including an assessment of their potential or actual impact on FGR, needs to be ongoing. Similarly for pests and diseases, international links will be crucial to monitor the movement of biotic threats.

Promoting the importance of FGR for the public and forestry practitioners

The importance of FGR needs to be clear to policy makers, forestry practitioners and the general public. For policy makers it is important that they understand the commitment needed to maintain our genetic resources in terms of funding and human capacity. Forestry practitioners should understand the role of FGR conservation within breeding programmes. The general public need be made aware so as to continue supporting initiatives to maintain and conserve FGR.

There are no national initiatives focused on promoting the importance of FGR (COFORD 2012). While the importance and the utility of FGR is taught in some universities, it has not infiltrated into mainstream dialogue. Potential opportunities to increase the awareness of FGR are through NGOs such as Crann, Woodlands of

Ireland, the Native Woodland Trust and the Forest Genetic Resources Trust (FGRT).

Geburek and Konrad (2008) suggested that demonstration plots are a very useful way of illustrating the importance of FGR to forestry practitioners. The research plots in the JFK Arboretum, New Ross, Co. Wexford were established for such demonstration (Kelly 2013). They are an excellent resource that show the importance of selecting the correct species and also illustrate the importance of provenance selection. However, they need investment to extract existing data, to maintain their condition and to continue establishing new trials.

Other measures

As suggested by Cahalane et al. (2007), the use of home-sourced Forest Reproductive Material (FRM) should be encouraged, for example, through increased premiums in forestry grants for use of native certified material. An emphasis on home sourced material will also help to develop the economic viability of the forestry sector. Use of native material could particularly apply to roadside planting and to rural development and would link with the protection of genetic resources as listed in Target 3 of The EU Biodiversity Strategy to 2020. Increasing the demand for native material will increase the incentive for nurseries to utilise and conserve native FRM.

Ireland needs to be prepared for dialogue with other European countries in relation to assisted migration. While many of our native trees will not be dramatically impacted by climate change in the short to medium term, populations of similar species in southern Europe will become extinct. Thus the movement of these populations is going to become an increasingly pressing issue. This may involve countries combining efforts to safeguard and share genetic resources and assisted migration may be part of the solution (IPCC 2014).

A list of actions

In order to facilitate implementation of this strategy, a set of steps have been summarised into a table of actions (Table 2). The order of these steps may not necessarily follow the order laid out in the table. This will depend on the availability of information. These actions are dependent on suitable funding and allocation of staff to undertake the work necessary.

Conclusion

Forest Genetic Resources (FGR) are the basis on which the health of our future forests are dependent. Taking a simplistic view, the greater the genetic diversity the greater the potential for adaptation and utilisation in future. A review of international best practice was undertaken in order to develop a strategy to conserve FGR in Ireland. The best practice is to set up a network of forest sites *in situ* to maintain adaptive potential in natural or semi-natural populations. The set of actions for implementation of a national FGR conservation programme presented would protect this resource..

Acknowledgements

This review and strategy was carried out as part of ForGen – Forest Genetic Resources Research Programme. Funding for this research was received from the Department of Agriculture, Food and the Marine, Ireland under the Conservation of Genetic Resources Grant Aid Scheme (project 11/GR/12) and the COFORD Science Technology and Innovation Platform.

References

Aitken, S.N., Yeaman, S., Holliday, J.A., Wang, T. and Curtis-McLane, S. 2008. Adaptation, migration or extirpation: climate change outcomes for tree populations. *Evolutionary Applications* 1: 95-111.

Aitken, S.N. and Whitlock, M.C. 2013. Assisted Gene Flow to Facilitate Local Adaptation to Climate Change. *Annual Review of Ecology, Evolution, and Systematics* 44: 367-388.

Alberto, F.J., Derory, J., Boury, C., Frigerio, J.M., Zimmermann, N.E. and Kremer, A. 2013. Imprints of natural selection along environmental gradients in phenology-related genes of Quercus petraea. *Genetics 195:* 495-512.

Alfaro, R.I., Fady, B., Vendramin, G.G., Dawson, I.K., Fleming, R.A., Sáenz-Romero, C., Lindig-Cisneros, R.A., Murdock, T., Vinceti, B., Navarro, C.M., Skrøppa, T., Baldinelli, G., El-Kassaby, Y.A. and Loo, J. 2014. The role of forest genetic resources in responding to biotic and abiotic factors in the context of anthropogenic climate change. *Forest Ecology and Management* 333: 76-87.

Aravanopoulos, F.A., Tollefsrud, M.M., Graudal, L., Koskela, J., K.tzel, R., Soto, A., Nagy, L., Pilipovic, A., Zhelev, P., Božic, G. and Bozzano, M. 2015. *Development of genetic monitoring methods for genetic conservation units of forest trees in Europe.* European Forest Genetic Resources Programme (EUFORGEN), Bioversity International, Rome, Italy. xvi+46 pp.

Bacles, C.F.E. and Ennos, R.A. 2008. Paternity analysis of pollen-mediated gene flow for *Fraxinus excelsior* L. in a chronically fragmented landscape. *Heredity* 101: 368-380.

Benito Garzón, M., Robson, T.M. and Hampe, A. 2019. ΔTraitSDMs: species distribution models that account for local adaptation and phenotypic plasticity. *New Phytologist* 222: 1757-1765.

Black, K., Xenakis, G. and Ray, D. 2010. Climate change impacts and adaptive strategies. *Irish Forestry* 67: 125-139.

Bonan, G.B. 2008. Forests and climate change: forcings, feedbacks, and the climate benefits of forests. *Science* 320(5882): 1444-1449.

Cahalane, G., Doody, P., Douglas, G., Fennessy, J., O'Reilly, C. and Pfeifer, A. 2007. Sustaining and Developing Ireland's Forest Genetic Resources. An Outline Strategy. COFORD, Dublin.

Christensen, O.B, Goodess, C.M., Harris, I. and Watkiss, P. 2011. European and global climate change projections: discussion of climate change model outputs, scenarios and uncertainty in the EC RTD ClimateCost Project. In The ClimateCost Project. Watkiss, P. (Ed.) 2011. Final Report. Volume 1: Europe. Published by the Stockholm Environment Institute, Sweden, 2011.

Chuine, I., X. Morin, and H. Bugmann. 2010. Warming, photoperiods and tree phenology. *Science* 329(5989): 277-278.

COFORD National Consultative Committee on Forest Genetic Resources (2012) Forest Genetic Resources in Ireland. COFORD, Dublin. Coll, J., Bourke, D., Gormally, M., Sheehy Skeffington, M. and Sweeney, J. 2012. *Winners and Losers: Climate Change Impacts on Biodiversity in Ireland*. EPA, Johnstown Castle, Co. Wexford.

Climate Change Research Programme (CCRP) 2007 - 2013 Report Series No. 19.

Cowan, R.S., Smith, R.J. and Fay, M.F. 2008. Genetic variation in Irish whitebeam, *Sorbus hibernica* E.F. Warb. (Rosaceae) and its relationship to a *Sorbus* from the Menai Strait, North Wales. *Watsonia* 27: 99-108.

Cubry, P., Gallagher, E., O'Connor, E. and Kelleher, C.T. 2015. Phylogeography and population genetics of black Alder (*Alnus glutinosa* (L.) Gaertn.) in Ireland: putting it in a European context. *Tree Genetics and Genomes* 11: 99.

DAFM. 2014. Forest Research Ireland – *A Strategic Agenda for Forest Research in Ireland*. Department of Agriculture, Food and the Marine.

Delzon, S., Urli, M., Samalens, J.-C., Lamy, J.-B., Lischke, H., Sin, F., Zimmermann, N.E. and Porté, A.J. 2013. Field evidence of colonisation by holm oak, at the northern margin of its distribution range, during the Anthropocene period. *PloS One* 8: e80443-e80443.

De Vries, S.M.G., Alan, M., Bozzano, M., Burianek, V., Collin, E., Cottrell, J., Ivankovic M., Kelleher, C.T., Koskela, J., Rotach, P., Vietto, L. and Yrjänä, L. 2015. *Pan-European Strategy for Genetic Conservation of Forest Trees and Establishment of a Core Network of Dynamic Conservation Units*. Bioversity International, Rome, Italy, 41 pp.

Donnelly, A., Salamin, N. and Jones, M.B. 2006. Changes in tree phenology: an indicator of spring warming in Ireland? *Biology and Environment: Proceedings of the Royal Irish Academy* 106B(1): 49-56.

Eriksson, G., Namkoong, G., and Roberds, J.H. 1993. Dynamic gene conservation for uncertain futures. *Forest Ecology and Management* 62(1-4): 15-37.

Fady, B., Aravanopoulos, F.A., Alizoti, P., Mátyás, C., von Wühlisch, G., Westergren, M., Belletti, P., Cvjetkovic, B., Ducci, F., Huber, G., Kelleher, C.T., Khaldi, A., Kharrat, M.B.D., Kraigher, H., Kramer, K., Mühlethaler, U., Peric, S., Perry, A., Rousi, M., Sbay, H., Stojnic, S., Tijardovic, M., Tsvetkov, I., Varela, M. C., Vendramin, G.G. and Zlatanov, T. 2016. Evolution-based approach needed for the conservation and silviculture of peripheral forest tree populations. *Forest Ecology and Management* 375: 66-75.

FAO. 2014. *The State of the World's Forest Genetic Resources*. Commission on Genetic Resources for Food and Agriculture. Food and Agriculture Organization of the United Nations, Rome 2014.

FAO, FLD, IPGRI. 2004. *Forest Genetic Resources Conservation and Management. Vol. 1: Overview, Concepts and Some Systematic Approaches*. International Plant Genetic Resources Institute, Rome, Italy.

Fussi, B., Westergren, M., Aravanopoulos, F., Baier, R., Kavaliauskas, D., Finzgar, D., Alizoti, P., Bozic, G., Avramidou, E., Konnert, M. and Kraigher, H. 2016. Forest genetic monitoring: an overview of concepts and definitions. *Environmental Monitoring and Assessment* 188: 493.

Gallagher, E., Douglas, C.G., Douglas, G.C., Kelly, D.L., Barth, S., Kelleher, C.T. and Hodkinson, T.R. 2013. Old age sex: a parentage study of different age cohorts in a native veteran pedunculate oak (*Quercus robur* L.) woodland using microsatellite markers. *Biology and Environment: Proceedings of the Royal Irish Academy* 113B: 155-167.

Gapare, W.J., Yanchuk, A.D. and Aitken S.N. 2008. Optimal sampling strategies for capture of genetic diversity differ between core and peripheral populations of *Picea sitchensis* (Bong.) Carr. *Conservation Genetics* 9(2): 411-418.

García, C., Guichoux, E. and Hampe, A. 2018. A comparative analysis between SNPs and SSRs to investigate genetic variation in a juniper species (*Juniperus phoenicea* ssp. *turbinata*). *Tree Genetics and Genomes* 14: 87.

Geburek, T. and Konrad, H. 2008. Why the Conservation of Forest Genetic Resources Has Not Worked. *Conservation Biology* 22(2): 267-274.

Gepts, P. 2006. Plant genetic resources conservation and utilization. *Crop Science* 46(5): *2278-2292.*

Government of Ireland. 2011. *Actions for Biodiversity 2011-2016 – Ireland's National Biodiversity Plan.* Department of Arts, Heritage and the Gaeltacht

Graudal, L., Aravanopoulos, F., Bennadji, Z., Changtragoon, S., Fady, B., Kjær, E.D., Loo, J., Ramamonjisoa, L. and Vendramin, G.G. 2014. Global to local genetic diversity indicators of evolutionary potential in tree species within and outside forests. *Forest Ecology and Management* 333: 35-51.

Graudal, L., Kjaer, E.D. and Canger, S. 1995. A systematic approach to the conservation of genetic resources of trees and shrubs in Denmark. *Forest Ecology* *and Management* 73: 117-134.

GSPC. 2012. *Global Strategy for Plant Conservation: 2011-2020*. Botanic Gardens Conservation International, Richmond, UK.

Hampe, A. and Petit, R.J. 2005. Conserving biodiversity under climate change: the rear edge matters. *Ecological Letters* 8: 461-7.

Harper, A.L., McKinney, L.V., Nielsen, L.R., Havlickova, L., Li, Y., Trick, M., Fraser, F., Wang, L., Fellgett, A., Sollars, E.S., Janacek, S.H., Downie, J.A., Buggs, R.J., Kjaer, E.D. and Bancroft, I. 2016. Molecular markers for tolerance of European ash (*Fraxinus excelsior*) to dieback disease identified using Associative Transcriptomics. *Science Reports* 6: 19335.

Hendrick, E. and Black, K.G. 2009. Climate change and Irish forestry. *COFORD Connects, Environment No. 9*.

Heuertz, M., Fineschi, S., Anzidei, M., Pastorelli, R., Salvini, D., Paule, L., Frascaria-Lacoste, N., Hardy, O.J., Vekemans, X. and Vendramin, G.G. 2004. Chloroplast DNA variation and postglacial recolonization of common ash (*Fraxinus excelsior* L.) in Europe. *Molecular Ecology* 13: 3437-52.

Holderegger, R., Kamm, U. and Gugerli, F. 2006. Adaptive vs. neutral genetic diversity: implications for landscape genetics. *Landscape Ecology* 21: 797-807.

IPCC. 2014. Summary for policymakers. In *Climate Change 2014: Impacts, Adaptation, and Vulnerability.Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R. and White, L.L. (Eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1-32.

IUCN. 2012.*IUCN Red List Categories and Criteria: Version 3.1. Second edition*. Gland, Switzerland and Cambridge, UK. IUCN. Iv+ 32 p.

Jump, A.S. and Penuelas, J. 2006. Genetic effects of chronic habitat fragmentation in a wind-pollinated tree. *Proceedings of the National Academy of Sciences USA* 103**:** 8096-100.

Keary, K., A'Hara, S., Whitaker, H. and Cottrell, J. 2005. Assessment of genetic variation in black poplar in Ireland using microsatellites. *Irish Forestry* 62: 6-18.

Kelleher, C.T. 2018. Evolution and conservation of trees – a review of salient issues. In *Annual Plant Reviews online* 1(2): J.A. Roberts (Ed.). doi:10.1002/9781119312994.apr0621.

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. 2005. *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.

Kelleher, C.T., Hodkinson, T.R., Douglas, G.C. and Kelly, D.L. 2005. Species Distinction in Irish Populations of *Quercus petraea* and *Q. robur:* Morphological versus Molecular Analyses. *Annals of Botany* 96: 1237-1246.

Kelleher, C.T., Hodkinson, T.R., Kelly, D.L. and Douglas, G.C. 2004a. Characterisation of chloroplast DNA haplotypes to reveal the provenance and genetic structure of oaks in Ireland. *Forest Ecology and Management* 189: 123-131.

Kelleher, C.T., Hodkinson, T.R., Kelly, D.L. and Douglas, G.C. 2010. Irish oak - genetic diversity and the Iberian connection. *COFORD Connects, Reproductive Material No. 18*.

Kelleher, C.T., Kelly, D.L. and Hodkinson, T.R. 2004b. Species status, hybridisation and geographic distribution of Irish populations of *Quercus petraea* (Matt.) Liebl. and *Q. robur* L. *Watsonia* 25: 83-97.

Kelly, C. 2013. John F. Kennedy Arboretum: a national botanical treasure. *Irish Forestry* 70: 232-244.

Kirk, H. and Freeland, J.R. 2011. Applications and Implications of Neutral versus Non-neutral Markers in Molecular Ecology. *International Journal of Molecular Sciences* 12: 3966-3988.

Körner, C. and Basler, D. 2010. Plant science. Phenology under global warming. *Science* 327: 1461-1462.

Koskela, J., Lefèvre, F., Schueler, S., Kraigher, H., Olrik, D. C., Hubert, J., Longauer, R., Bozzano, M., Yrjänä, L., Alizoti, P., Rotach, P., Vietto, L., Bordács, S., Myking, T., Eysteinsson, T., Souvannavong, O., Fady, B., De Cuyper, B., Heinze, B., von Wühlisch, G., Ducousso, A. and Ditlevsen, B. 2013. Translating conservation genetics into management: Pan-European minimum requirements for dynamic conservation units of forest tree genetic diversity. *Biological Conservation* 157: 39-49.

Lefèvre, F., Koskela, J., Hubert, J., Kraigher, H., Longauer, R., Olrik, D.C., Schüler, S., Bozzano, M., Alizoti, P., Bakys, R., Baldwin, C., Ballian, D., Black-Samuelsson, S., Bednarova, D., Bordács, S., Collin, E., de Cuyper, B., de Vries, S. M., Eysteinsson, T., Frýdl, J., Haverkamp, M., Ivankovic, M., Konrad, H., Koziol, C., Maaten, T., Notivol Paino, E., Öztürk, H., Pandeva, I.D., Parnuta, G., Pilipovič, A., Postolache, D., Ryan, C., Steffenrem, A., Varela, M.C., Vessella, F., Volosyanchuk, R.T., Westergren, M., Wolter, F., Yrjänä, L. and Zarina, I. 2013. Dynamic conservation of forest genetic resources in 33 European countries. *Conservation Biology* 27**:** 373-84.

Loo, J. 2003. Gene conservation: a view from Atlantic Canada. In *Proceedings of the*

Society of American Foresters National Convention (p. 201).

Lowe, A.J., Unsworth, C., Gerber, S., Davis, S., Kelleher, C.T., King, A., Brewer, S., White, A. and Cottrell, J. 2005. Route, speed and mode of oak postglacial colonisation across the British Isles: Integrating molecular ecology, palaeoecology and modelling approaches. *Botanical Journal of Scotland* 57: 59-81.

Metzger, M.J., Bunce, R.G.H., Jongman, R.H.G., Mücher, C.A. and Watkins, J.W. 2005. A climatic stratification of the environment of Europe. *Global Ecology and Biogeography* 14: 549-563.

Metzger, M.J., Bunce, R.G.H., Jongman, R.H.G., Sayre, R., Trabucco, A., Zomer, R. and Sykes, M. 2013. A high-resolution bioclimate map of the world: a unifying framework for global biodiversity research and monitoring. *Global Ecology and Biogeography* 22: 630-638.

Myking, T. 2002. Evaluating genetic resources of forest trees by means of life history traits – a Norwegian example. *Biodiversity and Conservation* 11(9): 1681-1696.

Nybom, H., Weising, K. and Rotter, B. 2014. DNA fingerprinting in botany: past, present, future. *Investigative Genetics* 5: 1.

Perdereau, A.C., Kelleher, C.T., Douglas, G.C. and Hodkinson, T.R. 2014. High levels of gene flow and genetic diversity in Irish populations of *Salix caprea* L. inferred from chloroplast and nuclear SSR markers. *BMC Plant Biology* 14: 202.

Perrin, P.M., Martin, J.R., Barron, S.J., O'Neill, F.H., McNutt, K.E. and Delaney, A.M. 2008. *National Survey of Native Woodlands 2003-2008. Volume I: Main Report*. Report to National Parks and Wildlife Service, pp 177.

Petit, R.J., El Mousadik, A. and Pons, O. 1998. Identifying populations for conservation on the basis of genetic markers. *Conservation Biology* 12(4): 844-855.

Petit, R.J., Csaikl, U.M., Bordács, S., Burg, K., Coart, E., Cottrell, J., van Dam, B., Deans, J.D., Dumolin-Lapègue, S., Fineschi, S., Finkeldey, R., Gillies, A., Glaza, I., Goicoechea, P.G., Jensen, J.S., König, A.O., Lowe, A.J., Madsen, S.F., Mátyás, G., Munro, R.C., Olalde, M., Pemonge, M.-H., Popescu, F., Slade, D., Tabbener, H., Taurchini, D., de Vries, S.G.M., Ziegenhagen, B. and Kremer, A. 2002. Chloroplast DNA variation in European white oaks: Phylogeography and patterns of diversity based on data from over 2600 populations. *Forest Ecology and Management* 156(1-3): 5-26.

Petit, R.J., Aguinagalde, I., de Beaulieu, J.-L., Bittkau, C., Brewer, S., Cheddadi, R., Ennos, R., Fineschi, S., Grivet, D., Lascoux, M., Mohanty, A., Müller-Starck, G., Demesure-Musch, B., Palmé, A., Martín, J.P., Rendell, S., Vendramin, G.G. 2003. Glacial refugia: hotspots but not melting pots of genetic diversity. *Science* 300(5625): 1563-1565.

Pletsers, A., Caffarra, A., Kelleher, C.T. and Donnelly, A. 2015. Chilling temperature and photoperiod influence the timing of bud burst in juvenile *Betula pubescens*

Ehrh. and *Populus tremula* L. trees. *Annals of Forest Science* 72(7): 941-953.

Rajora, Om P., and Mosseler, A. 2001. Challenges and opportunities for conservation of forest genetic resources. *Euphytica* 118(2): 197-212.

Ratnam, W., Rajora, O.P., Finkeldey, R., Aravanopoulos, F., Bouvet, J.-M., Vaillancourt, R. E., Kanashiro, M., Fady, B., Tomita, M. and Vinson, C. 2014. Genetic effects of forest management practices: Global synthesis and perspectives. *Forest Ecology and Management* 333: 52-65.

Ray, D., Xenakis, G., Tene, A. and Black, K. 2009. Developing a site classification system to assess the impact of climate change on species selection in Ireland. *Irish Forestry* 66: 101-123.

Roche, J.R. 2019. Recent findings on the native status and vegetation ecology of Scots pine in Ireland and their implications for forestry policy and management. *Irish Forestry* 76: 29-54.

Rotach, P. 2005. In situ conservation methods. In *Conservation and Management of Forest Genetic Resources in Europe.* Eds. Geburek, T., Turok, J. Eds. Arbora Publishers, Zvolen, pp. 535-565.

Schmeller, D.S., Evans, D., Lin, Y.P. and Henle, K. 2014. The national responsibility approach to setting conservation priorities – recommendations for its use. *Journal for Nature Conservation* 22: 349-357.

Theilade, I., Petri, L. and Engels, J. 2004. Ex situ conservation through storage and use. In *Forest Genetic Resources Conservation and Management*. Vol. 3, FAO, International Plant Genetic Resources Institute, Rome, Italy. pp. 47-59.

Thompson, I., Mackey, B., McNulty, S. and Mosseler, A. 2009. *Forest Resilience, Biodiversity, and Climate Change. A synthesis of the Biodiversity/resilience/ stability Relationship in Forest Ecosystems*. Secretariat of the Convention on Biological Diversity, Montreal. Technical Series no. 43, pp 67.

Trivedi, C., Cavers, S., Atkinson, N., Clark, J. and Cottrell, J.E. 2019. *A Strategy for UK Forest Genetic Resourc*es. Royal Botanic Gardens, Kew, London.

Vander Mijnsbrugge, K., Cox, K. and Van Slycken, J. 2005. Conservation approaches for autochthonous woody plants in Flanders. *Sylvae Genetica* 54: 197-206.

Webb, D.A., Parnell, J. and Doogue, D. 1996. *An Irish Flora*. Dundalk, Dundalgan Press (W. Tempest) Ltd.