EUROPEAN FOREST GENETIC RESOURCES PROGRAMME

EUFORGEN

Decision support tool for the management of dynamic genetic conservation units

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EFI

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The European Forest Genetic Resources Programme (EUFORGEN) is an instrument based on international cooperation which promotes the conservation and appropriate use of forest genetic resources in Europe. It was established in 1994 to implement Strasbourg Resolution S2 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 regarding forest genetic resources and relevant decisions of the Convention on Biological Diversity (CBD). In addition, 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 input 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, and the EUFORGEN Secretariat is hosted by the European Forest Institute (EFI). Further information about EUFORGEN can be found at www.euforgen.org. During its Fifth Phase (2015-2019) 28 countries (Austria, Belgium, Croatia, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Lithuania, Luxemburg, Moldova, Netherlands, Norway, Poland, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey, United Kingdom) financially contributed to the Programme.

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PREFACE

Conservation of forest genetic resources (FGR) mainly takes place in forests where specific populations have been identified and designated as Genetic Conservation Units (GCUs).

According to the European Information System on FGR (EUFGIS), Europe has more than 3200 of these GCUs, which between them harbour 4000 different populations of about 100 different species. EUFORGEN has published a Pan-European strategy for genetic conservation of forest trees (de Vries *et al.* 2015) to allow European countries to coordinate and monitor conservation efforts.

These GCUs contain living tree populations which adapt in response to natural dynamic processes and are subject to natural selection. As a result, genetic conservation strategies for forest trees focus on the *in situ* conservation of trees and the ecosystem of which they form part. The goal is to conserve the adaptive potential of the target population as a whole, not just the individual trees.

Under the pressure of climate change, lack of management, extreme events and pest and diseases, GCUs can face various levels of decline and may no longer serve their designed purpose. For this reason, the EUFORGEN Steering Committee decided to establish a Working Group to develop a standardised approach to define measures proportionate to the increasing threats.

At its 10th meeting in June 2014 (Edinburgh, United Kingdom), the EUFORGEN Steering Committee agreed to continue the work of two working groups, which have published "Approaches to the conservation of FGR in Europe in the context of climate change"[1] and "Genetic monitoring methods for genetic conservation units of forest trees in Europe"[2]). The aim was to extend the development of an already conceptualised decision cascade tool to provide decision making support for forest managers in relation to GCUs under different levels of threats. Therefore, at its 11th meeting in November 2015 (Dublin, Ireland) the EUFORGEN Steering Committee decided to prioritise the recommendation to progress the development of the decision cascade tool and therefore established a new working group on this subject.

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1 http://www.euforgen.org/about-us/how-we-operate/working-groups/strategy-in-climate-change/

2 http://www.euforgen.org/about-us/how-we-operate/working-groups/genetic-monitoring/

The working group met for the first time in Rome (Italy) on 24-28 October 2016, where Andreas Rudow (Switzerland) and Marjana Westergren (Slovenia) were respectively nominated chair and vice-chair of the working group. The group developed an outline of the report, which was further elaborated in 2017 and then peer-reviewed in 2018 by nominated national experts in all EUFORGEN member countries.

The main objective of the working group was to extend the development of such a functional tool relating threat indication to conservation action, and focusing on the following functional aspects: a) support for the management of dynamic GCUs; i.e., their target populations under different types and intensities of threat, b) identification of the marginal and peripheral populations most in need of conservation; in particular in the context of increasing threat by climate change, and c) verification of the applicability of the tool to introduced species important for forestry in several European countries.

During the 13th EUFORGEN Steering Committee in June 2018 (Bonn, Germany), Andreas Rudow gave an update on the working group results. The Steering Committee welcomed the decision support tool (DST) and expressed willingness to support its implementation. The Secretariat opened the report by the end of July for comments by the external contributors. In addition, the Steering Committee tasked the working group with two supplementary minor tasks: i) to elaborate case studies illustrating the functioning of the DST with regard to various scenarios, and ii) to complete the open list of implementation measures.

The report was approved at the 14th EUFORGEN Steering Committee. The case studies have been completed and are available in the report annexes. To make the DST operational, new fields need to be incorporated in an updated version of the EUFGIS information system. The report was endorsed by the Steering Committee and the Secretariat and finalised at the end of 2019.

The process described here covers a period of five years, but the work upstream of this decision support tool is linked to the management of the GCUs present in EUFGIS, and therefore to the initiation of EUFGIS itself more than 10 years ago. This work is the result of close collaboration between countries and experts in sustainable forest management and in the conservation of FGR; a process that is part of the pan-European forest conservation strategy and its implementation across Europe. We hope that this DST will prove useful for the management of genetic resources in Europe and will become a widely used tool for sustainable forest management.

The members of the EUFORGEN Steering Committee proposed valuable comments during consolidation of the report. The linguistic revision of the text was carried out by Stefanie Hayes and the layout of the print version was realized by Maria Cappadozzi. Many thanks to all of them.

Michele Bozzano, EUFORGEN Coordinator

May 2020

CONTENTS

EXECUTIVE SUMMARY

The diversity of forests at species and population levels is a vital resource, and in recent years many countries in Europe have made considerable progress in ensuring the conservation of forest genetic resources (FGR). An important contribution to the conservation of FGR was the establishment of a network of Genetic conservation units (GCUs) in forest areas. These GCUs are designed to contain tree populations that have adapted to specific environmental conditions, have distinct characteristics and are subject to natural selection. According to the European information system on FGR (EUFGIS), Europe has more than 3200 of these genetic conservation units, which between them harbour 4000 different populations of about 100 different species.

GCU management currently aims to maintain and enhance the long-term evolutionary potential of the target tree species they contain with regular monitoring, to confirm that they are still able to serve their purpose and have not been damaged or destroyed.

In its Phase IV (2010-2014), EUFORGEN established a comprehensive Pan-European strategy for genetic conservation of forest trees in order to allow European countries to coordinate and monitor their conservation efforts. However, the strategy was not specifically designed to conserve FGR under climate change, which will result in new and intensified challenges in relation to ecology and adaptation as well as competing socio-economic demands on land use and for forest goods. Therefore, the EUFORGEN Steering Committee initiated additional measures *via* working groups in Phase IV (2010-14) and Phase V (2015-2019).

One of these working groups was tasked to further develop a previously considered Decision Cascade Tool, which has now been updated and renamed a decision support tool (DST).[3] The DST is intended to relate indications of threat from climate change to possible

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[3] Previous work on the DST is linked to the management of the GCUs present in EUFGIS, and therefore to the creation of EUFGIS itself as an EU-funded project more than ten years ago. Work on this report started in 2016 and was further elaborated in 2017. It was peer-reviewed by nominated national experts in all EUFORGEN member countries in 2018 and finalised at the end of 2019.

conservation actions within GCUs. The tool is to be added to EUFGIS, which contains details of GCUs across Europe and is maintained by the EUFORGEN programme.

This report of EUFORGEN Working Group 7 on the *decision support tool for the management of dynamic genetic conservation units* thoroughly explores and gives practical details and process overviews of all relevant aspects of an operational decision support tool for GCU managers that would identify threats and provide guidance on the management of GCUs with a long term perspective. It also looks at the possibility of introducing new types of GCU, for example including marginal and peripheral populations, and integrating additional basic information from GCUs into EUFGIS. The working group considered how best to identify suitable marginal and peripheral populations to add to the GCU network because such populations are likely to contain unique genetic diversity. It also made recommendations for the further development and elaboration of the DST.

Most of the open questions around the decision support tool have been answered and a practically applicable and effective tool is ready for implementation within EUFGIS. However, the information system requires additional features to be developed in order for the data to be visualised so that the tool can serve as an early warning system.

The Working Group recommends that once final corrections to the data structure and clarification of the relationship with existing databases have been completed, the DST be implemented in EUFGIS as soon as possible and made available for use by national GCU coordinators and managers. A brief user manual and an introductory course for users should also be developed.

The Working Group hopes that this decision support tool will prove useful and valuable for the management of forest genetic resources in Europe and that it will become an internationally-used tool within sustainable forest management.

INTRODUCTION

Background

Forests are highly valued by society not only for the timber they produce, but also for the ecosystem services they provide in the form of carbon storage, oxygen production, flood management, wildlife habitats and recreational and cultural facilities. In recent decades, European countries have become increasingly aware of the value of forests, and consequently much greater effort has been invested in conserving our Forest Genetic Resources (FGR). More recently, there has been an appreciation of the threat posed by climate change and greater recognition of the key role that forest genetic diversity will play in enabling adaptation to climate change. As a result of climate change, our forests will face new and intensified challenges, such as increased drought in the Mediterranean, increased forest disturbances (forest fires, invasive species, pests) and competing socio-economic demands on land use and for forest goods (e.g., renewable energy).

To date, most conservation efforts have focused on relatively few common, stand-forming tree species; as a consequence, many species with scattered or limited distributions have received less attention (de Vries *et al.*, 2015). The impact of climate change will not be experienced in a uniform way across Europe (IPCC 2007). The genetic differentiation in adaptive traits of trees is generally high (Savolainen *et al.*, 2007, Alberto *et al.*, 2013); however, marginal populations on the edge of distribution ranges or those located at the environmental limits of a species range, especially in Southern Europe, are likely to be the most threatened (Hampe e*et al.*, 2005, Allen *et al.*, 2010). For some of these more threatened populations, there is increasing discussion regarding the potential use of "assisted migration" (assisted translocation, assisted gene flow) as a strategy to mitigate the impacts of climate change (Aitken 2008, O'Neill *et al.*, 2008, Loss *et al.*, 2011). However, to date there has been no detailed assessment of the benefits and risks of assisted translocation or assisted gene flow in relation to FGR in Europe.

In Phase IV (2010-2014), EUFORGEN established a comprehensive Pan-European strategy for genetic conservation of forest trees (de Vries *et al.*, 2015). In recognition of the threat that climate change poses to European FGR, a further working group was established to develop complementary approaches to this strategic baseline. In its report, the working group gives several recommendations including a) enhancing cooperation among countries and enlarging the pan-European collaboration on the conservation of FGR, b) establishing additional Genetic Conservation Units (GCUs) with a focus on marginal and peripheral populations, c) developing a "decision cascade tool" for the future management of GCUs (decision support tool), d) developing lists for threatened populations (including endemic species), e) conducting further research on aspects of the adaptability of marginal and peripheral populations and f) conducting further research on "assisted migration" (assisted translocation, assisted gene flow) (Kelleher *et al.*, 2015).

At the 10th Steering Committee Meeting in 2014, it was agreed that several of the report's recommendations would need follow-up work during Phase V. It was suggested that in order to continue the work done by two of the working groups in Phase IV, further development of the decision cascade tool and the genetic monitoring scheme could be combined. During Phase V (2015-2019), EUFORGEN continued the pan-European implementation of Strasbourg Resolution 2 and other relevant FOREST EUROPE commitments on FGR. Furthermore, the Programme contributed to the implementation of relevant decisions of the Convention on Biological Diversity and the Global Plan of Action on FGR adopted by the FAO Conference in 2013 (FAO, 2013). At the 11th EUFORGEN Steering Committee Meeting in 2015, three working groups were established for Phase V.

The main objective of the working group on "the further development of a decision cascade tool for genetic conservation of forest trees" was to further develop the tool by building on the preliminary ideas for it; relating threat indication to conservation action and focusing on the following functional aspects: a) support for management of dynamic GCUs (i.e., their target populations under different types and intensities of threat), b) identification of marginal and peripheral populations most in need of conservation, in particular in the context of increasing threat by climate change, and c) verification of applicability of the tool to introduced species important for forestry in several European countries.

The 12th Steering Committee Meeting in 2017 agreed on this consolidation of the goals and the methodical differentiation of the two foci, a and b. Furthermore, the Steering Committee responded to various open questions regarding the integration of GCUs for introduced species, as well as necessary management actions in the case of threat (e.g., assisted translocation) resulting in the establishment of new *ex situ* GCUs. Such units are part of the GCU network and are already largely covered by existing EUFGIS standards. Finally, EUFGIS remains the appropriate database for implementation of the tool (although additional fields will need to be incorporated into the EUFGIS database structure).

Genetic conservation units (GCUs)

The diversity of forests at species and population levels is a vital resource and in recent years many countries in Europe have made considerable progress in ensuring the conservation of FGR. An important contribution to the conservation of FGR is the establishment of a network of GCUs in forest areas containing tree populations which have adapted to specific environmental conditions or have distinct characteristics, and which are typically located in forests managed for multiple uses, protected areas or seed stands. An EU funded project established EUFGIS, the European Information System on Forest Genetic Resources, a database containing details of GCUs across Europe. In order to be entered into the EUFGIS database, the GCUs must meet a specific set of criteria (Lefevre *et al.*, 2013). EUFGIS was a successful project and it continues to be a core resource and a central tool in conservation of FGR in Europe (de Vries *et al.*, 2015, Kelleher *et al.*, 2015).

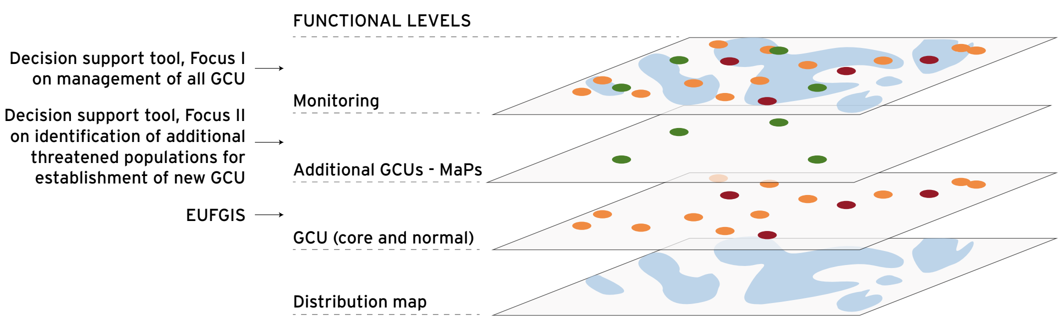
According to the EUFGIS portal, there were 3390 GCUs listed in the database in 2017 containing more than 4300 populations of approximately 100 tree species. Units entered into the EUFGIS database, are designated the status of national forest tree genetic conservation areas. The management of the units aims to maintain and enhance the long-term evolutionary potential of the targeted tree species they contain. They are regularly monitored to confirm that they are still able to serve their purpose and have not been damaged or destroyed. GCU listing, management and monitoring are coordinated by National Focal Points, who are appointed by the country concerned.

Although this initiative represents a major initial achievement, an analysis of the information in the EUFGIS database revealed significant gaps in the conservation efforts, in terms of the species covered and the geographical distribution of the units within the species' ranges (de Vries *et al.*, 2015). In order to identify these gaps, the EUFORGEN Steering Committee established a working group in Phase IV to develop the pan-European genetic conservation strategy for forest trees. For each of the fourteen pilot tree species, the strategy calls for the selection of one unit per climate zone per country in order to form a core network of GCUs. The objective of this core network is to capture the current genetic diversity or adaptive potential of the target species across the European continent. The aim is now for countries to continue uploading all outstanding data to the EUFGIS database and to monitor all progress made on this task. In addition, it is hoped that resources will be allocated for the maintenance and updating of the EUFGIS database.

The monitoring and management of the targeted tree populations in GCUs are crucial elements of the purpose and use of the GCU network. In this regard, there is a strong need for support of national GCU managers and Focal Points. According to a working group in Phase IV and as confirmed by the EUFORGEN Steering Committee, a decision support tool for GCU management could help implement best practice management based on demographic and - as soon as available - genetic monitoring data; this will thereby allow decisions regarding specific management actions to be based on an objective set of criteria (Kelleher *et al.*, 2015). In light of climate change and the increasing threats posed by land use changes, a decision support tool is needed to facilitate a coordinated and potentially uniform approach when managing the GCU network. The adoption of such a tool could potentially make the most of the GCU network by incorporating standard practices into GCU management and the documentation of management actions and their effects. Consequently, the tool could also be used to assess trends and responses to management practices.

When establishing the current network of GCUs, there was no particular focus on the inclusion of marginal and peripheral populations. The conservation of such populations is very important as they are likely to contain unique genetic diversity, but they are particularly vulnerable to threats of fragmentation and the effects of climate change, especially when they are located at the southern limits of their distribution range (rear edge of assumed direction of migration) (Lesica 1995, Hampe *et al.*, 2005; Fady *et al.*, 2016). For instance, the southern populations are located near the glacial refugial regions or near refugial contact zones, which generally represent areas of high genetic diversity (Petit *et al.*, 2003). In addition, natural selection has led these populations to adapt to hot, dry conditions; they may consequently contain genetic elements that are particularly valuable in terms of climate change adaptation. These edge range GCUs are likely to be the first to exhibit the impacts of climate change and to display early signs of maladaptation. It will also be necessary to assess whether these populations will need assisted translocation or assisted gene flow. According to suggestions made by the working group on further development and complementary approaches to the conservation of FGR in the context

FIGURE 1. Functional levels of the conservation in GCUs and the two focuses of the decision support tool.



of climate change in Phase IV, and findings of the COST Action FP1202 aiming to define, identify and map marginal and peripheral (MaP) forest tree populations, the GCU network should be expanded to integrate MaP populations of GCU target tree species (Kelleher *et al.*, 2015).

Furthermore, a subsequent working group in Phase IV suggested that consideration should be given to extending the area of the pan-European network beyond Europe to include most southern marginal populations of some species; e.g., populations in Northern Africa or in East Mediterranean countries (Kelleher *et al.*, 2015).

In addition, introduced species that are important for forestry in several European countries should be taken into account. Such *ex situ* populations in Europe may have undergone specific selection resulting in genetic differentiation and may therefore contain potentially unique and valuable genetic diversity (Schlaepfer *et al.*, 2011).

There is potential for collaboration with the current IUCN Global Tree Assessment initiative, led by the Botanic Gardens Conservation International (BGCI) and the IUCN/SSC Global Tree Specialist Group (GTSG), although this initiative concentrates its efforts on the species rather than population level. Adrian Newton, vice-chair of IUCN GTSG, acknowledged the important position of EUFORGEN in the cooperation with IUCN, but pointed out the difficulties in maintaining the high credibility of the brand IUCN Red Lists of Threatened Species and that its extension to the population level would not be realistic at this time.

Goals

A "Decision Cascade Tool" was the first working title for a decision support tool to help the management of GCUs listed in the EUFGIS database at a national level. The "cascade" aspect stemmed from a desire to link management action to specific threats triggered by climate change. In this regard, initial concepts were built on the general assumption that increasing intensity levels of management (e.g., *in situ*, *ex situ*) must respond, and therefore correspond, to threats of increasing levels of severity. However, with more consideration, it became clear that this relationship does not necessarily follow a cascade pattern. The goal therefore evolved into the development of an open decision system or decision support tool (DST), following a decision matrix based on decision theory and decision making under uncertainty (e.g., Bitz, 1981, Resnik, 1987).

Due to the impact of threat triggered by climate change, it was initially assumed that the decision support tool and its indicators and verifiers could be simultaneously used for identifying the marginal and peripheral populations to be integrated into the GCU network. However, due to the different functional levels of the two foci (Figure 1), the analysis of the underlying decision processes of both goals differ fundamentally. First, the identification of management action in GCUs is mostly related to threat indicators, and second, the identification of MaP populations primarily focuses on securing additional genetic value; in short, importance prior to urgency (c.f. Eisenhower Decision Matrix). This means that not one, but two, different support tools or mechanisms need to be targeted (c.f. Table 1).

TABLE 1. Characterisation of the two tools according to their Criteria, Input Data and Output Data, and to the two different functional levels (Foci).

Tool/Mechanism	**Criteria** for decision making (indicators/verifiers)	**Input data** for decision making	**Output data** from decision making
Decision support tool for management of GCUs (Focus I)	**Indication of threat** to target tree species populations in GCUs	**Basic GCU data in EUFGIS** using • GCU **establisment and demographic monitoring data** • **genetic monitoring data** (if available) • additional **data on relevant ecological/ environmental processes**	**Recommendation for management action** concerning conservation of all GCUs within the EUFGIS database
Mechanism for the identification and integration of important MaP populations (Focus II)	**Assumption of particular genetic value of MaP populations** in the pan-European context	**Iterative process** using: • national **expert knowledge/data** • geographic and ecological **marginality model data** • **genetic data** (if available)	**Recommendation for the integration of valuable MaP** populations into the GCU network in the EUFGIS database.

The detailed goals are reflected in the report structure as follows:

1. Development of an operational DST for GCU managers which identifies any threats and provides guidance on GCU management. It is essential to establish common standards for basic GCU monitoring, indicators and verifiers, and recommended management action. These standards can form the basis of consistent documentation of management practices in order to gain knowledge of their impact. Future application of best practice management will improve GCU management in an iterative fashion. With respect to GCU monitoring, the tool should aim to meet the challenge of having to evolve and adapt to new technologies, while maintaining the continuity of data collection. More details are given in chapters Fundamentals (p. 9), Indicators and verifiers (p. 13) and Management actions (p. 27).

2. Verification of the following complementary aspects of the decision support tool:

   a) potential for new types of GCU (including MaP populations and populations of introduced tree species important for forestry in several European countries) to be integrated into the GCU network (described in chapter Applicability of the decision support tool for new types of GCUs, p. 39), and

   b) possibility of integrating additional basic GCU data into the EUFGIS data structure and database (described in chapter Integration oft the decision suppot tool into the EUFGIS information system, p. 41).

3. Description of a supportive mechanism for the identification of additional valuable genetic resources in marginal and peripheral (MaP) populations, in order to integrate respective additional GCUs. The mechanism may be built on the results of COST Action FP1202 and iteratively make use of expert knowledge, marginality models and genetic data. Its elements and functioning are described in chapter Identification and integration of marginal and peripheral (MaP) populations of pan-European interest (p. 49).

4. Recommendations for further development and implementation of the elaborated support tool and mechanism. Listed in chapter Conclusions and recommendations (p. 55).

DECISION SUPPORT TOOL FOR GCU MANAGEMENT

Fundamentals

Overall principles

The DST aims to identify threats to FGR at a population level and to guide the prioritisation of actions for target tree species populations in all GCUs. Therefore, the tool uses a basic set of standardised data on demography, genetics (if available) and identified threats to target tree populations of GCU.

The aim is for the tool to have high applicability and long-term utility. The dataset is thus based on a range of alternative qualitative attributes, including data based on assessments that are easy and cheap to obtain (low costs). Data are held in the simplest format possible (reduction).

The tool will help and guide those responsible for the management of the national networks of GCUs (national GCU coordinators/managers) in making appropriate management decisions with a long-term perspective. In particular, it will simplify the identification of threats at a population level and link appropriate management actions to them. While the current IUCN Red List Categories and Criteria (IUCN 2012) is used as a standard for the classification of threat at the species level, it does not perfectly match the description of population level threats.

The tool is an add-on to the EUFGIS information system maintained by the EUFORGEN programme. The EUFGIS database is already designed to deal with time series data, whereby a change of date creates a new dataset. It supports data entry and maintenance by national focal points. Some attributes necessary for the DST are covered by the current EUFGIS data standard (fields), and others need to be added to it. Some features also need to be added to the EUFGIS interface.

The aim of the tool is to provide a warning system that alerts national focal points of a possible threat to a GCU. The tool will compare the data of a GCU entered into the EUFGIS database by following monitoring cycles. If the comparison reveals a decline in variables important for the viability of the GCU, the system will notify the focal point, who will then consider whether enhanced management actions are required.

FIGURE 2. Systemic view on the decision process using standardised flowchart symbols for input/output (parallelogram) and decision (diamond).

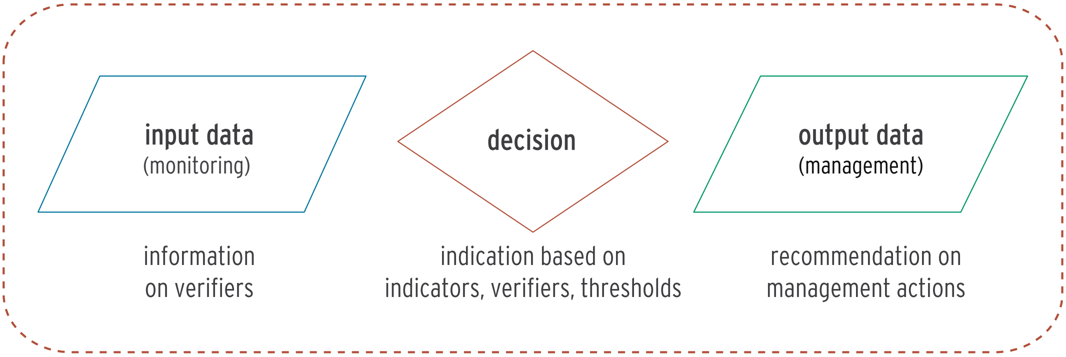
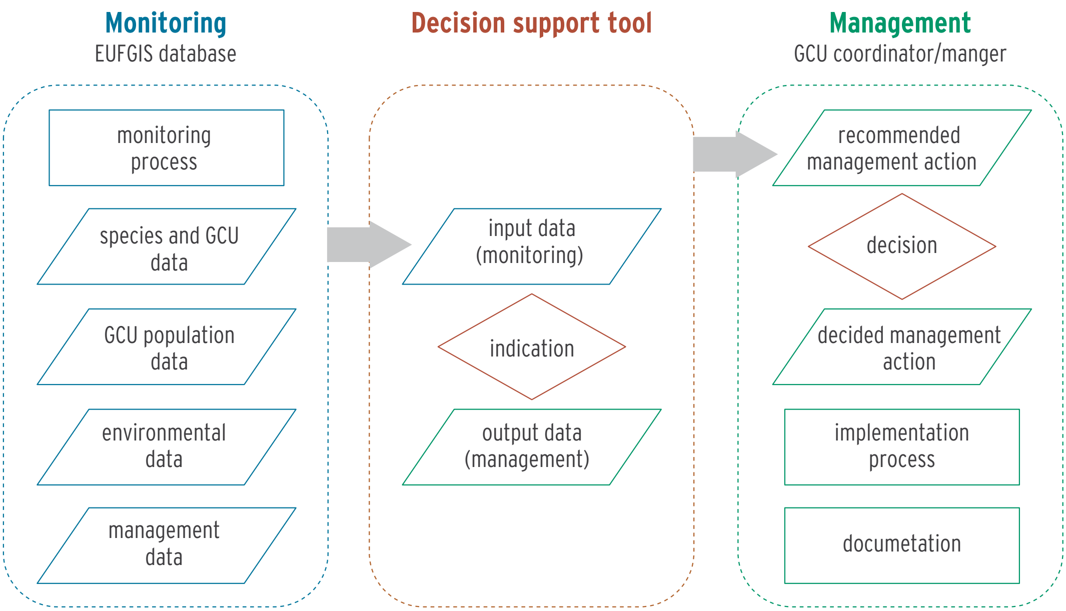


FIGURE 2. Embedding of the decision support tool between data provider (Monitoring, blue) and data user (Implementation, green) using standardised flowchart symbols for input/output (parallelogram), decision (diamond) and process (rectangle).



This basic set of standardised data can form the basis of consistent documentation of management practices in order to build knowledge on the impact of management actions. The future application of best practices could improve GCU management in an iterative way. With respect to GCU monitoring, the tool aims to meet the challenge of how to evolve and adapt to new technologies while maintaining the continuity of data collection (open system).

Basically, any decision support is based on i) input data, ii) a mechanism using these data to indicate a result, and iii) output of the result, which will be used by decision makers (output data). The decision support tool for GCU management is therefore functionally embedded between the data providers (EUFGIS database and others) and the data users (GCU coordinators and managers) (c.f. Figures 2 and 3).

Structure

The decision support tool has three main elements:

- **Indicators (I) –** these describe the status of the target population within a GCU.
- **Verifiers (Ix) –** these are used to measure the indicator; several alternative verifiers can relate to one indicator.
- **Actions (A) –** these are the management actions that should be implemented to mitigate threats to FGR.

Indicators (I) and verifiers (Ix) provide an indication of GCU status (Figure 3); for example, the number of reproducing trees can give an indication of potential adaptability within a population. The verifiers can then be used to guide potential management actions. Indicators must be measurable and verifiable, and verifiers comprise either quantitative or qualitative parameters. For example, the indicator "presence of biotic endangering factors" includes several verifiers: pests and diseases, invasive neophytes, competing species and seed predation and browsing.

Verifiers should be simple to measure, cheap and easy to report and, if possible, form part of the standard GCU monitoring process. The results of the measurements must also be recorded in a clear and unambiguous manner, so that they can be handed down to successive generations of staff without confusion or misinterpretation. Initially, the verifiers will be based on demographic information derived from measurements and on information used to estimate risk from factors such as potential pests and diseases (disturbances). At a later stage, once genetic information becomes more widely available, genetic diversity estimates will also be incorporated as indicators.

Indicators (I) and their verifiers can be subdivided into three groups:

- **Indicators/verifiers based on demographic monitoring (I1, I2, I3, I4)**
- **Indicators/verifiers based on genetic monitoring (I8, I9)** – depending on the availability of genetic information, these indicators can complement or even replace the respective indicators I1 and I4
- **Indicators/verifiers based on information about immediate or future disturbances (I5, I6, I7)**

Indicators and verifiers can be applied singly or in combination to gauge the level of intervention required and to guide the appropriate and necessary management action. Where not explicitly defined to the contrary, indicators and verifiers are always handled alternatively (logical operator OR). A single indicator can be used as the basis on which to carry out a management action.

Management actions (A) form the other part of the decision support tool and should be carried out when indicators point to important changes in the GCU status. The intensity of management actions differs depending on the intensity of the threat: indications of low threat will lead to actions involving minor interventions; as indicators point to increasing threat, the level of intervention will also increase. This is based on an action scale of A1 to A8, with A1 actions involving standard maintenance of a GCU and A8 actions involving the most extreme *ex situ* measures.

The actions can be grouped as follows:

- **Baseline management continued (A1)**
- **Additional *in situ* management actions (A2, A3, A4)**
- **Additional *ex situ* management actions (A5, A6, A7, A8)**

As is the case with the indicators and verifiers, management actions can be applied individually or in combination, depending on the level of threat. The highest threat will determine the priority action to be taken.

Further relevant considerations

The following points should be taken into consideration when using the DST:

- Establishing new GCUs or replacing the threatened ones with existing units in the EUFGIS database, sites with ecological diversity including vertical buffers should be preferred. The focus species is expected to have greater adaptive potential on a site with greater ecological diversity than on a site that offers a a narrow ecological niche.
- The tool is designed around the utilisation of demographic information. As soon as more specific genetic information becomes available, it will be used to identify risk for genetic

erosion, etc. This is addressed within the indicators and verifiers chapter in subchapter Indicators/verifiers based on genetic monitoring (p. 24).

- Existing risks in the neighbourhood (e.g., pests and diseases, invasive neophytes) that could endanger the long-term survival of the population should be taken into account when making GCU management decisions.
- As more refined predictions on climate change become available, they should be used to develop future management plans. Risks due to abiotic threats, such as drought, should be considered (e.g., when determining the level of intervention needed). The tool needs to be able to adapt to potentially changing abiotic conditions.
- It should be possible to replace a threatened GCU with an equivalent GCU in the case of imminent extinction or drastic genetic erosion (management action A4).

Indicators and verifiers

Indicators/verifiers based on demographic monitoring

General considerations

Indicators and verifiers based on demographic information are intended to serve as the first step in assessing the risk of either local decline or extinction of the target species in a given GCU. Many of the demographic verifiers can be estimated from standard forest inventory information. For each indicator, we list a range of verifiers which each provide several ways to measure the indicator.

I1 Decline in population size

The indicator reflects changes in the number of potentially reproducing trees in the population/GCU for a target species. The number of potentially reproducing trees can be counted, estimated or inferred within a time series of approximately 10 years. The number of trees capable of reproduction, or indicators based on demographic information, can help assess population extinction risk and ability to adapt to changing environmental conditions. Small populations are expected to have reduced ability to adapt to environmental change, because genetic variation is positively correlated with population size. The smaller a population, the more vulnerable it is to random demographic changes, environmental events and reductions in genetic diversity. These three factors often work together and ensure that the population size will decrease further and will ultimately lead to population extinction (according to theories on minimal viable populations and extinction vortices (Gilpin & Soulé 1986)).

Verifiers for this indicator are:

- I1a A decline in the number of reproducing trees
- I1b An increase in the number of dead trees
- I1c A decline in the proportion of the total population containing target species (decreasing area of occupancy by target species)

There are different methods for measuring each verifier:

- **Total visual counts:** (I1a, I1b) for number of dead trees (I1b, it does not make sense to count single dead trees (in terms of costs), except when there is obvious massive dieback (e.g., due to a drought event). In this respect, it is difficult to define thresholds which will correspond to the indicator classes.
- **Estimation based on incomplete counts:** in large areas, small sampling plots can be used to estimate total number of individuals in the GCU. There are a range of methods for estimating number of trees (e.g., quadrats and circular plots). Total number of trees can be estimated by counting the reproducing individuals in each plot, averaging the figure over number of plots and extrapolating the result to total area of the CGU. It may be more appropriate to use line transects in areas with patchy population distribution. The size of the sample plot should be appropriate for the species under investigation (I1a, I1b)
- **Inference from proxy data:** for example, available growing stock in the GCU is defined as the volume of all living trees with more than a certain diameter at breast height. This information can be derived from forest inventories. Data on timber harvest which might affect growing stock in the GCU need to be integrated.
- **Remote sensing**: Number of trees (I1a) and decline in target species population share/area of occupancy (I1c) can also be recorded (counted or estimated) using remote sensing techniques. Any decline can be determined by analysing a series of remote sensing images through time (e.g. airborne LiDAR (Shi *et al.*, 2018) or UAV-based LiDAR (Morsdorf *et al.*, 2018)).

TABLE 2. Operational definition of Indicator I1 (bold) and its verifiers I1a-c.

Code and short name	Unit of measurement	Definition of classes and corresponding action levels	(>> A)
I1 **Decline in population size**	**% / 10 years**	**1 < 25%** **2 25-50%** **3 50-75%** **4 >75%**	**>> A1** **>> A2** **>> A3** **>> A5 or A6**
I1a Decline in number of reproducing trees	% / 10 years	1 < 25% 2 25-50% 3 50-75% 4 >75%	
I1b Increase in number of dead trees	% / 10 years	1 < 25% 2 25-50% 3 50-75% 4 >75%	
I1c Decline in population share	% / 10 years	1 < 10% 2 25-50% 3 50-75% 4 >75%	

I2 Lack of natural regeneration

This indicator estimates the existence of established regeneration in the GCU and only has one verifier: sufficient amount of established regeneration for the long-term sustainable management of the population in sites where regeneration would be expected within the GCU. The threshold for the specific minimum amount of established regeneration in every single case should be set according to regional experience. This is an easy verifier to use as only the presence or absence of established natural regeneration (not seedlings) is recorded, which can be done by local experts. Any cases of insufficient established regeneration over a certain time will need to be examined taking into account silvicultural measures (A2) (e.g., seed fall, saplings, browsing, etc).

TABLE 3. Operational definition of Indicator I2 (bold) and its verifier I2a.

Code and short name	Unit of measurement	Definition of classes and corresponding action levels		(>> A)
I2 **Lack of natural regeneration**	**no/yes** **0/1**	**0** **1**	**established regeneration present** **established regeneration absent**	**>> A1** **>> A2**
I2a Lack of natural regeneration	no/yes 0/1	0 1	established regeneration present no established regeneration over more than 10 years	

I3 Expected decline in population size due to biotic factors

Changes in biotic factors, such as pests and diseases, competitors, predation and browsing, may cause variation in population size. These threats are expected to have stronger or more widespread effects on the population size under climate change. The verifiers belonging to this indicator measure the severity of biotic threats to a population, which is defined as the proportion of trees affected/damaged by the biotic factor (Potter and Crane, 2010). Comprehensive lists of invasive plants are available on the EPPO website. The verifiers can be counted or estimated in the same way as I1. This indicator has several verifiers addressing different biotic threats such as presence of a specific pest or disease, presence of a severe competing species including invasive neophytes, or presence of seed predation and browsing.

Expected severity levels of threatening biotic factors correspond to expected decline in population within 10 years and are maximum-oriented; i.e., the maximum value is considered in all verifiers and included threats. The focus of this indicator does not involve the addition of scores for different pests and diseases (cf. Potter and Crane, 2010), but concentrates instead on specific and harmful pests and diseases (a single one is able to massively reduce a target population).

The presence of severe specific and intense seed predation or browsing over several decades will lead to an irregular distribution of age classes and to a strong fluctuation of population size in the long term (I3c).

TABLE 4. Operational definition of Indicator I3 (bold) and its verifiers I3a-c.

Code and short name	Unit of measurement	Definition of classes and corresponding action levels			(>> A)
I3 **Expected decline in population size due to immediate threatening biotic factor**	**% / 10 years**	**1**	**<20%**	**very low severity**	**>> A1**
		2	**20-40%**	**low severity**	**>> A2**
		3	**40-60%**	**medium severity**	**>> A3**
		4	**60-80%**	**high severity**	**>> A5 or A6**
		5	**>80%**	**very high severity**	**>> A7**
I3a Expected decline in population size due to presence of a severe specific pest or disease	% / 10 years	1	<20%	pest/disease not present in region	
		2	20-40%	pest/disease present in surroundings and minor mortality expected	
		3	40-60%	pest/disease present in surroundings and moderate mortality expected	
		4	60-80%	pest/disease present in surroundings and significant mortality expected	
		5	>80%	pest/disease present in surroundings and complete mortality of all mature trees expected	
I3b Expected decline in population size due to presence of a severe competing species including invasive neophytes	% / 10 years	1	<20%	severe competing species not present in region	
		2	20-40%	severe competing species present in surroundings and minor mortality expected	
		3	40-60%	severe competing species present in surroundings and moderate mortality expected	
		4	60-80%	severe competing species present in surroundings and significant mortality expected	
		5	>80%	severe competing species present in surroundings and complete mortality of all mature trees expected	
I3c Expected decline in population size or long-term fluctuation of population size due to presence of severe specific seed predation or browsing	% / 30 years	1	<20%	severe seed predation/browsing not present in region	
		2	20-40%	severe seed predation/browsing present in surroundings and minor lack of regeneration expected	
		3	40-60%	severe seed predation/browsing present in surroundings and moderate lack of regeneration expected	
		4	60-80%	severe seed predation/browsing present in surroundings and significant lack of regeneration expected	
		5	>80%	severe seed predation/browsing present in surroundings and complete lack of regeneration expected	

I4 Number of potentially reproducing trees declining to below the minimum requirement

This indicator is connected to the minimum requirement regarding number of reproducing trees needed for a specific conservation objective of the GCU. It includes three verifiers which are all described as the number of reproducing trees declining under the threshold for i) widely occurring and stand-forming species (I4a), ii) marginal or scattered tree populations (I4b), and iii) remaining populations of rare or endangered tree species (I4c). Number of reproducing trees is always considered in relation to minimum requirements (mr) given the goal of conservation in a specific GCU. The number itself can be counted or estimated as for I1 and the number of trees transformed to an ordinal scale with five classes.

TABLE 5. Operational definition of Indicator I4 (bold) and its verifiers I4a-c.

Code and short name	Unit of measurement	Definition of classes and corresponding action levels			(>> A)
I4 **Number of potentially reproducing trees declining to below the minimum requirement**	**Ne(pot)** **in relation to GCU entry of fields 38/39 in the EUFGIS database**	**1**	**> mr**	**above the minimal requirements**	**>> A1**
		2	**< mr**	**Slightly below the min. req.**	**>> A2**
		3	**<< mr**	**clearly below the min. req.**	**>> A3**
		4	**<<< mr**	**markedly below the min. req.**	**>> A5 or A6**
		5	**<<<< mr**	**only a few living individuals remaining**	**>> A7**
I4a Number of potentially reproducing trees declining to below the threshold for widely occurring and stand-forming species	Ne(pot)	1	>500		
		2	250-500		
		3	100-250		
		4	50-100		
		5	<50		
I4b Number of potentially reproducing trees declining to below the threshold for marginal or scattered tree populations	Ne(pot)	1	>50		
		2	25-50		
		3	15-25		
		4	<15	(cumulative action)	
		5	<15	(cumulative action)	
I4c Number of potentially reproducing trees declining to below the threshold for remaining populations of rare or endangered tree species	Ne(pot)	1	>15		
		2	<15	(cumulative action)	
		3	<15	(cumulative action)	
		4	<15	(cumulative action)	
		5	<15	(cumulative action)	

TABLE 6. Overview of Ne thresholds for indicator I4, corresponding to minimum requirements for field 39 in the EUFGIS information system.

EUFGIS data standards		Management action levels			
Field 38 (Population Justification)	**Field 39** (Population Reproduc. Trees)	**A3** (*in situ*)	**A5/A6** (*ex situ*, assisted)	**A7** (*ex situ*, living trees)	**A8** (*ex situ*, in stasis)
1 (I4a)	**500**	500	250	100	50
2 (I4b)	**50**	50	25	15	15
3 (I4c)	**15**	15	15	15	15

Indicators/verifiers based on information about immediate or future disturbances

General considerations

The following indicators reflect the potential or directly forthcoming loss of a population/GCU for a particular species. Due to habitat decline, *in situ* conservation may no longer be sustainable (Koskela *et al.*, 2013). *Ex situ* conservation is a necessary complementary system to *in situ* conservation strategies (Fady *et al.*, 2016). In general, it will not be possible to conserve an entire population/GCU, because *ex situ* collections typically contain relatively few trees and will therefore only be able to capture a proportion of the genetic diversity present in the *in situ* populations that they replace. *Ex situ* conservation should thus be chosen as a last resort, on a case by case basis, when specific indicators point to a risk of severe extirpation (Koskela *et al.*, 2013).

These indicators, which have a stochastic background and huge impact on the target population, can lead to the recommendation of several alternative management actions depending on the specific predisposition of the GCU and the realisation of the factor. The national manager decides which alternative action will be the most appropriate.

The risk of extinction of a population is the product of the severity (degree of damage) of a stochastic event and its probability of occurrence (recurring period). In order to combine different origins of events with similar consequences for the target population of a GCU, the subdivision of these indicators is based on the likelihood of occurrence of such events (c.f. Table 7).

TABLE 7. Subdivision of Indicators I5, I6, I7 according to the likelihood of occurrence of the disturbance.

Probability of Occurrence	Immediate population loss (actually happening/ happened)	High probability of population loss	Low probability of population loss
Explanation	Actual loss of the population due to a natural stochastic catastrophe (e.g., fire, avalanches, storm, ice sleet, frost, flooding, land slide).	High probability of population loss due to a foreseeable natural stochastic catastrophe or a foreseen anthropogenic event (e.g., land use change)	Low probability of the population loss due to a potential natural stochastic catastrophe or a potential anthropogenic event (e.g., land use change)
Indicator	**I5**	**I6**	**I7**
Verifiers	I5a – I5c	I6a – I6c	I7a – I7c

I5 Actual loss of population

A natural stochastic catastrophe can destroy a population (GCU). As a result of, for example, fire, avalanches, storm, and other events, such as ice sleet, frost, flooding, and landslides, only single trees in a GCU may survive. It might be possible to recover material (grafting or recovering seeds) and to store some genotypes in archives as seeds to establish a new population. However, the only feasible action may be the replacement of the unit with another unit in the same country/zone. The verifier has a binary form (y/n).

TABLE 8. Operational definition of Indicator I5(bold) and its verifiers I5a-c.

Code and short name	Unit of measurement	Definition of classes and corresponding action levels	(>> A)
I5 **Population size has collapsed to below minimum requirements (but conservation of genotypes is still possible)**	**Ne(pot)** **in relation to GCU entry of fields 38 in the EUFGIS database**	**1 > mr over minimal requirements** **2 < mr clearly under min. req.**	**>> A1** **>> A4**
I5a Number of potentially reproducing trees has collapsed to below the threshold for widely occurring and stand-forming species	Ne(pot)	1 > 500 2 < 500	>> A1 >> A4
I5b Number of potentially reproducing trees has collapsed to below the threshold for marginal or scattered tree populations	Ne(pot)	1 > 50 2 < 50	>> A1 >> A4
I5c Number of potentially reproducing has collapsed to below the threshold for remaining populations of rare or endangered tree species	Ne(pot)	1 >15 2 <15	>> A1 >> A4

I6 High Probability of population loss

Natural stochastic catastrophes are frequent and generally happen with little or no advanced warning in areas endangered by avalanches, forest fire, and air pollution, etc. Relict populations often grow in such areas and when a significant portion of a GCU is deemed likely to vanish as a result of a stochastic catastrophe, evacuation should be planned and carried out. In other words, FRM will need to be collected from the GCU to preserve genetic information in areas with a high probability of population loss due to such natural stochastic events or to changing environmental conditions leading to increased risk.

This approach has been used, for example, in the case of silver fir in the 1980s under the threat of air pollution; pilot studies were carried out in which silver fir populations were secured in areas with clean air (e.g., Melchior *et al.*, 1988, Stephan & Padro, 1993).

GCUs should not be established in areas where they risk not surviving or where target populations risk being destroyed recurrently within a short period of time. In such cases, the valuable genetic resource should be secured *ex situ* in a safe place.

TABLE 9. Operational definition of Indicator I6 (bold) and its verifiers I6a-c.

Code and short name	Unit of measurement	Definition of classes and corresponding action levels			(>> A)
I6 **Population size is in great danger of declining to below the minimum requirements due to a high probability natural or anthropogenic event**	**Ne(pot)** **in relation to GCU entry of fields 38 in the EUFGIS database**	**1** **2**	**> mr** **< mr**	**over minimal requirements** **clearly under min. req.**	**>> A1** **>> A4** **or A6**
I6a Number of potentially reproducing trees is in danger of declining to below threshold for widely occurring and stand-forming species	Ne(pot)	1 2	> 500 < 500		>> A1 >> A4 or A6
I6b Number of potentially reproducing trees is in danger of declining to below the threshold for marginal or scattered tree populations	Ne(pot)	1 2	> 50 < 50		>> A1 >> A4 or A6
I6c Number of potentially reproducing trees is in danger of declining to below the threshold for remaining populations of rare or endangered tree species	Ne(pot)	1 2	>15 <15		>> A1 >> A4 or A6

I7 Low probability of population loss

Losses can occur as a result of land use change and are mainly a consequence of long-term planning processes. Land use change may be in the form of loss of area starting at an edge, reducing the total area of a GCU; for example, transformation to gravel-pits (mining area), leisure parks, industrial estates, etc. In addition fragmentation can result from the dissection of a GCU; for example, power lines, motorways, railway routes, pipelines, etc. (Michalczyk 2008; Mosner *et al.*, 2012; Rathmacher *et al.*, 2010).

TABLE 10. Operational definition of Indicator I7 (bold) and its verifiers I7a-c.

Code and short name	Unit of measurement	Definition of classes and corresponding action levels	(>> A)
I7 **Population size is in danger of declining to below the minimum requirements due a low probability natural or anthropogenic event**	**Ne(pot)** **in relation to GCU entry of fields 38 in the EUFGIS database**	**1 > mr over minimal requirements** **2 < mr clearly under min. req.**	**>> A1** **>> A4 or A6 or A7 or A8**
I7a Number of potentially reproducing trees will decline to below the threshold for widely occurring and stand-forming species	Ne(pot)	1 > 500 2 < 500	>> A1 >> A4 or A6
I7b Number of potentially reproducing trees will decline to below the threshold for marginal or scattered tree populations	Ne(pot)	1 > 50 2 < 50	>> A1 >> A4 or A6 or A7
I7c Number of potentially reproducing trees will decline to below the threshold for remaining populations of rare or endangered tree species	Ne(pot)	1 >15 2 <15	>> A1 >> A4 or A6 or A7 or A8

Indicators/verifiers based on genetic monitoring

General considerations

The indicators of the first subchapter Indicators / verifiers based on demographic monitoring (p.13) are intended to be based on demographic changes assessed by simple measurements taken in the field. However, in an ideal situation, direct genetic measurements should be taken in addition to demographic assessments (Konnert *et al.*, 2011, Aravanopoulos, 2011; Graudal *et al.*, 2014; Aravanopoulos, 2016). This is feasible for more intensively monitored units or for those used as part of a genetic monitoring programme. The field of molecular genetics is advancing rapidly, with a shift from neutral genetic markers to markers linked to, or responsible for, adaptive traits. As soon as genetic data on adaptive traits become available for a target species, corresponding verifiers, or eventually even a new indicator, should be added to the indicator list. If it is possible to obtain direct measures of genetic diversity, in addition to demographic ones, the indicators below can be used. The methods suggested here are placeholders ahead of future methodological developments; collecting samples now and storing them appropriately are key to their future utilisation as baseline data when rapid cost effective genotyping methods become accessible.

I8 Decline in genetic variation (genetic erosion)

This genetic indicator can be used in conjunction with indicator *I1 Relative decline in number of potentially reproducing trees*. It is a direct measure of the relative decline in genetic variation over time. The genetic variation should be estimated as soon as possible to provide baseline data. Subsequently, it should be assessed on a regular basis; for example, every ten years or after significant impacts, such as natural disasters or significant forester intervention on the site. A minimum of 50 individuals should be sampled, but greater numbers will yield greater accuracy (Hoban *et al.*, 2014). Different age cohorts can be used to estimate change over time, taking care to make like-with-like-comparisons when tracking changes in the variation over time; i.e., a particular age cohort should be compared over time, rather than assessing all trees over time. Sample numbers should be temporally consistent, but when this is not possible, measures such as allelic richness can be used to address differences in sample sizes over time. Data from each tree can be used for future studies and therefore a detailed map with the geographical locations of individual trees should be prepared.

The potential verifiers to indicate change in status of genetic variation are:

- Temporal changes in the number of alleles (Na) or allelic richness (Ar) in the case of unequal sample sizes
- Temporal changes in expected heterozygosity (He)
- Changes in allele frequency (A%), specifically for gene variants of adaptive traits or rare alleles
- Decline in effective population size (Ne)

All verifiers are relevant, but number of alleles or allelic richness are perhaps the most informative ones. Hoban *et al.* (2014) evaluated six genetic diversity metrics: number of alleles, allelic size range, observed heterozygosity, expected heterozygosity, the Garza-Williamson M-ratio bottleneck statistic, and Wright's inbreeding coefficient (Fis). Their results showed that the number of alleles provided the clearest response and highest power for monitoring genetic decline. Both number of alleles (richness) and He (evenness) perform better, and are more straightforward and basic, than Fis, which is a 'compound' indicator. The threshold of decline will be species dependent and further research is necessary to determine this. In the absence of quantitative data on actual allelic richness or heterozygosity values for different species, it has been proposed to use levels analogous to the IUCN criteria for categorising the threatened status of a species (IUCN 2012). We propose a reduction of either allelic richness or frequencies of particular alleles, in accordance with IUCN criteria for threat (IUCN 2012); a reduction of 30% or more is considered to indicate that a population is potentially vulnerable, while a reduction of 50% or more suggests that a population is potentially endangered (Table 11).

A reduction in the frequency of rare and private alleles should be given high importance. It is useful to monitor changes in the frequency of rare alleles is useful, because genetic drift may become evident at an earlier stage by assessing the reduction of rare alleles (low frequency alleles) rather than, for example, heterozygosity.

An important point to be taken into consideration is the efficacy of correlating genetic diversity parameters (Ar, He, etc.) with the number of reproducing trees. Small populations will tend to exhibit lower levels of genetic diversity than large populations, because of increased genetic drift and /or inbreeding. A population's effective size is lower than its census size, but the relationship between these verifiers differs substantially between species. Furthermore, it has been shown that the population size is positively correlated with population fitness and genetic variation in plants (Leimu *et al.*, 2006).

TABLE 11. Operational definition of Indicator I8 (bold) and its verifiers I8a-c.

Code and short name	Unit of measurement	Definition of classes and corresponding action levels	(>> A)
I8 Decline in genetic variation (genetic erosion)	**% / 10 years**	**1 < 30% of baseline 2 > 30% of baseline 3 > 50% of baseline**	**>> A1 >> A2 or A3 >> A4 or A5 or A6**
I8a Decline in number of alleles (Na) or allelic richness (Ar)	**% / 10 years**	1 < 30% of baseline 2 > 30% of baseline 3 > 50% of baseline	>> A1 >> A2 or A3 >> A4 or A5 or A6
I8b Decline in expected heterozygosity (He)	**% / 10 years**	1 < 30% of baseline 2 > 30% of baseline 3 > 50% of baseline	>> A1 >> A2 or A3 >> A4 or A5 or A6
I8c Decline in allele and genotype frequencies	**% / 10 years**	1 < 30% of baseline 2 > 30% of baseline 3 > 50% of baseline	>> A1 >> A2 or A3 >> A4 or A5 or A6
I8d Decline in effective population size (Ne)	**% / 10 years**	1 < 30% of baseline 2 > 30% of baseline 3 > 50% of baseline	>> A1 >> A2 or A3 >> A4 or A5 or A6

I9 Decline in genetic variation to below a minimum threshold

This genetic indicator is to be considered as a placeholder for future work. It is a direct estimate of genetic variation via inbreeding effects, allelic richness and heterozygosity. It can be used in conjunction with indicator *I4 Absolute number of reproducing trees declining under minimum requirement* with particular emphasis on a lower threshold below which the genetic variation should not fall. The threshold will be species dependent and the minimum below which a population cannot recover; i.e., it cannot adapt to the changes in the environment. Currently, there is insufficient knowledge to provide meaningful thresholds for this indicator, and therefore more research in the field is needed in order to be able to estimate theoretical or empirical levels for it. In common with the indicator on general decline in variation, the loss of rare - and especially private - alleles should be given particular importance in the context of marginal and peripheral populations.

Management actions

General considerations

According to the pan-European minimum requirements for GCUs of forest genetic diversity, the units comprise either natural or planted tree populations which are managed with the objective of maintaining evolutionary processes and adaptive potential across generations. Each GCU should have a designated status and a management plan, and one or more tree species must be recognised as target species for genetic conservation. The minimum sizes of the GCUs are set at 500, 50 or 15 reproducing individuals, depending on tree species and conservation objectives. Furthermore, silvicultural interventions which aim to promote genetic processes should be allowed as needed, and field inventories should be conducted to monitor regeneration and estimate population size. Activities can be carried out either *in-situ* or *ex-situ* (Koskela *et al.*, 2013).

The level of action A1 can be considered to reflect the current baseline management status of the GCU. If this level is insufficient for maintaining genetic processes, then a series of gradually escalating management intervention actions aiming to help the GCU meet the evolutionary conservation objectives are suggested.

We do not consider the Forest Europe protected area categories (MCPFE classes) to be particularly relevant for this tool; their integration would distract from the indicator concept and thereby dilute its core function of easing decision-making. The tool should therefore aim to retain its universal application and the GCU managers who use it are expected to develop appropriate ways of implementing management actions for their specific cases (every GCU is different).

An important aspect of the decision support tool is the standardisation of terms. This not only applies to input data related to the threat to GCU target populations, but also to output data on recommendations for management actions. To supply optimal support for the documentation of and communication on management being undertaken in a GCU, it should be made clear how each management action has been implemented (cf. table 12a). We propose an open list of concrete measures defining the method and its units of documentation. Even an extensive literature search could not reveal any universal standardized compilation of forest management implementation measures. Therefore, we created a synthesis on the basis of most relevant literature in this field, notably the work of Verkerk *et al.* (2019), Duncker *et al.* (2012) and Bell *et al.* (2008) (cf. table 12b).

Baseline GCU management (A1)

A1 Baseline management continued

This option entails the continuation of current GCU management; current guidelines and management are effective in maintaining the evolutionary potential of a GCU. Once again, we stress that management for maintaining and promoting the long-term evolutionary potential of tree populations is one of the minimum requirements for inclusion of a GCU on the EUFGIS database.

Additional in situ management actions (A2, A3, A4)

A2 Particular silvicultural management

In contrast to current management discussed above, *in situ* silvicultural management is intended to promote dynamic genetic processes to favour adaptation and preserve genetic diversity in the targeted population; flowering is maintained in a sufficient number of reproducing trees while seedling production, growth and survival through adequate light penetration, fire prevention and herbivore control are promoted (references in Koskela *et al.*, 2013; Rauch & Bar-Yam, 2005; Faith *et al.*, 2008). Such management should ensure the continued existence of target tree populations and create favourable conditions for growth and vitality of the target tree species and their natural regeneration (Koskela *et al.*, 2013; Rotach, 2005).

Thinning may be needed to maintain the vitality of the populations and to enhance seed production. However, a sufficient number of reproducing individuals has to be left to maintain the genetic diversity in the next generation. In some situations which experience a Mediterranean climate, light thinning and superficial soil disturbance may help regeneration of many mesophytic species, such as *Abies spp*, and hardwoods, such as

Italian alder, beech, silver birch, etc. Thinning to various target densities is also applied in northern GCUs to enhance regeneration.

When silvicultural treatment is not effective in creating natural regeneration, it will be necessary to resort to artificial regeneration. This involves various options such as: i) collecting seeds (scions?) from the GCU or from a neighbouring autochthonous stand, if no prior collections have been made (the number of mother trees from which seed is collected must meet minimum requirements), ii) growing the FRM needed for the artificial regeneration, or iii) preparing area for planting (cutting and site preparation). These measures also enhance natural regeneration, which can complement artificial regeneration.

A further option is the removal of other species (bushes, shrubs) to promote regeneration of the target species and to reduce competition/pathogens.

Additional actions that should be considered are fencing to reduce grazing pressure on seedling generation and measures to protect adult trees and seedling population from fire, such as firebreaks and pruning.

A3 Redefining the boundaries of an existing GCU

This action is required when a population no longer meets the minimum size requirements for a GCU; for example, as a consequence of a catastrophic event (e.g., forest fire) that has reduced the number of reproducing trees to below the threshold. In order to continue satisfying minimum requirements, redefinition of GCU boundaries may be applied: its dimensions can be extended to incorporate adjacent or neighbouring areas of suitable autochthonous stands and concurrently remove any non-local conspecific material from inside the enlarged GCU. Non-autochthonous material should be replaced by autochthonous material, ensuring that genetic diversity is maintained by collecting seed from an adequate number of mother trees. In Parkano (Finland), for example, the population size of the new target species failed to meet minimum requirements due to the inclusion of additional target species in the GCU; in order to rectify this, the GCU was enlarged by an additional 60 hectares.

A4 Replacing an existing GCU with another

A GCU may become unavailable due to pressures such as changes in land use or catastrophic events. In such cases, in order to maintain a GCU of the same species in the same environmental zone, it will be necessary to replace and relocate the GCU with one of similar characteristics within the surroundings and habitat, or to recombine duplicated and similar units.

For example, in Puolanka (Northern Finland), two rare moss species were found in a GCU of Norway spruce. The presence of these rare mosses demanded the creation of a strict nature conservation area covering most of the GCU, and as a result, silvicultural interventions could no longer be carried out. Due to its northern location (64° 39′) and high altitude (290 – 370 mas), regeneration is not expected to happen without silvicultural intervention on this site. As the two uses of the area could not co-exist, the only option was to establish another GCU. A replacement area was found nearby, in which one spruce stand with non-autochthonous origin was clear cut and replaced with local material collected from a nearby autochthonous stand.

Additional *ex situ* management actions (A5, A6, A7, A8)

A5 Assisted gene flow into a GCU

Manipulating gene flow can have simple and direct applications: it can either disrupt local adaptation of pests or maintain local adaptation of endangered species (Lenormand 2002). However, both positive and negative consequences of gene flow are difficult to predict and future research is needed to improve the integration of dispersal biology into evolutionary quantitative genetics (Kremer *et al.*, 2012).

Under climate change (e.g., recurrent drought spells) or other threats, the persistence of GCUs can be evaluated, especially when showing consistent signs of decline in tree numbers over time. In order to maintain the genetic diversity of the GCU, this management action involves the introduction of material (seeds or plants) from close neighbouring populations which are expected to be adapted to similar conditions.

A6 Assisted translocation of a GCU

When the only option is to move to a new site (e.g., when a land use change is planned for the area), it is possible to relocate a short ecological distance from the original GCU. The number of mother trees for seed or scion collection must meet the minimum requirements (≥ 50 plants at least 50 m apart) in order to sample a representative amount of the population gene pool. In the case of small populations, such as white birch on the Italian Apennines or *Abies nebrodensis* (Sicilian fir), and other scattered species, the whole gene pool must be duplicated. Individuals from meta-populations which have been isolated for centuries due to anthropogenic and/or environmental reasons (e.g., *Quercus petraea* and *Q. robur* in the Po valley) must be placed in a similar ecological area, in order for them to genetically connect within a new, combined GCU and re-establish the original genetic flow.

The number of mother trees for seed or scion collection must meet the minimum requirements. For minimum viable population sizes, Skroppa (2015) recommends establishment with at least 5000 seedlings/saplings collected from populations that contain at least 500 adult individuals. Seeds should be collected during at least two seasons from a minimum of 50 spatially separated mother trees growing across the range of ecological conditions within the site (Kelleher *et al.*, 2015).

A7 Preservation in collections/gardens

In serious situations, such as the need for preventing extinction in a threatened habitat, GCU preservation can be achieved outside its physical and ecological borders by collecting a representative part of the population and placing it in a new location. This can be done by vegetatively propagating the remaining individuals or growing seedlings and planting them in a collection. The collection can be supplemented by material gathered from other populations from the same climatological/ecological zone. It is wise to duplicate the collection at two sites in order to minimise the risk of losing the population. The number of mother trees for seed or scion collection must meet GCU minimum requirements (c.f. A6).

Depending on the size of the unit there are some options: seeds can be collected from the endangered population and a new population established with the plants from the seeds (dynamic approach) or seeds can be stored (static approach). Furthermore, the genotypes can be secured by vegetative propagation

A8 Preservation in seedbank/cryo-preservation

Another form of *ex-situ* preservation is that of storing seeds (seedbank) or storing parts of plants at low temperatures (cryopreservation): seeds or plant tissues are collected from a declining GCU and stored in a seedbank or cryo-preservation facility, with the aim of re-introducing the species to natural conditions as soon as possible.

TABLE 12a. Operational Management action levels (Ax) with exemplary Measures of implementation (Mx) from the open list of standardized Measures of implementation (cf. Tab 12b).

Code and action level Exemplary measures	**Unit of implementation**	**Remark**
A1 **Baseline management continued**		Management "as usual" to ensure continued existence, vitality and natural regeneration of target tree populations (possibly the same as under A2, but as regular silvicultural measures and not as a reaction to an indicated threat)
M183 Group selection cutting	ha and % (volume) or m3	
M124 Natural regeneration (generative)	ha	
...		
A2 **Particular silvicultural management**		Particular silvicultural management to ensure the continued existence of target tree populations and to create favourable conditions for growth and vitality of the target tree species and their natural regeneration
M111 Crown thinning	m (mother trees)	
M171 Elimination of invasive species	ha and % (share) and type	
M124 Natural regeneration (generative)	ha	
M142 Protection of single plants	ha and n (individuals) and type	
...		
A3 **Redefining the boundaries of existing GCU**		Enlargement of the unit's boundaries to cover suitable autochthonous stand adjacent to the GCU
M312 Continuation of existing GCU via enlargement of GCU perimeter	ha (increase)	
...		
A4 **Replacement of the existing GCU with another GCU**		Replacement of GCU to a site of similar characteristics where the population and natural conditions correspond best to the former GCU
M313 Replacement of existing GCU via shift of GCU perimeter	ha (reduction) and ha (increase)	
...		

(Table 12a continued)

Code and action level Exemplary measures	Unit of implementation	Remark
A5 **Assisted gene flow into GCU**		Introduction of FRM from neighbouring populations which are expected to be adapted to similar conditions
M112 Seed yield	n (seeds) and m (mother trees)	
M121 Plantation of seedlings	ha and n (individuals) and provenance	
...		
A6 **Assisted translocation of GCU**		Relocation at short ecological distance from the original GCU
M321 Establishment of equivalent GCU via assisted translocation of GCU target population	GCU (creation of new entry acc. to EUFGIS standard)	
M112 Seed yield	n (seeds) and m (mother trees)	
M121 Plantation of seedlings	ha and n (individuals) and provenance (GCU)	
...		
A7 **Preservation in collections/gardens**		The remaining individuals from a declining GCU will be cloned (or seedlings grown) and planted in a collection as a preservation of living trees outside of natural habitat
M322 Establishment of an *ex si*tu conservation unit conserving GCU target population as living trees	ID (*ex situ* unit) and type (*ex situ* unit)	
M113 Cuttings yield	n (individuals) and m (clones)	
M122 Plantation of cuttings	ha and n (individuals) and m (clones) and provenance	
M151 Pesticide application	ha and type	
...		

(Table 12a continued)

Code and action level Exemplary measures	Unit of implementation	Remark
A8 **Preservation in seedbank/cryo-conservation**		Seed or tissue collected from a declining GCU stored in a seedbank or cryo-conservation facility as a form of preservation in stasis in order to get naturalized later
M323 Establishment of an *ex situ* conservation unit conserving GCU target population in stasis	ID (*ex situ* unit) and type (*ex situ* unit)	
M116 Seedbank	n (seeds) and m (mother trees)	
M117 Cryo-conservation	n (individuals)	
...		

FIGURE 12b. Open list of standardized Measures of implementation for the Management of GCU (Tab 12a), defining the measures and their unit(s) for standardised documentation of Management action (numbering with open slots for additions of measures or groups of measures).

Group, code and name	Unit of implementation	Definition of method/technique
Stand level (M100)		Measures taken for GCU target population and its stands
Reproductive material		Reproductive material from GCU target population
M111 Crown thinning	m (mother trees)	Deliberation of mother trees of GCU target population
M112 Seed yield	n (seeds) and m (mother trees)	Generative FRM
M113 Cuttings yield	n (cuttings) and m (clones)	Vegetative FRM
M114 Seed bank	n (seeds) and m (mother trees)	Generative FRM
M115 Cuttings bank	n (cuttings) and m (clones)	Vegetative FRM
M116 Seedbank	n (seeds) and m (mother trees)	
M117 Cryo-conservation	n (individuals)	
...		
Regeneration		Regeneration of GCU target population
M121 Plantation of seedlings	ha and n (individuals) and provenance	Generative FRM
M122 Plantation of cuttings	ha and n (individuals) and m (clones) and provenance	Vegetative FRM
M123 Seeding	ha and n (seeds) and provenance	
M124 Natural regeneration (generative)	ha	
M125 Coppice/rootsuckers (vegetative)	ha	
...		
Protection against browsing		Direct protection of regeneration of GCU target population
M141 Fencing	ha	
M142 Protection of single plants	ha and n (individuals) and type	Type of single plant protection (e.g. chemical, mechanical, tube)
...		

(Table 12b continued)

Group, code and name	Unit of implementation	Definition of method/technique
Protection against pests		Direct protection of regeneration of GCU target population
M151 Pesticide application	ha and type	Type of pesticide
M152 Removal of affected plants	ha and n (individuals) and type	Type of pest
...	...	
Tending/Thinning		Intervention in favor of GCU target population and/or in favor of natural stand composition
M171 Elimination of invasive species	ha and % (share) and type	Share of GCU target species and type of invasive species
M172 Removal of competitors	ha and % (share)	Share of GCU target species
M173 Removal of coverage	ha and % (coverage) or m3	
...		
Final harvest		Intervention in favor of the generation cycle (drive rotation)
M181 Clear cutting	ha and % (volume) or m3	% of standing volume
M182 Shelterwood cutting	ha and % (volume) or m3	% of standing volume
M183 Group selection cutting	ha and % (volume) or m3	% of standing volume
M184 Selective cutting	ha and % (volume) or m3	% of standing volume
...		
Site level (M200)		Technical measures taken for GCU site factors
Soil cultivation		
M211 Physical site preparation	ha and type	Type of physical preparation
M212 Chemical site preparation	ha and type	Type of chemical preparation
M213 Fertilization for growth/yield	ha and type	Type of fertilizer
M214 Liming	ha and type	Type of active lime
M215 Nutrient compensation	ha and type	Type of nutrient
M216 Vegetative nitrogen-fixation	ha and n (individuals) and type	Type of nitrogen-fixing species
...		

(Table 12b continued)

Group, code and name	Unit of implementation	Definition of method/technique
Drainage		
M221 Physical drainage system	ha and Euro (cost)	Construction cost of physical drainage system
M222 Nurse crop drainage	ha and n (individuals) and type	Type of nurse crop species
...		
Irrigation		
M231 Physical irrigation system	ha and Euro (cost)	Construction cost of physical irrigation system
M232 Irrigation	ha and m3 (water)	
...		
Forest fire control		
M251 Physical fire-fighting system	ha and Euro (cost)	Construction cost of physical fire-fighting system
M252 Crown fire control/extinction	ha	
M253 Ground fire control/extinction	ha	
M254 Preventive controlled ground fire	ha	Reduction of flammable biomass
...		
Avalanche control		
M261 Permanent avalanche protection	ha and Euro (cost)	Construction cost of permanent avalanche protection system
M262 Temporary avalanche protection	ha and Euro (cost)	Construction cost of temporary avalanche protection system
...		
Landslide control		
M271 Physical slope shoring	ha and Euro (cost)	Construction cost of permanent avalanche protection system
M272 Vegetative slope shoring	ha and n (individuals) and type	Type of slope shoring species
...		

(Table 12b continued)

Group, code and name	Unit of implementation	Definition of method/technique
Windstorm control		(in general via stand stabilization measures, cf. stand level M100)
...		
Unit level (M300)		Organisational measures taken for GCU redefinition
Organizational redefinition of existing GCU		
M311 Abandonment of GCU	GCU	Dataset of abandoned GCU to be maintained
M312 Continuation of existing GCU via enlargement of GCU perimeter	ha (increase)	Integration of perimeters in the surroundings with shares of the same GCU target population (cf. management action level A3)
M313 Replacement of existing GCU via shift of GCU perimeter	ha (reduction) and ha (increase)	Shift to another GCU perimeter in the surroundings with shares of the same GCU target population (cf. management action level A4)
...		
Organizational redefinition of type of conservation of GCU target population		
M321 Establishment of equivalent GCU via assisted translocation of GCU target population	GCU (creation of new entry acc. to EUFGIS standard)	Translocation of reproductive material from an endangered or collapsed GCU target population to a new GCU with more favourable conditions (cf. management action level A6)
M322 Establishment of a living *ex situ* conservation unit conserving GCU target population as living trees	ID (*ex situ* unit) and type (*ex situ* unit)	Conservation of reproductive material from an endangered or collapsed GCU target population to *ex situ* conservation unit (cf. management action level A7)
M323 Establishment of an *ex situ* conservation unit conserving GCU target population in stasis	ID (*ex situ* unit) and type (*ex situ* unit)	Conservation of reproductive material from an endangered or collapsed GCU target population to *ex situ* conservation unit (cf. management action level A8)
...		

Applicability of the decision support tool for new types of GCUs

The decision support tool is also designed to be applicable to new types of GCUs.

The EUFGIS information system can already incorporate new types of GCUs, with or without minor modifications. As soon as new types of GCUs have been added to the EUFGIS database, they should be monitored via the decision support tool based on the same data input as all the other GCUs. Furthermore, new GCUs of marginal and peripheral populations, as well as of populations of introduced species, must fulfil the same minimum requirements as all other GCUs in the EUFGIS database.

Marginal and peripheral (MaP) populations

Geographical marginality could be dealt with by including marginal and peripheral (MaP) populations in GCUs, thus potentially enriching the overall representation of GCU genetic diversity. (cf. chapter Identification and integration of marginal and peripheral populations of pan-European interest, p. 49). In the EUFGIS information system, the case of GCU for MaP populations is only partially and ambiguously covered by the existing field 38 Population Justification. Designating MaP populations as GCUs could be justified by applying class 2 ("to conserve specific and/or phenotypic traits in scattered tree populations which are often relatively small") and class 3 ("to conserve rare or endangered tree species with populations consisting of a low number of remaining individuals"). However, these two justifications for conservation do not imply that the target population is marginal or peripheral *per se*. Therefore, an additional field needs to be added to EUFGIS in order to flag the MaP populations.

If the population does not meet the requirements of an *in situ* GCU, but contains potential valuable genetic diversity, it could be included in an *ex situ* conservation unit to be maintained for future generations.

Populations of introduced species

GCUs focusing on introduced species could be incorporated into the EUFGIS information system if such species have been present for several generations, during which time they may have begun to adapt to the local conditions to form landraces. Those species have developed traits that are, or may become, a valuable genetic resource for the country in question (cf. chapter Identification and integration of marginal and peripheral populations of pan-European interest, p.49).

In the past, interest in FGR from introduced species was mainly related to wood production (e.g. *Larix kaempferi*, *Picea sitchensis*, *Pseudotsuga menziesii*, *Quercus rubra* and *Juglans nigra*).

However, in the context of climate change there is an increasing interest in introduced species due to their specific tolerances and adaptive capacities to drought stress (e.g., *Pinus nigra, Cedrus atlantica,* and *Robinia pseudoacacia*). For both the above reasons, the conservation of FGR containing specific adaptations (landraces) of introduced species is important.

In the EUFGIS information system, the case of GCUs for populations of introduced species is already covered by field 35, ("Population Origin"), class 2 ("introduced"). However, in field 38, ("Population Justification") an appropriate class is missing and needs to be added as class 4 ("conservation of specific adaptive and/or phenotypic traits in populations/ landraces of introduced species"). For this new class, the minimum requirement concerning population size needs to be defined in relation to the classes belonging to field 39 ("Population Reproducing Trees").

Defining an introduced species/population is not a straightforward task. There are different systems and criteria leading to a huge variety of cases of non-nativeness exist throughout European countries:

1) Botanical standards (autochthony/"indigenism" vs. nativeness/"exoticism");

2) Degree of exoticism (geographical distance/country level vs. ecological distance/ environmental level);

3) Degree of breeding (wide range of provenances vs. directional selection of provenances);

4) FGR species (tree species vs. phanaerophytes, including. shrub species).

For the moment, the national interest in conserving FGR is the main criterion for integration of GCUs with populations of introduced species into the EUFGIS database. Nevertheless, these differences will impede the development of consistent standards in the future.

Integration of the decision support tool into the EUFGIS information system

TABLE 13. Existing and additional Fields and Values for the integration of the DST into EUFGIS information system in relation to the actual EUFGIS data standard.

Code and short name	EUFGIS data standard: Fields and Values (or predefined Classes) (* = mandatory)	
	Existing	Additional
Time series data		
Creation of a new dataset for existing GCU/population	***Field 22** Unit Data Collection Year (integer, YYYY) ***Field 32** Population Last Visit Year (integer, YYYY)	[new key feature, for creation of a new dataset on population level]
New types of GCU		
GCU for marginal and peripheral populations (MaP populations)	***Field 38** Population Justification **Class 2)** ... specific traits in marginal or scattered tree populations ... **Class 3)** ... rare or endangered tree species ... low number of remaining individuals	**new Field** Population Marginality/Periphery for unambiguously flagging these MaP populations
GCU for Introduced species populations	***Field 38** Population Justification	**new Class 4)** to conserve specific adaptive and/or phenotypic traits in populations/ and races of introduced species [minimum requirement of population size has to be defined for this new class]
Verifiers of DST		
I1a Decline in number of reproducing trees		***Field I1a_Ne** Number of reproducing trees (integer) [>> this new field is also used for new arithmetical fields I4a/I4b/I4c (see below)]
		***Field I1a_Q** 1) counted 2) estimated 3) inferred
I1b Increase in number of dead trees		***Field I1b_Nd** Number of dead trees (integer)

(Table 13 continued)

Code and short name	EUFGIS data standard: Fields and Values (or predefined Classes) (* = mandatory)	
	Existing	Additional
		***Field I1b_Q** 1) counted 2) estimated 3) inferred
I1c Decline in the population share	***Field 43** Population Share (integer, %)	
		***Field I1c_Q** 2) estimated 3) inferred
I2a Lack of natural regeneration	**Field 41** Population Regeneration **Classes** **1)** continuous **2)** sporadic **3)** requires management intervention	*** new mandatory** [classes 1+2 = no, no lack/sufficient reg. class 3 = yes, lack/insufficient reg.]
		Field I2a_REM (string) [remarks on potential/observed factors causing lack of regeneration]
I3a Expected decline in population size due to presence of a severe specific pest or disease		***Field I3a_PD%** 1) <20% 2) 20-40 % 3) 40-60% 4) 60-80% 5) >80%
I3b Expected decline in population size due to presence of a severe competing species including invasive neophytes		***Field I3b_PD%** 1) <20% 2) 20-40 % 3) 40-60% 4) 60-80% 5) >80%

(Table 13 continued)

Code and short name	**EUFGIS data standard: Fields and Values** (or predefined Classes) **(* = mandatory)**	
	Existing	**Additional**
I3c Expected decline in population size or long-term fluctuation of population size due to presence of severe specific seed predation or browsing		***Field I3c_PD%** 1) <20% 2) 20-40 % 3) 40-60% 4) 60-80% 5) >80%
		Field I3a_REM (string) [remarks on potential/observed factors causing decline in population size]
I4a Number of potentially reproducing trees declining to below the threshold for widely occurring and stand-forming species	***Field 38** Population Justification **Class 1)** to maintain genetic diversity in large tree populations	***arithmetical Field I4a_Nmin** [using also new **Field I1a_Ne**] 1) >500 2) 250-500 3) 100-250 4) 50-100 5) <50
I4b Number of potentially reproducing trees declining to below the threshold for marginal or scattered tree populations	***Field 38** Population Justification **Class 2)** to conserve specific adaptive and/or phenotypic traits in marginal or scattered tree populations which are often relatively small	***arithmetical Field I4b_Nmin** [using also new **Field I1a_Ne**] 1) >50 2) 25-50 3) 15-25 4) <15 5) <15
I4c Number of potentially reproducing trees declining to below the threshold for remaining populations of rare or endangered tree species	***Field 38** Population Justification **Class 3)** to conserve rare or endangered tree species with populations consisting of a low number of remaining individuals	***arithmetical Field I4c_Nmin** [using also new **Field I1a_Ne**] 1) >15 2) <15 3) <15 4) <15 5) <15
		Field I3a_REM (string) [remarks on potential/observed factors causing decline in population size]

(Table 13 continued)

Code and short name	EUFGIS data standard: Fields and Values (or predefined Classes) (* = mandatory)	
	Existing	Additional
I5a Number of potentially reproducing trees has collapsed to below the threshold for widely occurring and stand-forming species	***Field 38** Population Justification **Class 1)** to maintain genetic diversity in large tree populations	***arithmetical Field I5a_Nmin** [using also new **Field I1a_Ne**] 1) >500 2) <500
I5b Number of potentially reproducing trees has collapsed to below the threshold for marginal or scattered tree populations	***Field 38** Population Justification **Class 2)** to conserve specific adaptive and/or phenotypic traits in marginal or scattered tree populations which are often relatively small	***arithmetical Field I5b_Nmin** [using also new **Field I1a_Ne**] 1) >50 2) <50
I5c Number of potentially reproducing has collapsed to below the threshold for remaining populations of rare or endangered tree species	***Field 38** Population Justification **Class 3)** to conserve rare or endangered tree species with populations consisting of a low number of remaining individuals	***arithmetical Field I5c_Nmin** [using also new **Field I1a_Ne**] 1) >15 2) <15
I6a Number of potentially reproducing trees in danger of declining to below the threshold for widely occurring and stand-forming species	***Field 38** Population Justification **Class 1)** to maintain genetic diversity in large tree populations	***arithmetical Field I6a_Nmin** [using also new **Field I1a_Ne**] 1) >500 2) <500
I6b Number of potentially reproducing trees in danger of declining to below the threshold for marginal or scattered tree populations	***Field 38** Population Justification **Class 2)** to conserve specific adaptive and/or phenotypic traits in marginal or scattered tree populations which are often relatively small	***arithmetical Field I6b_Nmin** [using also new **Field I1a_Ne**] 1) >50 2) <50
I6c Number of potentially reproducing trees is in danger of declining to below the threshold for remaining populations of rare or endangered tree species	***Field 38** Population Justification **Class 3)** to conserve rare or endangered tree species with populations consisting of a low number of remaining individuals	***arithmetical Field I6c_Nmin** [using also new **Field I1a_Ne**] 1) >15 2) <15

(Table 13 continued)

Code and short name	EUFGIS data standard: Fields and Values (or predefined Classes) (* = mandatory)	
	Existing	Additional
I7a Number of potentially reproducing trees will decline to below the threshold for widely occurring and stand-forming species	***Field 38** Population Justification **Class 1)** to maintain genetic diversity in large tree populations	***arithmetical Field I7a_Nmin** [using also new **Field I1a_Ne**] 1) >500 2) <500
I7b Number of potentially reproducing trees will decline to below the threshold for marginal or scattered tree populations	***Field 38** Population Justification **Class 2)** to conserve specific adaptive and/or phenotypic traits in marginal or scattered tree populations which are often relatively small	***arithmetical Field I7b_Nmin** [using also new **Field I1a_Ne**] 1) >50 2) <50
I7c Number of potentially reproducing trees will decline to below the threshold for remaining populations of rare or endangered tree species	***Field 38** Population Justification **Class 3)** to conserve rare or endangered tree species with populations consisting of a low number of remaining individuals	***arithmetical Field I7c_Nmin** [using also new **Field I1a_Ne**] 1) >15 2) <15
		Field I5/6/7_REM (string) [remarks on potential/observed danger from stochastic or anthropogenic events]
I8a Decline in number of alleles (Na) or allelic richness (Ar)		**Field I8a_Ar** [using a defined specific baseline for Ar] < 30% of baseline > 30% of baseline > 50% of baseline
I8b Decline in expected heterozygosity (He)		**Field I8b_He** [using a defined specific baseline for He] < 30% of baseline > 30% of baseline > 50% of baseline
I8c Decline in allele and genotype frequencies (A%)		**Field I8c_A%** [using a defined specific baseline for A%] < 30% of baseline > 30% of baseline > 50% of baseline

(Table 13 continued)

Code and short name	EUFGIS data standard: Fields and Values (or predefined Classes) (* = mandatory)	
	Existing	**Additional**
I8d Decline in effective population size (Ne)		**Field I8d_Ne** [using a defined specific baseline for Ne] < 30% of baseline > 30% of baseline > 50% of baseline
		Field I8_REM (string) [remarks on potential/observed danger from genetic erosion]
Management action		
Ax recommendation of management actions (by decision support tool)		**Field A_rec** (multiple choice) **1) A1** **2) A2** **3) A3** **4) A4** **5) A5** **6) A6** **7) A7** **8) A8**
Ay decision on management actions to be implemented (by national coordinator and GCU manager)		**Field A_dec** (multiple choice) **1) A1** **2) A2** **3) A3** **4) A4** **5) A5** **6) A6** **7) A7** **8) A8**
Az realisation of management actions (by GCU manager)		**Field A_real** (multiple choice) **1) A1** **2) A2** **3) A3** **4) A4** **5) A5** **6) A6** **7) A7** **8) A8**

(Table 13 continued)

Code and short name	EUFGIS data standard: Fields and Values (or predefined Classes) (* = mandatory)	
	Existing	Additional
In future this field could be extended to a more precise documentation of the implementation of measures (c.f. Table 12b)		**Field Ay_REM** (string) [remarks on the implementation of measures related to the realisation of management actions]

IDENTIFICATION AND INTEGRATION OF MARGINAL AND PERIPHERAL (MAP) POPULATIONS OF PAN-EUROPEAN INTEREST

General considerations

MaP populations combine potential uniqueness and genetic value. Marginal (Ma) populations are populations growing in ecologically (climatically) marginal conditions. This means that they are growing at the edges of their ecological niche space. Whereas Peripheral (P) populations are populations growing at the edge of the geographic distribution of a species. These populations can be found at the leading edge or at the rear edge of the distribution range, as well as on altitudinal edges of the distribution of a species. Populations can be both marginal and peripheral, but this is not necessarily the case. Peripheral populations may be disjunct; i.e., not or very poorly connected by gene flow with the other populations of the same species (Fady *et al.*, 2016 and references therein).

The current geographic distribution of European species and their genetic structure are the result of climatic oscillations during the Quaternary period (Hewitt, 2004). Persistence in several isolated, discrete refugia of many species during these long glacial episodes has allowed population divergence (Hampe & Petit, 2005) and intraspecific microevolution to occur. In addition to higher genetic differentiation of geographically peripheral populations, they are also expected to exhibit lower genetic diversity than central populations, owing to chronic genetic drift, low gene flow and excess of inbreeding. Hence, peripheral populations are likely to be at higher risk of extinction and have therefore been considered by some to be of little significance in terms of future evolutionary potential (Eckert *et al.*, 2008). However, as marginal or peripheral populations can be subject to strong selective pressure when exposed to harsh and extreme environmental conditions, they may also contain intrinsic evolutionary potential for adaptation and speciation (Sexton *et al.*, 2009). As well as containing populations in which the most significant evolutionary changes may occur, marginal and peripheral (MaP) populations may also be the source of migrants for the colonisation of new areas at leading edges or genetic novelty for reinforcing standing genetic variation in various parts of the range (Fady *et al.*, 2016).

According to the COST Action FP1202 Policy brief, unique genetic information may be found to exist in MaP populations, once these data are available, because:

- they have distinctive evolutionary histories, and may often contain unique genetic variants;
- they may harbour genes specific for the extreme conditions of the environments they occupy, which are unlikely to be found in core populations;
- they may be hotspots of biodiversity and may contain particular phenotypic and genetic forms.

Therefore, the inclusion of MaP populations in the GCU network will add value to the network as a whole by providing genetic resources locally adapted to marginal conditions and range edges. This is the reason for their inclusion in the GCU network, rather than the fact that MaP populations may be facing an increasing risk of extinction. In order to avoid confusion, the marginal populations will not form part of the "core network", but will refer to a few selected GCUs representing the whole distribution area as defined by the pan-European conservation strategy (de Vries *et al.*, 2015). In EUFGIS, for ease of identification GCUs for marginal populations will have a different flag and name (e.g., network of MaP-GCUs).

Overview of the process

In addition to developing the DST for the management of existing GCUs, the working group was tasked by the EUFORGEN 2015 Steering Committee Meeting to extend the DST, in order to aid the identification of MaP populations and to include them as additional units in the network. The main reason for this is their potential 'genetic value' (cf. Table 1, p.6). These populations may contain unique genetic resources absent elsewhere in their natural distribution range. How the GCUs representing MaP populations should be integrated into the Pan-European Conservation Strategy requires further deliberation and is not addressed here.

As with all other GCUs, MaP populations must meet minimum requirements to be entered into the EUFGIS database. Unfortunately, the value of most MaP populations cannot yet be assessed on the basis of genetic data, as such information is only available for a small proportion of the populations. Therefore, most decisions regarding the value of MaP populations will be made on the basis of available geographic information. The identification and inclusion of MaP populations in the EUFGIS database will follow a three-step approach:

1. The identification of a MaP GCU based on the peripheral or marginal location of a population utilising available geographical and ecological (climatic) information.
2. The evaluation of the "genetic value" of the MaP population. This step will involve research on the GCU and will most likely be postponed.
3. The decision at the national level on the inclusion of a MaP population into the EUFGIS database on the basis of information from points 1 and 2 (if available).

In the first step, areas which fit the definition of marginality and periphery are identified per species and mapped via an automated process. Subsequently, they are shared with the EUFGIS national focal points to help them determine whether any of the existing GCUs in their country are marginal or peripheral and to then identify an area where such populations could be located/searched for at the national level. Ecological (climatic) marginality can be assessed following a niche modelling approach of environmental suitability per species, developed by the Joint Research Centre or COST Action FP1202. In addition to ecological (climate) marginality, geographic marginality must be taken into account. In order to model geographic periphery, indices which are under development in the COST Action FP1202 can be used. To assess geographic marginality (i.e., periphery), the COST Action used three different indices, namely Central/Peripheral (C/P) index, population size and isolation index (see also paragraph 3.2 how these indices are calculated). Three historical factor indices were used to reflect the migration and demographic changes of the species (including the most common geographical trends known in forest species and those related to the putative glacial refugia described for the species): i) North/South (N/S) edge index, ii) West/East (W/E) edge index, and iii) Leading/Rear (L/R) index. Alternatively, a bottom up approach relying on national information sources and expert knowledge could be used to identify MaP populations already in the EUFGIS database, as well as new ones to add value to the (core) network. In the COST action, such an approach was followed by obtaining expert knowledge about, for example, the ecological marginality of the population, type of marginality related to geography (Core/ Leading edge/ Rear Edge) and type of fragmentation (Peripheral/ Disjunct).

An evaluation of the “genetic value” of the MaP GCU should be carried out as soon as possible (given the technological constraints) to determine whether the MaP GCU will add value to the core network. The precondition is that the core network should also be genetically characterised. It will often only be possible to carry this out as the final step of the process, thereby changing the sequence of the steps to 1, 3 and 2.

The decision to add a MaP population to the EUFGIS database will always be made at national level. An automated approach to the process of identifying marginal areas should be preferred and this could be embedded in the EUFGIS intranet. This would require expanding the EUFGIS information system to incorporate the new functionalities. Once marginal areas have been automatically identified on maps, local experts at national level can search them for MaP populations. It will also be possible to suggest MaP populations based on local expert knowledge. This means that populations identified as being marginal/peripheral based on national perspective - even in the areas not detected as ‘potentially peripheral or marginal’ by the automated approach - can be entered into the EUFGIS database.

All MaP populations should be flagged in the EUFGIS database. EUFGIS National Focal points will have the authority and facility to mark an existing GCU as "marginal or peripheral" or create new MaP-GCU as appropriate. These new MaP-GCUs will be recommended as add-ons to the core network, but should not form an integral part of it. The new functionalities (automatically identifying marginal areas, etc.) will not be immediately available, but flagging the MaP-GCUs will allow the decision support tool to be operational, even in their absence.

Once the MaP populations have been added to the EUFGIS database, the national focal point should at a later stage assess whether the potential MaP GCU will add value to the network.

Description of the steps

Once the national level decision to add a MaP population to the GCU network has been made, it will be identified using the approach developed by the COST FP1202 MaP-FGR action. In the absence of genetic data, ecological (climatic) and/or geographic marginality of a population will be determined via an automatic procedure. The final decision about whether the identified MaP populations can add value to the GCU network from a genetic point of view (at national and European levels) will be made by national experts based on either genetic data or expert knowledge. The identification process will include the following:

A. Modelling of potential ecological (climatic) and geographical marginality utilising indices which: (to be refined according to Marchi *et al.* under development)

a) Reflect the environmental (climate) niche of populations
- Climatic marginality: Assessed as the z-value corresponding to a given population with respect to the climatic niche within the entire distribution of the species.

b) Reflect population geography
- Central/Peripheral (C/P) index. The C/P index is the absolute z-value of a given population in the distribution function of the distance to the centre of mass of the species distribution.
- Population size: patch size in hectares in which a specific target population is included. This value can be considered as a proxy of effective population size (Ne).
- Isolation index: especially useful for discontinuous distributions, this index represents the distance of each patch to the nearest conspecific patch (>100 ha) and outside a 50 km buffer.

c) Reflect historical migration and demographic changes of the species, including the most common geographical trends known in forest species, and those related to the putative glacial refugia described for the species
   - North/South (N/S) edge index: z-value of a given population in the North/South axis of the distribution of a given species.
   - West/East (W/E) edge index: z-value of a given population in the West/East axis of the distribution of a given species.
   - Leading/Rear (L/R) index: z-value of a given population in the distance distribution from the closest putative glacial refugium of the species.

d) Show the derived information on European coverage maps per index separately. These maps will be available on the EUFGIS website. Recommendations exist in the form of maps to be utilised by NFPs for identification of national MaP GCUs.

The scripts for calculation of the indices developed by COST MaP FGR action (Marchi *et al.* under development) will be handed in to the EUFORGEN secretariat and European Commission Joint Research Centre (JRC), so that the process for all species with available distribution ranges can be automated. This process will allow maps with European coverage to be available on the EUFGIS website, and higher resolution maps with national coverage to be available in the EUFGIS database. As a result of the latter, it will be possible to identify those GCUs already entered in the EUFGIS database as MaP populations, as well as any potential new MaP populations to be included as GCUs at national level.

B. Determining potential marginality of a GCU as suggested by the automated process and identifying populations that could become new MaP GCUs. At the national level:

a) EUFGIS Focal Points will be informed of areas with potential presence of MaP populations based on geographic and/or ecological features. GCUs already located in these areas should be provisionally flagged as MaP, pending national decision.

b) EUFGIS focal points should, together with national experts, search possible MaP populations that would add value to the GCU network in identified areas. Additionally, MaP populations could also be suggested based on national experience, even if they are located outside the area suggested by the automated process (point "A" above).

c) The status of marginality can be accepted or rejected by applying national expert knowledge

d) Existing GCUs that have been identified as comprising MaP populations should be flagged as such in the EUFGIS database. Other populations that have been identified as MaPs that could add value to the GCU network should be entered into the process of becoming GCUs at national level. In such cases, the identified population can gain the status of a new MaP-GCU and can be added to the network, without being part of the core network of GCUs.

The EUFGIS database should automatically flag GCUs recognised as MaP populations by the automated process pending approval by the national focal point.

C. Validating the additional genetic value of the MaPs (at a later stage)

The additional genetic value of the MaPs will need to be demonstrated in support of their inclusion in the system. This applies to all GCUs that have not yet been genetically characterised. Assessing the additional genetic value can be achieved by carrying out genetic studies, rating their diversity (e.g., estimating gene diversity and/or allelic richness), rating their differentiation from core populations, carrying out phylogeographic studies (trying to reconstruct the past population size and gene flow and assessing the spatial dynamic of the species in the continent over time) and conducting provenance tests (comparing the different fitness and relevant phenotypic characters between central and marginal populations).

CONCLUSIONS AND RECOMMENDATIONS

The pan-European strategy for the genetic conservation of forest trees was not specifically designed to conserve FGR under climate change. Therefore, additional measures are needed and were initiated by the EUFORGEN Steering Committee via working groups in phases IV (2010-14) and V (2015-2019).

This report gives the results of the working group regarding two very relevant aspects concerning the conservation management of FGR in Europe in the context of climate change.

Firstly, threats to GCU target populations triggered or reinforced by climate change must be anticipated, or at least recognised, and adequate management action must be taken into consideration. In this context, Working Group 7 has developed a decision support tool to guide national GCU coordinators and managers. Most of the open questions around this tool have been solved and a practically applicable tool is ready for implementation within the EUFGIS information system. The tool aims to serve two functions: i) directly support the decision-makers responsible for the national GCUs, ii) make decision processes transparent and provide standardised documentation related to the development of FGR in GCUs, as well as of the realised management actions and their impact. The latter might be one of the key factors for long-term monitoring and bring us insights into the effectiveness of management actions.

Secondly, increasing threats by climate change might primarily affect populations which are already suffering under certain environmental pressure. This is particularly likely in marginal populations in southern areas that are on the rear edge of the potential direction of migration. Not only do these populations potentially contain unique genetic diversity, but they also show the first signs of population decline and are at greatest risk of being lost. There is a consensus that such marginal and peripheral (MaP) populations must be analysed now, and if found to have high genetic value, they must be integrated into the pan-European conservation strategy and its GCU network. For the identification and integration of MaP populations, an effective procedure or mechanism will need to be developed.

The working group considers the delineated Decision Support Tool on GCU management to be an effective instrument with high applicability. Once final corrections to the data structure and clarification of the relationship with existing databases have been completed, the tool should be implemented in the EUFGIS information system as soon as possible.

In addition, we propose that a brief user manual and an introductory course for the users be developed. We recommend immediate finalisation and implementation so that it can be made available for use by national GCU coordinators and managers.

In order to make best use of the time series data on GCU populations in relation to implemented management actions (communication on best practice, knowledge on effectiveness) we propose that measures for implementation of management actions (method/technique, unit quantity/intensity, definitions, cf. Tables 12a+b, p. 32) be further standardised.

The integration of the tool into the EUFGIS information system and its data standard means that it can be simultaneously used for documentation, decision-making related to GCU management and basic monitoring purposes (entry of time series data). Appropriate features of the EUFGIS information system need to be developed in order for the data to be visualised and the decision support tool to serve as a warning system. To this end, the budget for EUFGIS will need to be adjusted accordingly.

Countries should integrate populations and landraces of introduced species of national interest into the GCU network. In parallel, and because climate change will increasingly necessitate different forms of assistance via species migration and gene flow, progress needs to be made in developing consistent standards and definitions of species introduction. These standards must include the handling of *ex situ* populations originating from assisted translocation, which are potentially representing future *in situ* tree species compositions.

The results of the integration of MaP populations into the GCU network are also a form of preparation for future climate change impact on FGR. However, the development process of such a mechanism, starting from defining marginality in unequivocal terms, is just beginning and is highly complex. We recommend the establishment of a subsequent working group to further develop this mechanism in collaboration with the community of the former COST action FP1202 MaP-FGR and subsequent work on the topic, and by making use of the EUFORGEN/EUFGIS information system and the European Commission Joint Research Centre (JRC).

For the MaP populations identification mechanism integrating marginality and geographical periphery and for mapping potential abiotic treats, a more accurate climatic classification of the "species populations" and the "distribution ranges of species" is necessary and has to be developed. Ideally also soil classification should be included.

Further development of the mechanisms around the conservation of genetic resources of MaP populations, including marginal and peripheral endemic species, should interact as far as possible and be coordinated with IUCN Red List Categories and Criteria development and IUCN Global Tree Assessment initiatives.

Furthermore, consideration should be given to extending the area of the pan-European GCU network beyond that of Europe (e.g. Northern Africa, East Mediterranean) to include most southern marginal populations of certain species.

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ANNEX 1. Matrix of the decision support tool for GCU management

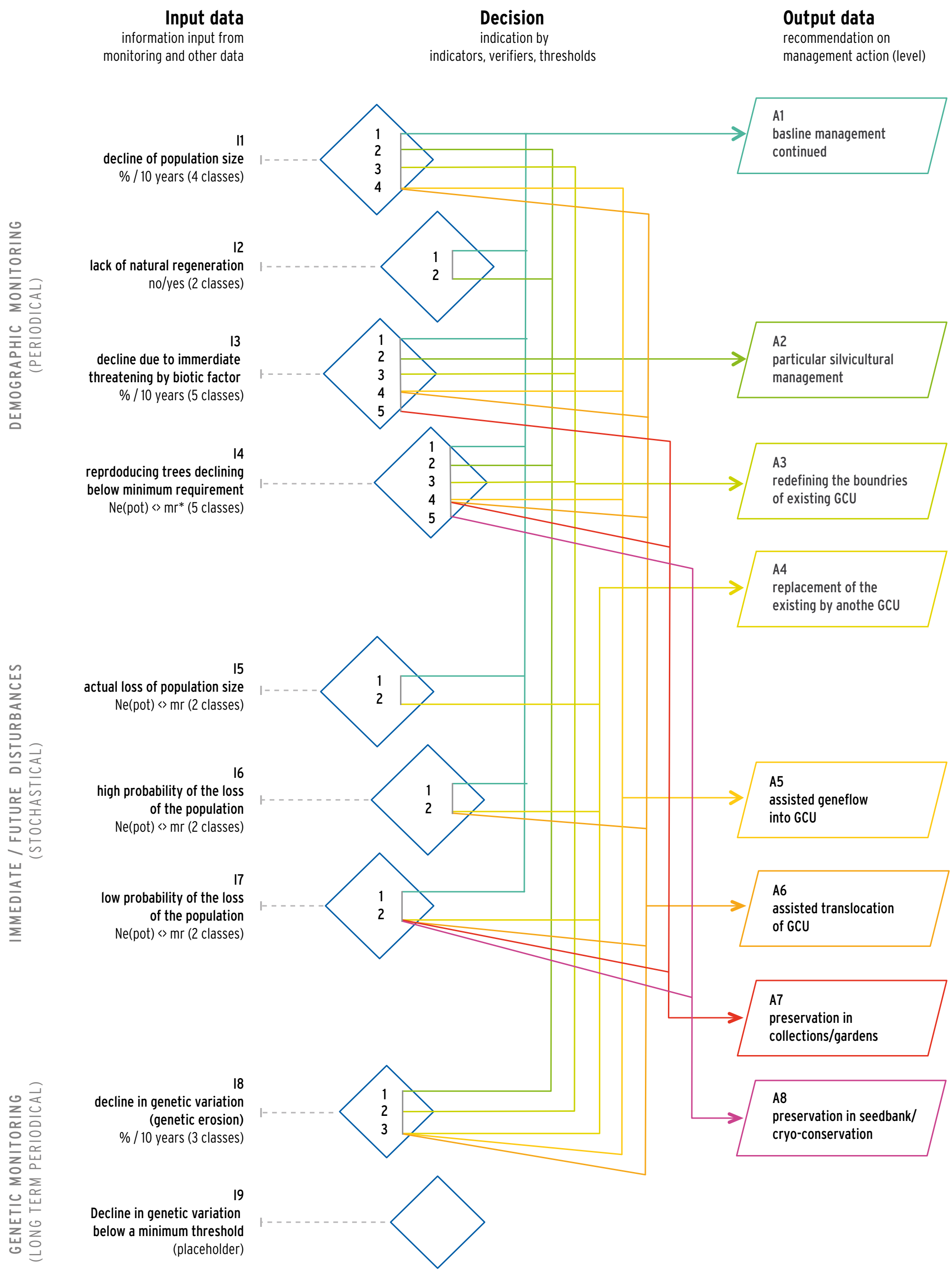
I to A relations by Threshold classes

° = alternative relations (boolean operator OR)

mr = minimum requirement mr* derived minimum requir. (cf. Table 6) gr = genetic minimum requir. (absolute baseline)

Management Action (Level)			**Indicators**, Verifiers, Units and Threshold classes								
			demographic monitoring				immediate/future disturbances			genetic monitoring	
			I1 a/b/c % / 10 years	I2 a no / yes	I3 a/b/c % / 10 years	I4 a/b/c Ne(pot) <> mr*	I5 a/b/c Ne(pot) <> mr	I6 a/b/c Ne(pot) <> mr	I7 a/b/c Ne(pot) <> mr	I8 a/b/c/d % / 10 years	I9 a/b/c/d Fs/Ar/He <> gr
			1 < 25% 2 25-50% 3 50-75% 4 > 75%	1 no 2 yes	1 < 20% 2 20-40% 3 40-60% 4 60-80% 5 > 80%	1 > mr* 2 < mr* 3 << mr* 4 <<< mr* 5 <<<< mr*	1 > mr 2 < mr	1 > mr 2 < mr	1 > mr 2 < mr	1 < 30% 2 30-50% 3 > 50%	(placeholder for future genetic knowledge)
	standard	A1	1	1	1	1	1	1	1	1	
	in situ	A2	2	2	2	2				2°	
		A3	3		3	3				2°	
		A4					2	2°	2°	3°	
	ex situ	A5	4°		4°	4°				3°	
		A6	4°		4°	4°		2°	2°	3°	
		A7			5°	5			2°		
		A8			5°				2°		

ANNEX 2. Flowchart of the decision support tool for GCU management



ANNEX 3. Exemplary case studies

Data processing tables and visualisations

The case studies (1) and (2) are starting with real data (2018), the starting points of the other case studies and all future scenarios (diverse*, 2030, 2040) are using assumed data:

(1) **Beech, scenario of a stable forest stand**
Beech seed stand & LIFEGENMON monitoring plot Pri Studencu, Slovenia

(2) **Silver fir, scenario of an unstable forest stand, incl. dieback + browsing**
Silver fir seed stand & LIFEGENMON monitoring plot Smolarjevo, Slovenia

(3) **Common ash, scenario of continuously increasing dieback**
Common ash, standforming in wet mixed broadleaves stands, alluvial forest Wasserschloss, Brugg AG, Switzerland

(4) **Common ash, scenario of a sudden massive dieback, detected soon after establishing GCU in 2021***
Common ash, admixed in mountainous beech silver fir forest (in mosaic), Bettlachstock, Bettlach SO, Switzerland

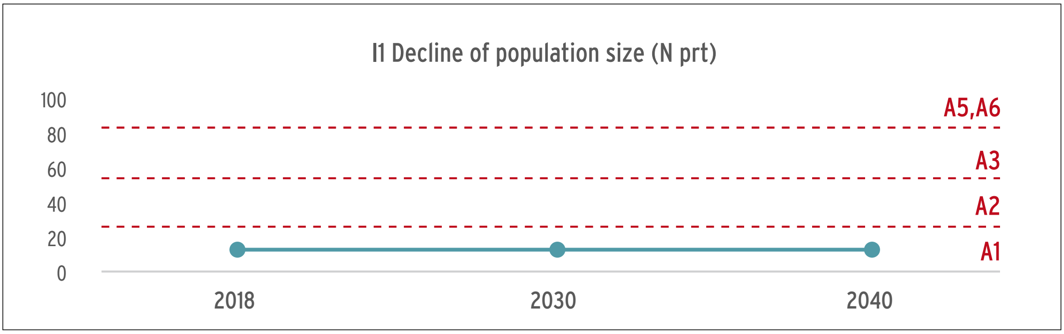
(5) **Swiss stone pine, scenario of loss of 60% of population destroyed by avalanches in winter 2024/25***
Swiss stone pine marginal population, valley 2000 ha, Murgtal, Murg SG, Switzerland

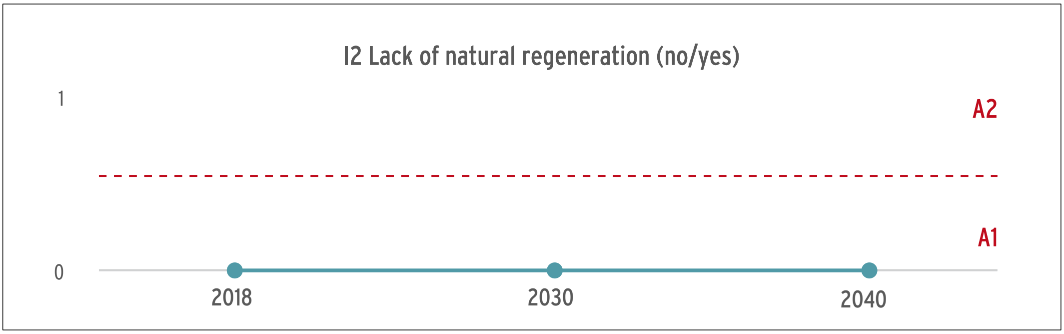
(6) **Aleppo pine, scenario of a stable forest stand, with increasing forest fire threat 2 years in a row, based on JRC data in 2027***
Aleppo pine population, seed stand, Kassandra, Chalkidiki, Greece

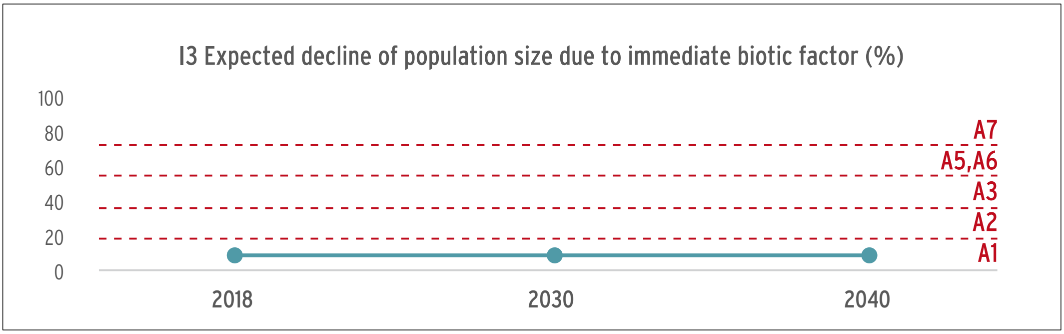
(1) Beech, scenario of a stable forest stand

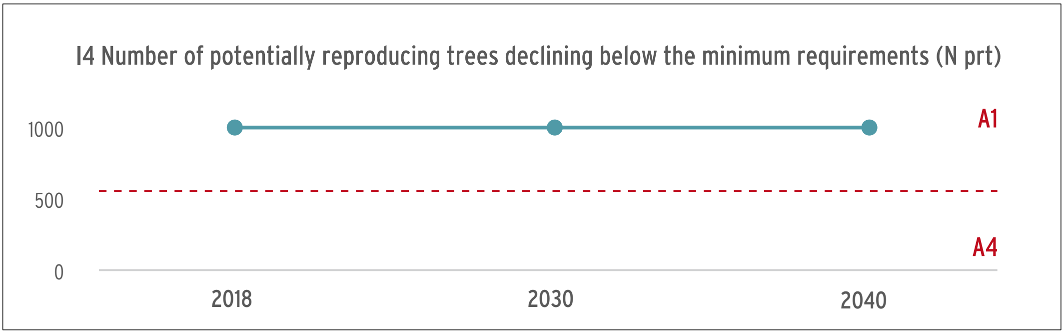
Beech seed stand & LIFEGENMON monitoring plot Pri Studencu, Slovenia (starting with real data 2018)		Monitoring values			Verifier values			Management action		
Indicator & verifier		2018	2030	2040	2018	2030	2040	2018	2030	2040
I1	**Decline of population size**									
I1a	Decline of the number of reproducing trees	17900	15000	13800	< 25%	< 25%	< 25%	A1	A1	A1
I1b	Increase of the number of dead trees									
I1c	Decline of the population share									
I2	**Lack of natural regeneration**									
I2a	Lack of natural regeneration	continous	sporadic	sporadic	no	no	no	A1	A1	A1
I3	**Expected decline of population size due to immediate threatening biotic factor**									
I3a	Due to presence of a severe specific pest or disease	25100	23500	23400	<20%	<20%	<20%	A1	A1	A1
I3b	Due to presence of a severe competing species including invasive neophytes	25100	23500	23400	<20%	<20%	<20%	A1	A1	A1
I3c	Due to presence of severe specific seed predation or browsing	25100	23500	23400	<20%	<20%	<20%	A1	A1	A1
I4	**Number of potentially reproducing trees declining below the minimum requirement**									
I4a	Below the threshold for widely occurring and stand-forming species	17900	15000	13800	>500	>500	>500	A1	A1	A1
I4b	Below the threshold for marginal or scattered tree populations									
I4c	Below the threshold for remaining populations of rare or endangered tree species									
I5	**Population size had broken down to below minimum requirements (but conservation of genotypes is still possible)**									
I5a	Below the threshold for widely occurring and stand-forming species	25100	23500	23400	>500	>500	>500	A1	A1	A1
I5b	Below the threshold for marginal or scattered tree populations									
I5c	Below the threshold for remaining populations of rare or endangered tree species									

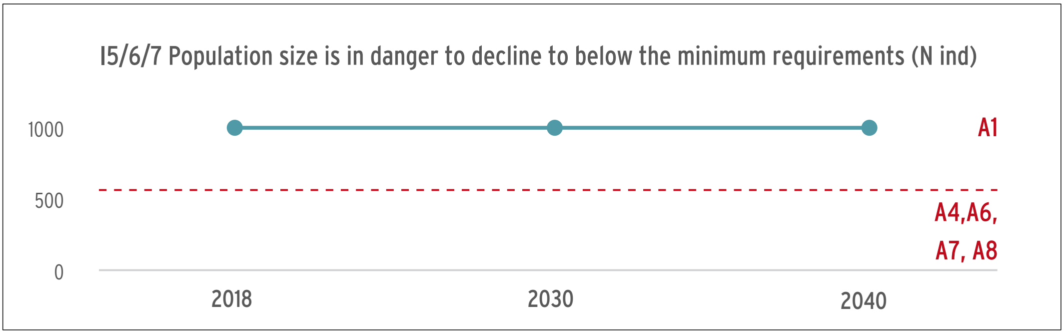
Beech seed stand & LIFEGENMON monitoring plot Pri Studencu, Slovenia (starting with real data 2018)		Monitoring values			Verifier values			Management action		
Indicator & verifier		2018	2030	2040	2018	2030	2040	2018	2030	2040
I6	**Population size is in great danger to decline to below the minimum requirements due to a natural or anthropogenic event of high probability**									
I6a	Below the threshold for widely occurring and stand-forming species	trend 25000	trend 22000	trend 23000	>500	>500	>500	A1	A1	A1
I6b	Below the threshold for marginal or scattered tree populations									
I6c	Below the threshold for remaining populations of rare or endangered tree species									
I7	**Population size is in danger to decline to below the minimum requirements due a natural or anthropogenic event of low probability**									
I7a	Below the threshold for widely occurring and stand-forming species	trend 25000	trend 22000	trend 23000	>500	>500	>500	A1	A1	A1
I7b	Below the threshold for marginal or scattered tree populations									
I7c	Below the threshold for remaining populations of rare or endangered tree species									
I8	**Decline in genetic variation (genetic erosion)**									
I8a	Decline in number of alleles (Na) or allelic richness (Ar)	9,28	9,2	9,13	< 30% of baseline	< 30% of baseline	< 30% of baseline	A1	A1	A1
I8b	Decline in expected heterozygosity (He)	0,700	0,701	0,703	< 30% of baseline	< 30% of baseline	< 30% of baseline	A1	A1	A1
I8c	Decline in allele and genotype frequencies									
I8d	Decline in effective population size (Ne)									
Recommended management action								**A1**	**A1**	**A1**

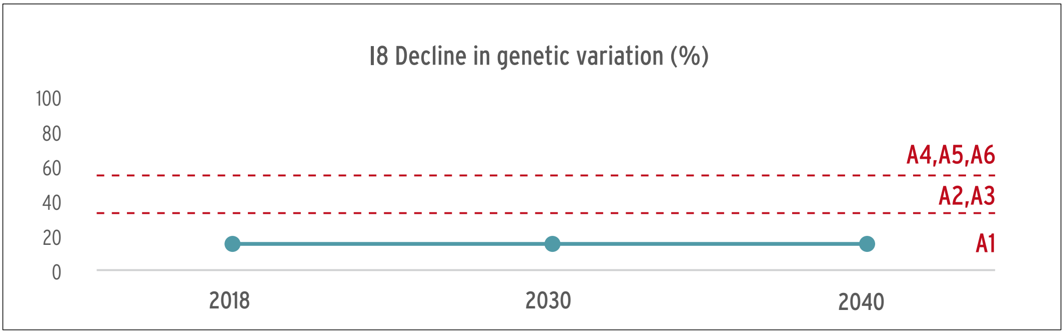

I1 Decline of population size (N prt)
100
80
60
40
20
0
A5,A6
A3
A2
A1
2018
2030
2040


I2 Lack of natural regeneration (no/yes)
1
0
A2
A1
2018
2030
2040


I3 Expected decline of population size due to immediate biotic factor (%)
100
80
60
40
20
0
A7
A5,A6
A3
A2
A1
2018
2030
2040


I4 Number of potentially reproducing trees declining below the minimum requirements (N prt)
1000
500
0
2018
2030
2040
A1
A4

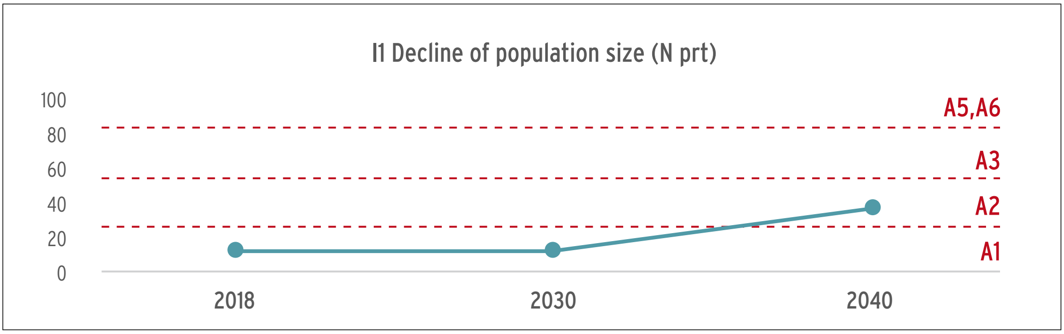

I5/6/7 Population size is in danger to decline to below the minimum requirements (N ind)
1000
500
0
2018
2030
2040
A1
A4,A6,
A7, A8

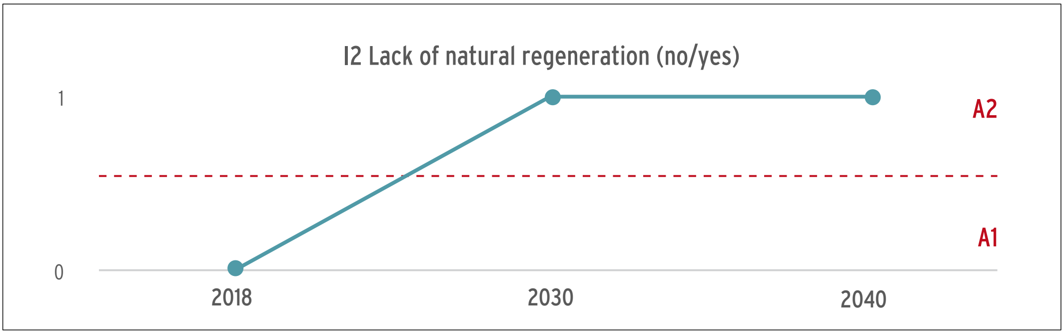

I8 Decline in genetic variation (%)
100
80
60
40
20
0
2018
2030
2040
A4,A5,A6
A2,A3
A1

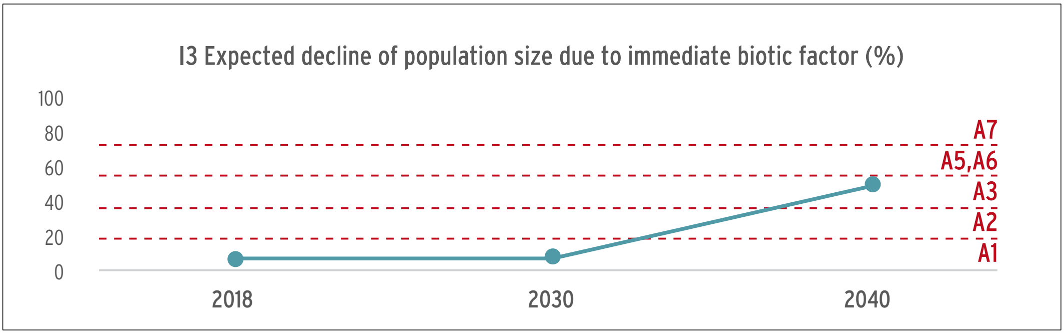
(2) Silver fir, scenario of an unstable forest stand, incl. dieback + browsing

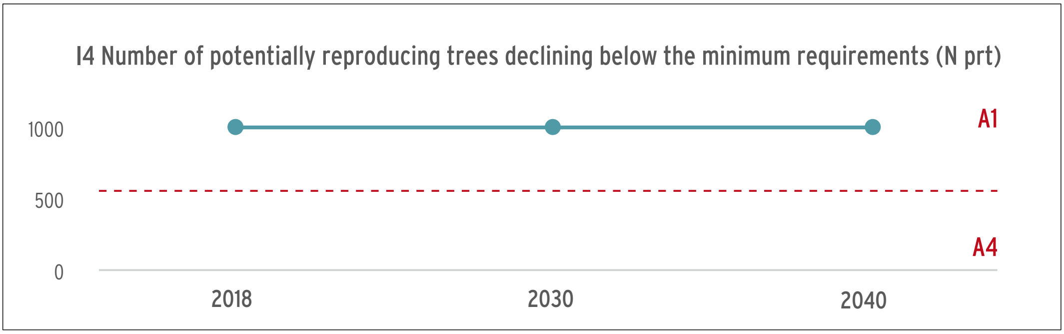
Silver fir seed stand & LIFEGENMON monitoring plot Smolarjevo, Slovenia (starting with real data 2018)		Monitoring values			Verifier values			Management action		
Indicator & verifier		2018	2030	2040	2018	2030	2040	2018	2030	2040
I1	**Decline of population size**									
I1a	Decline of the number of reproducing trees	1800	1500	1000	< 25%	< 25%	25-50%	A1	A1	A2
I1b	Increase of the number of dead trees									
I1c	Decline of the population share									
I2	**Lack of natural regeneration**									
I2a	Lack of natural regeneration	sporadic	requires managemt.	requires managemt.	no	yes	yes	A1	A2	A2
I3	**Expected decline of population size due to immediate threatening biotic factor**									
I3a	Due to presence of a severe specific pest or disease	1800	1500	1000	<20%	<20%	<20%	A1	A1	A1
I3b	Due to presence of a severe competing species including invasive neophytes	1800	1500	1000	<20%	<20%	<20%	A1	A1	A1
I3c	Due to presence of severe specific seed predation or browsing	1800	1500	1000	<20%	<20%	40-60%	A1	A1	A3
I4	**Number of potentially reproducing trees declining below the minimum requirement**									
I4a	Below the threshold for widely occurring and stand-forming species	1800	1500	1000	>500	>500	>500	A1	A1	A1
I4b	Below the threshold for marginal or scattered tree populations									
I4c	Below the threshold for remaining populations of rare or endangered tree species									
I5	**Population size had broken down to below minimum requirements (but conservation of genotypes is still possible)**									
I5a	Below the threshold for widely occurring and stand-forming species	1800	1500	1000	>500	>500	>500	A1	A1	A1
I5b	Below the threshold for marginal or scattered tree populations									
I5c	Below the threshold for remaining populations of rare or endangered tree species									

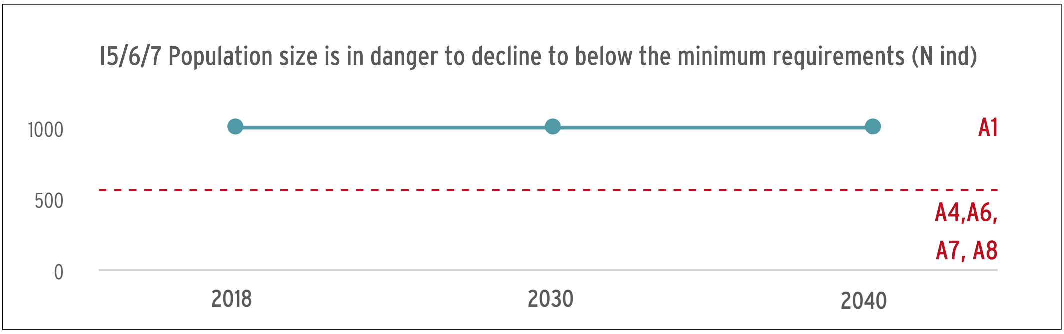
Silver fir seed stand & LIFEGENMON monitoring plot Smolarjevo, Slovenia (starting with real data 2018)		Monitoring values			Verifier values			Management action		
Indicator & verifier		**2018**	**2030**	**2040**	**2018**	**2030**	**2040**	**2018**	**2030**	**2040**
I6	**Population size is in great danger to decline to below the minimum requirements due to a natural or anthropogenic event of high probability**									
I6a	Below the threshold for widely occurring and stand-forming species	trend 1800	trend 1200	trend 650	>500	>500	>500	A1	A1	A1
I6b	Below the threshold for marginal or scattered tree populations									
I6c	Below the threshold for remaining populations of rare or endangered tree species									
I7	**Population size is in danger to decline to below the minimum requirements due a natural or anthropogenic event of low probability**									
I7a	Below the threshold for widely occurring and stand-forming species	trend 1800	trend 1200	trend 650	>500	>500	>500	A1	A1	A1
I7b	Below the threshold for marginal or scattered tree populations									
I7c	Below the threshold for remaining populations of rare or endangered tree species									
I8	**Decline in genetic variation (genetic erosion)**									
I8a	Decline in number of alleles (Na) or allelic richness (Ar)	10,52	10,5	9,5	< 30% of baseline	< 30% of baseline	< 30% of baseline	A1	A1	A1
I8b	Decline in expected heterozygosity (He)	0,580	0,575	0,564	< 30% of baseline	< 30% of baseline	< 30% of baseline	A1	A1	A1
I8c	Decline in allele and genotype frequencies									
I8d	Decline in effective population size (Ne)									
Recommended management action								**A1**	**A1, A2**	**A2, A3**

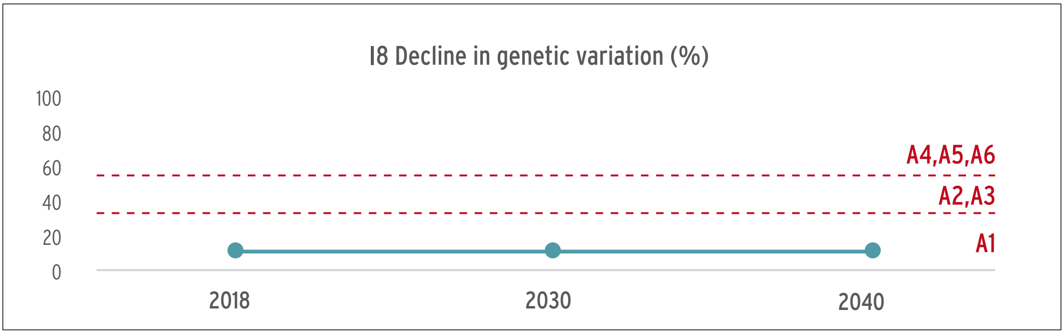

I1 Decline of population size (N prt)
100
80
60
40
20
0
A5,A6
A3
A2
A1
2018
2030
2040


I2 Lack of natural regeneration (no/yes)
1
0
A2
A1
2018
2030
2040


I3 Expected decline of population size due to immediate biotic factor (%)
100
80
60
40
20
0
A7
A5,A6
A3
A2
A1
2018
2030
2040


I4 Number of potentially reproducing trees declining below the minimum requirements (N prt)
1000
500
0
2018
2030
2040
A1
A4

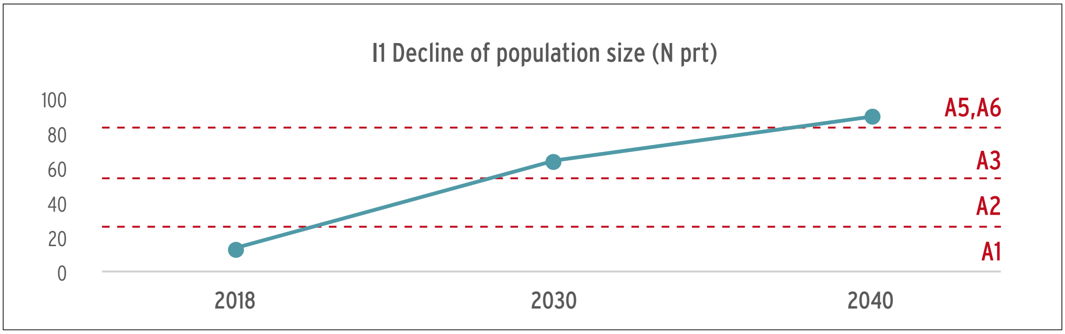

I5/6/7 Population size is in danger to decline to below the minimum requirements (N ind)
1000
500
0
2018
2030
2040
A1
A4,A6,
A7, A8

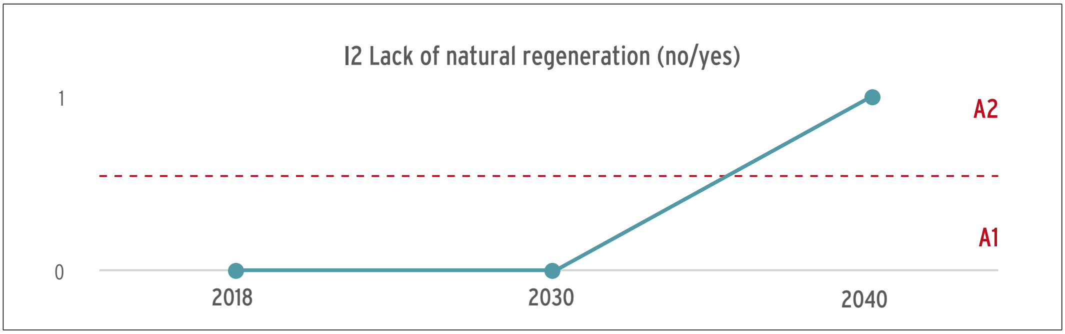

I8 Decline in genetic variation (%)
100
80
60
40
20
0
2018
2030
2040
A4,A5,A6
A2,A3
A1

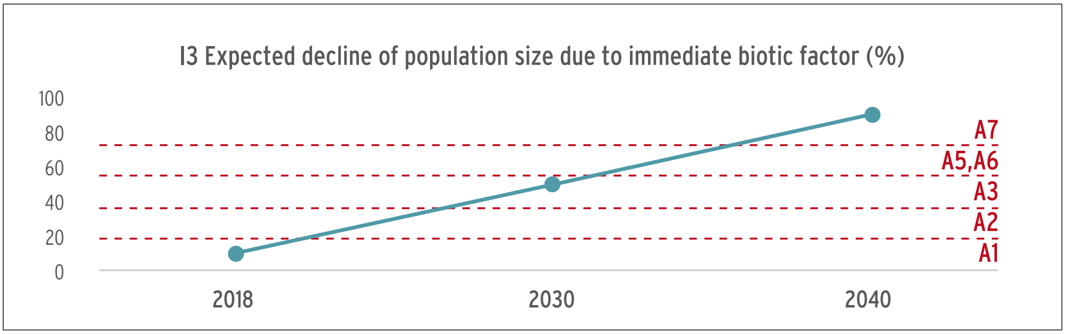
(3) Common ash, scenario of continuously increasing dieback

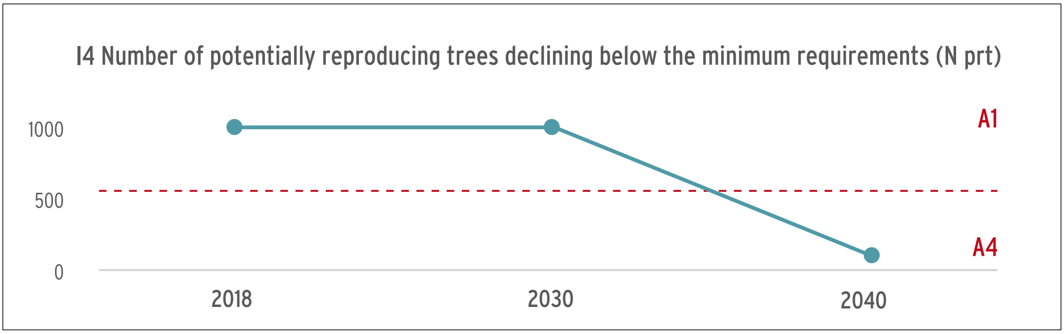
Common ash, standforming in wet mixed broadleaves stands, alluvial forest unit Wasserschloss, Brugg AG, Switzerland (starting with assumed data 2018)		Monitoring values			Verifier values			Management action		
Indicator & verifier		**2018**	**2030**	**2040**	**2018**	**2030**	**2040**	**2018**	**2030**	**2040**
I1	**Decline of population size**									
I1a	Decline of the number of reproducing trees	4000	2000	200	< 25%	50-75%	>75%	A1	A3	A5 or A6
I1b	Increase of the number of dead trees									
I1c	Decline of the population share									
I2	**Lack of natural regeneration**									
I2a	Lack of natural regeneration	continous	sporadic	requires managemt.	no	no	yes	A1	A1	A2
I3	**Expected decline of population size due to immediate threatening biotic factor**									
I3a	Due to presence of a severe specific pest or disease	4000	2000	200	<20%	40-60%	>80%	A1	A2	A7
I3b	Due to presence of a severe competing species including invasive neophytes									
I3c	Due to presence of severe specific seed predation or browsing									
I4	**Number of potentially reproducing trees declining below the minimum requirement**									
I4a	Below the threshold for widely occurring and stand-forming species	4000	2000	200	>500	>500	100-250	A1	A1	A3
I4b	Below the threshold for marginal or scattered tree populations									
I4c	Below the threshold for remaining populations of rare or endangered tree species									
I5	**Population size had broken down to below minimum requirements (but conservation of genotypes is still possible)**									
I5a	Below the threshold for widely occurring and stand-forming species	4000	2000	200	>500	>500	<500	A1	A1	A4
I5b	Below the threshold for marginal or scattered tree populations									
I5c	Below the threshold for remaining populations of rare or endangered tree species									

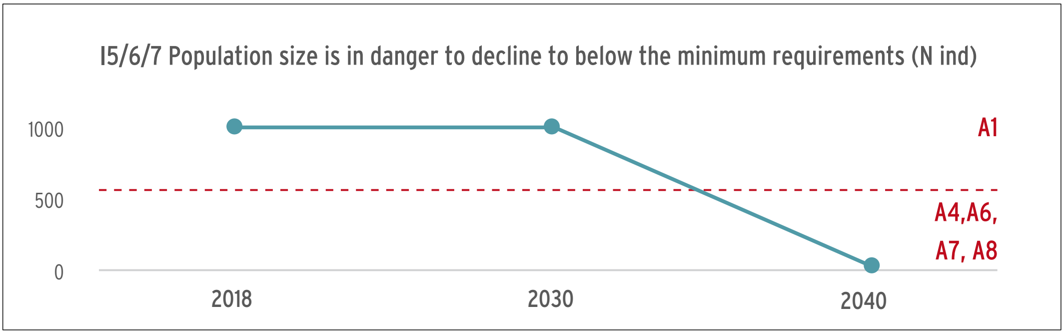
Common ash, standforming in wet mixed broadleaves stands, alluvial forest unit Wasserschloss, Brugg AG, Switzerland (starting with assumed data 2018)		Monitoring values			Verifier values			Management action		
Indicator & verifier		**2018**	**2030**	**2040**	**2018**	**2030**	**2040**	**2018**	**2030**	**2040**
I6	**Population size is in great danger to decline to below the minimum requirements due to a natural or anthropogenic event of high probability**									
I6a	Below the threshold for widely occurring and stand-forming species	trend 3000	trend 1000	trend 20	>500	>500	<500	A1	A1	A4 or A6
I6b	Below the threshold for marginal or scattered tree populations									
I6c	Below the threshold for remaining populations of rare or endangered tree species									
I7	**Population size is in danger to decline to below the minimum requirements due a natural or anthropogenic event of low probability**									
I7a	Below the threshold for widely occurring and stand-forming species	trend 3000	trend 1000	trend 20	>500	>500	<500	A1	A1	A4 or A6
I7b	Below the threshold for marginal or scattered tree populations									
I7c	Below the threshold for remaining populations of rare or endangered tree species									
I8	**Decline in genetic variation (genetic erosion)**									
I8a	Decline in number of alleles (Na) or allelic richness (Ar)									
I8b	Decline in expected heterozygosity (He)									
I8c	Decline in allele and genotype frequencies									
I8d	Decline in effective population size (Ne)									
Recommended management action								**A1**	**A1, A2, A3**	**A2, A3, A5, A6, A7**

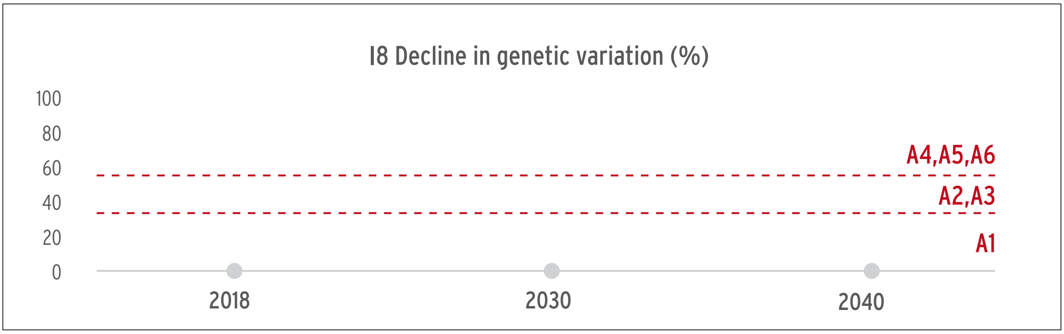

I1 Decline of population size (N prt)
100
80
60
40
20
0
A5,A6
A3
A2
A1
2018
2030
2040


I2 Lack of natural regeneration (no/yes)
1
0
A2
A1
2018
2030
2040


I3 Expected decline of population size due to immediate biotic factor (%)
100
80
60
40
20
0
A7
A5,A6
A3
A2
A1
2018
2030
2040


I4 Number of potentially reproducing trees declining below the minimum requirements (N prt)
1000
500
0
2018
2030
2040
A1
A4

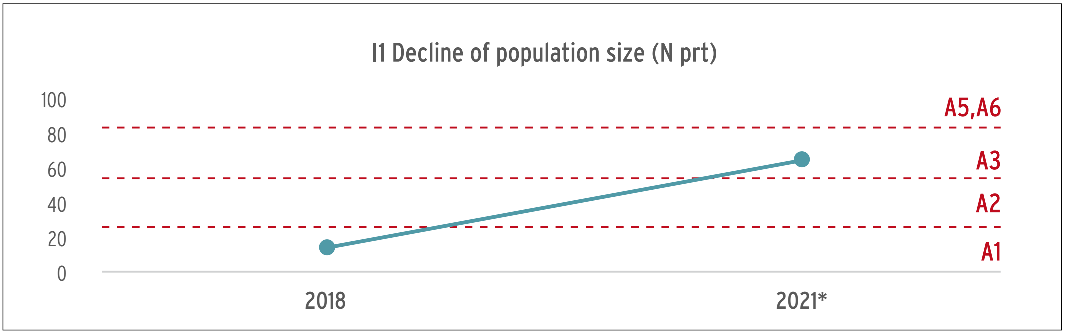

I5/6/7 Population size is in danger to decline to below the minimum requirements (N ind)
1000
500
0
2018
2030
2040
A1
A4,A6,
A7, A8

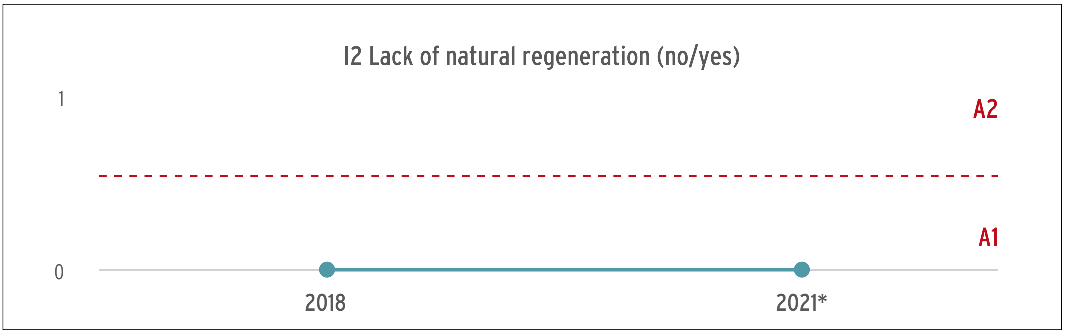

I8 Decline in genetic variation (%)
100
80
60
40
20
0
2018
2030
2040
A4,A5,A6
A2,A3
A1

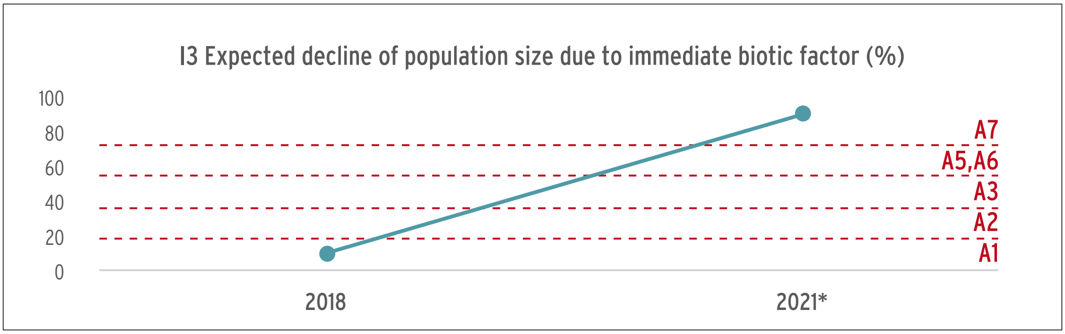
(4) Common ash, scenario of a sudden massive dieback, detected soon after establishing GCU in 2021*

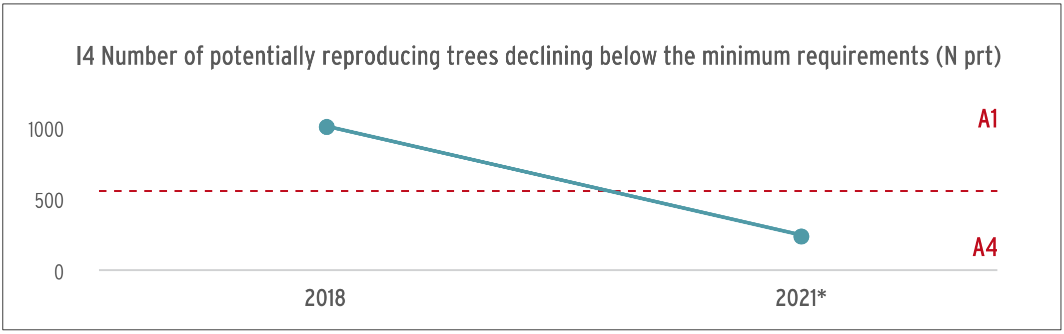
Common ash, admixed in montanuous beech silver fir forest (in mosaic), Bettlachstock, Bettlach SO, Switzerland (starting with assumed data 2018)		Monitoring values			Verifier values			Management action		
Indicator & verifier		2018	2021*(2030)	2040	2018	2021*(2030)	2040	2018	2021*(2030)	2040
I1	**Decline of population size**									
I1a	Decline of the number of reproducing trees	3000	1000		<20%	50-75%		A1	A3	
I1b	Increase of the number of dead trees		2000			50-75%			A3	
I1c	Decline of the population share									
I2	**Lack of natural regeneration**									
I2a	Lack of natural regeneration	continous	sporadic		no	no		A1	A1	
I3	**Expected decline of population size due to immediate threatening biotic factor**									
I3a	Due to presence of a severe specific pest or disease	3000	1000		<20%	>80%		A1	A7	
I3b	Due to presence of a severe competing species including invasive neophytes									
I3c	Due to presence of severe specific seed predation or browsing									
I4	**Number of potentially reproducing trees declining below the minimum requirement**									
I4a	Below the threshold for widely occurring and stand-forming species	3000	1000		>500	>500		A1	A1	
I4b	Below the threshold for marginal or scattered tree populations									
I4c	Below the threshold for remaining populations of rare or endangered tree species									
I5	**Population size had broken down to below minimum requirements (but conservation of genotypes is still possible)**									
I5a	Below the threshold for widely occurring and stand-forming species	3000	1000		>500	>500		A1	A1	
I5b	Below the threshold for marginal or scattered tree populations									
I5c	Below the threshold for remaining populations of rare or endangered tree species									

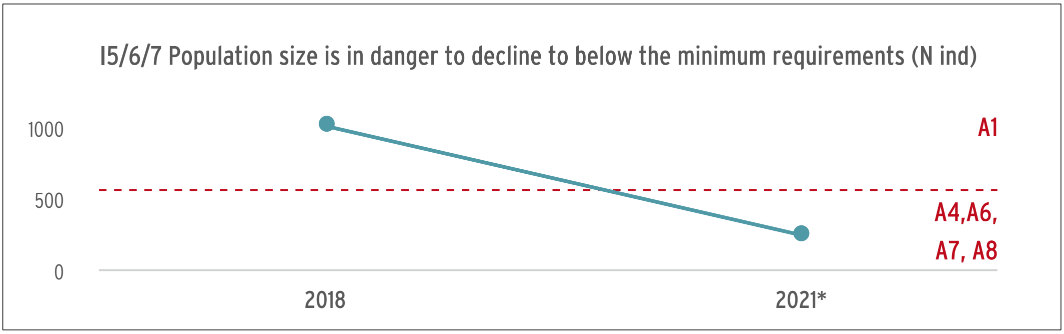
Common ash, admixed in montanuous beech silver fir forest (in mosaic), Bettlachstock, Bettlach SO, Switzerland (starting with assumed data 2018)		Monitoring values			Verifier values			Management action		
Indicator & verifier		2018	2021*(2030)	2040	2018	2021*(2030)	2040	2018	2021*(2030)	2040
I6	**Population size is in great danger to decline to below the minimum requirements due to a natural or anthropogenic event of high probability**									
I6a	Below the threshold for widely occurring and stand-forming species	trend 3000	trend 300		>500	<500		A1	A4 or A6	
I6b	Below the threshold for marginal or scattered tree populations									
I6c	Below the threshold for remaining populations of rare or endangered tree species									
I7	**Population size is in danger to decline to below the minimum requirements due a natural or anthropogenic event of low probability**									
I7a	Below the threshold for widely occurring and stand-forming species	trend 3000	trend 300		>500	<500		A1	A4 or A6	
I7b	Below the threshold for marginal or scattered tree populations									
I7c	Below the threshold for remaining populations of rare or endangered tree species									
I8	**Decline in genetic variation (genetic erosion)**									
I8a	Decline in number of alleles (Na) or allelic richness (Ar)									
I8b	Decline in expected heterozygosity (He)									
I8c	Decline in allele and genotype frequencies									
I8d	Decline in effective population size (Ne)									
Recommended management action								**A1**	**A1, A3, A4, A6, A7**	

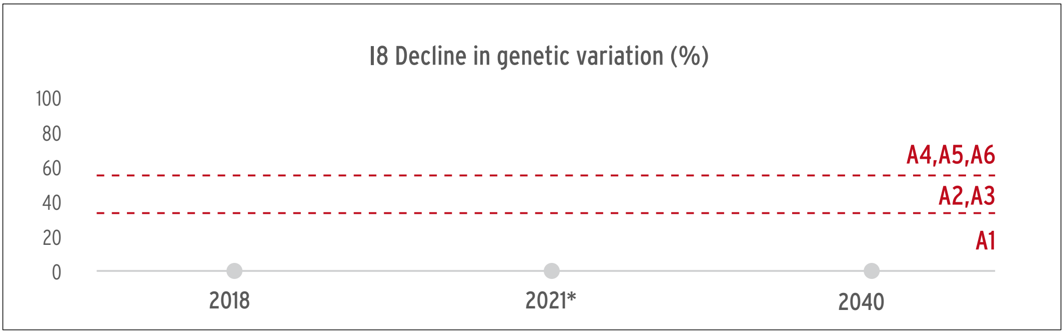

I1 Decline of population size (N prt)
100
80
60
40
20
0
A5,A6
A3
A2
A1
2018
2021*


I2 Lack of natural regeneration (no/yes)
1
0
A2
A1
2018
2021*


I3 Expected decline of population size due to immediate biotic factor (%)
100
80
60
40
20
0
A7
A5,A6
A3
A2
A1
2018
2021*


I4 Number of potentially reproducing trees declining below the minimum requirements (N prt)
1000
500
0
2018
2021*
A1
A4

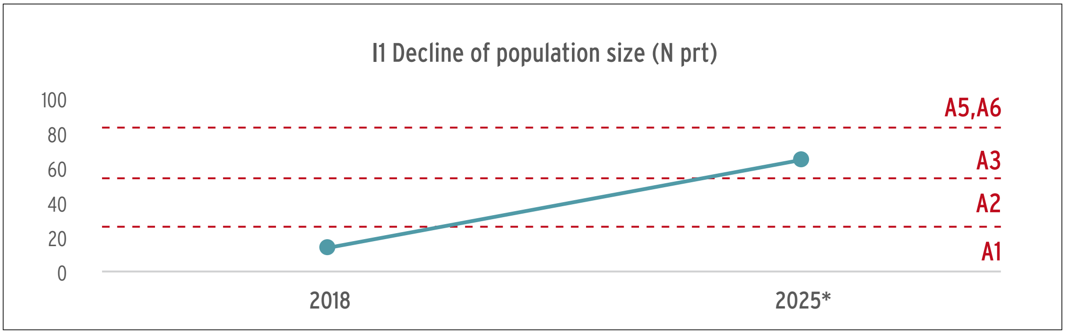

I5/6/7 Population size is in danger to decline to below the minimum requirements (N ind)
1000
500
0
2018
2021*
A1
A4,A6,
A7, A8

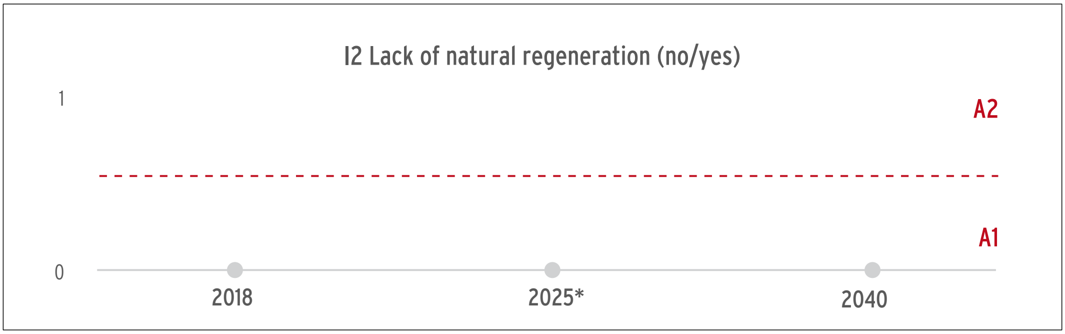

I8 Decline in genetic variation (%)
100
80
60
40
20
0
2018
2021*
2040
A4,A5,A6
A2,A3
A1

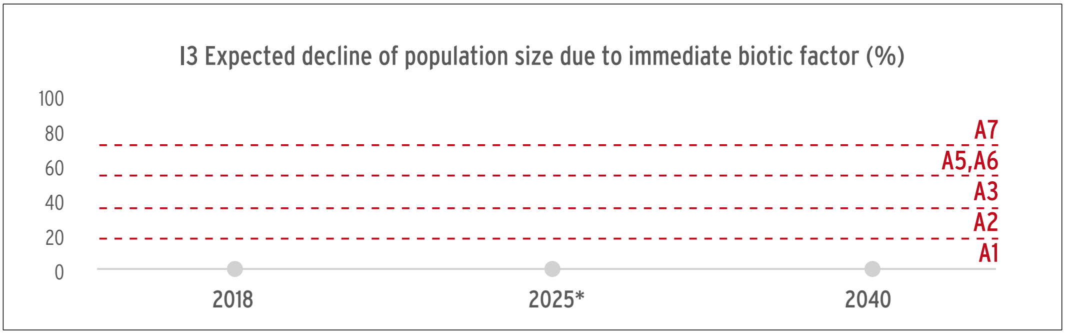
(5) Swiss stone pine, scenario of loss of 60% of population destroyed by avalanches in winter 2024/25*

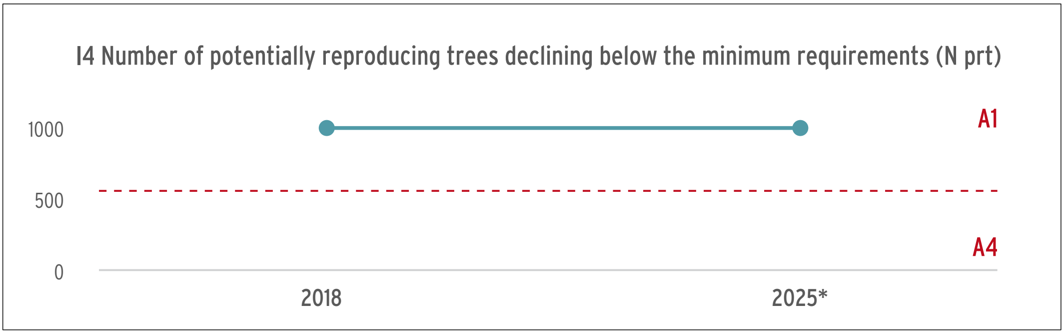
Swiss stone pine marginal population, valley 2000 ha, Murgtal, Murg SG, Switzerland (starting with assumed data 2018)		Monitoring values			Verifier values			Management action		
Indicator & verifier		**2018**	**2025*(2030)**	**2040**	**2018**	**2025*(2030)**	**2040**	**2018**	**2025*(2030)**	**2040**
I1	**Decline of population size**									
I1a	Decline of the number of reproducing trees	5200	2000		< 25%			A1		
I1b	Increase of the number of dead trees									
I1c	Decline of the population share	35%	15%		< 10%	50-75%		A1	A3	
I2	**Lack of natural regeneration**									
I2a	Lack of natural regeneration	sporadic								
I3	Expected decline of population size due to immediate threatening biotic factor									
I3a	Due to presence of a severe specific pest or disease									
I3b	Due to presence of a severe competing species including invasive neophytes									
I3c	Due to presence of severe specific seed predation or browsing									
I4	**Number of potentially reproducing trees declining below the minimum requirement**									
I4a	Below the threshold for widely occurring and stand-forming species									
I4b	Below the threshold for marginal or scattered tree populations	5200	2100		>50	>50		A1	A1	
I4c	Below the threshold for remaining populations of rare or endangered tree species									
I5	**Population size had broken down to below minimum requirements (but conservation of genotypes is still possible)**									
I5a	Below the threshold for widely occurring and stand-forming species									
I5b	Below the threshold for marginal or scattered tree populations	5200	2100		>50	>50		A1	A1	
I5c	Below the threshold for remaining populations of rare or endangered tree species									

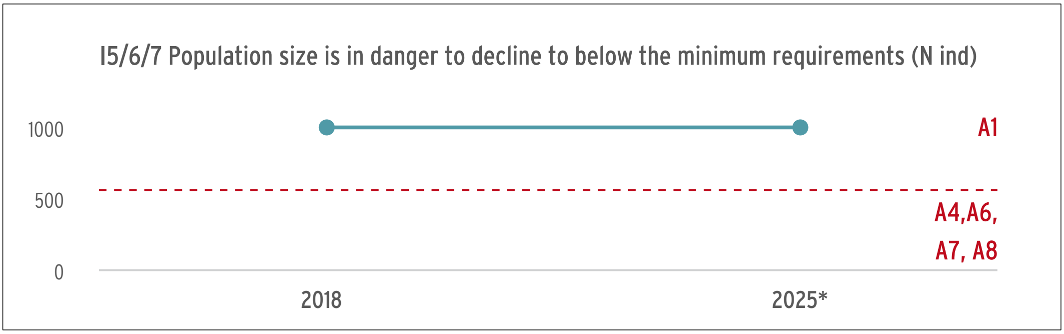
Swiss stone pine marginal population, valley 2000 ha, Murgtal, Murg SG, Switzerland (starting with assumed data 2018)		Monitoring values			Verifier values			Management action		
Indicator & verifier		2018	2025*(2030)	2040	2018	2025*(2030)	2040	2018	2025*(2030)	2040
I6	**Population size is in great danger to decline to below the minimum requirements due to a natural or anthropogenic event of high probability**									
I6a	Below the threshold for widely occurring and stand-forming species									
I6b	Below the threshold for marginal or scattered tree populations	trend 5200	trend 2100		>50	>50		A1	A1	
I6c	Below the threshold for remaining populations of rare or endangered tree species									
I7	**Population size is in danger to decline to below the minimum requirements due a natural or anthropogenic event of low probability**									
I7a	Below the threshold for widely occurring and stand-forming species									
I7b	Below the threshold for marginal or scattered tree populations	trend 5200	trend 1000		>50	>50		A1	A1	
I7c	Below the threshold for remaining populations of rare or endangered tree species									
I8	**Decline in genetic variation (genetic erosion)**									
I8a	Decline in number of alleles (Na) or allelic richness (Ar)									
I8b	Decline in expected heterozygosity (He)									
I8c	Decline in allele and genotype frequencies									
I8d	Decline in effective population size (Ne)									
Recommended management action								A1	A1, A3	

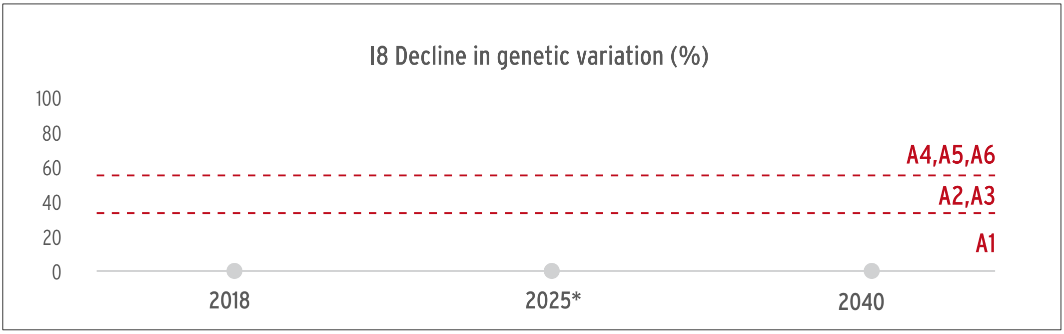

I1 Decline of population size (N prt)
100
80
60
40
20
0
A5,A6
A3
A2
A1
2018
2025*


I2 Lack of natural regeneration (no/yes)
1
0
A2
A1
2018
2025*
2040


I3 Expected decline of population size due to immediate biotic factor (%)
100
80
60
40
20
0
A7
A5,A6
A3
A2
A1
2018
2025*
2040


I4 Number of potentially reproducing trees declining below the minimum requirements (N prt)
1000
500
0
2018
2025*
A1
A4

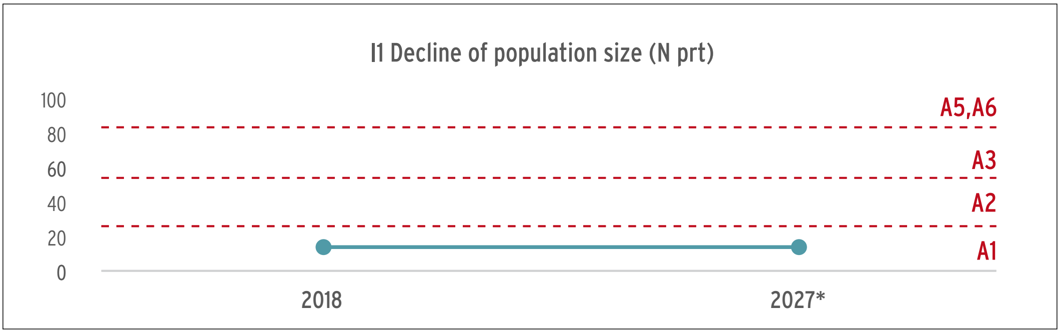

I5/6/7 Population size is in danger to decline to below the minimum requirements (N ind)
1000
500
0
2018
2025*
A1
A4,A6,
A7, A8

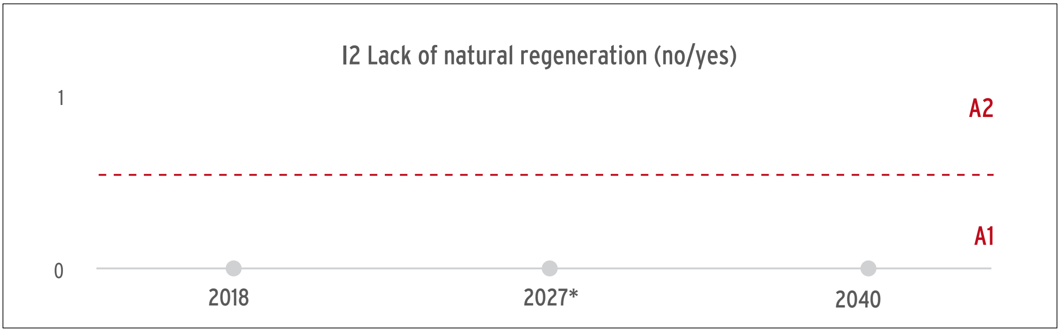

I8 Decline in genetic variation (%)
100
80
60
40
20
0
2018
2025*
2040
A4,A5,A6
A2,A3
A1

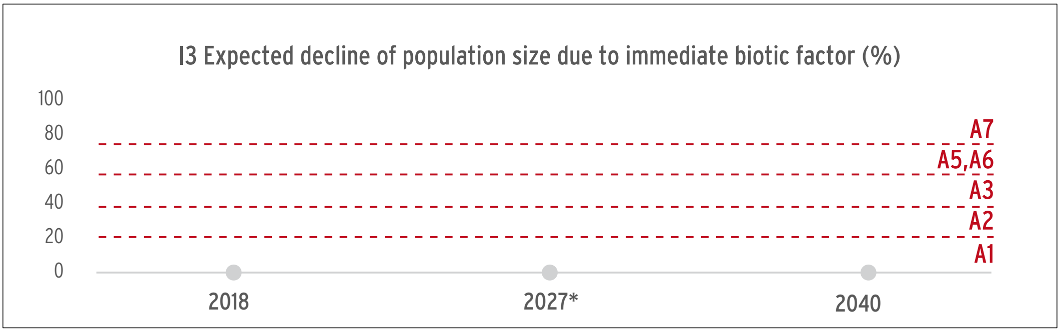
(6) Aleppo pine, scenario of a stable forest stand, with increasing forest fire threat 2 years in a row, based on JRC data in 2027*

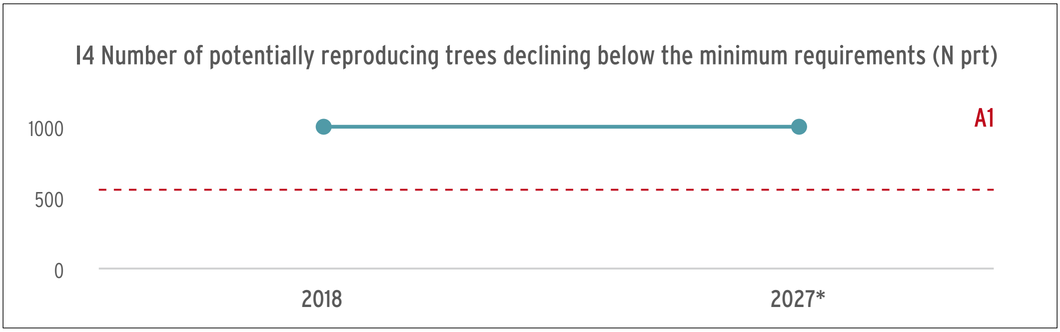
Aleppo pine population, seed stand, Kassandra, Chalkidiki, Greece (starting with assumed data 2018)		Monitoring values			Verifier values			Management action		
Indicator & verifier		2018	2027*(2030)	2040	2018	2027*(2030)	2040	2018	2027*(2030)	2040
I1	**Decline of population size**									
I1a	Decline of the number of reproducing trees	18000	18000		<20%	<20%		A1	A1	
I1b	Increase of the number of dead trees									
I1c	Decline of the population share									
I2	**Lack of natural regeneration**									
I2a	Lack of natural regeneration	continuous	continuous							
I3	**Expected decline of population size due to immediate threatening biotic factor**									
I3a	Due to presence of a severe specific pest or disease									
I3b	Due to presence of a severe competing species including invasive neophytes									
I3c	Due to presence of severe specific seed predation or browsing									
I4	**Number of potentially reproducing trees declining below the minimum requirement**									
I4a	Below the threshold for widely occurring and stand-forming species									
I4b	Below the threshold for marginal or scattered tree populations									
I4c	Below the threshold for remaining populations of rare or endangered tree species									
I5	**Population size had broken down to below minimum requirements (but conservation of genotypes is still possible)**									
I5a	Below the threshold for widely occurring and stand-forming species	18000	18000		>500	>500		A1	A1	
I5b	Below the threshold for marginal or scattered tree populations									
I5c	Below the threshold for remaining populations of rare or endangered tree species									

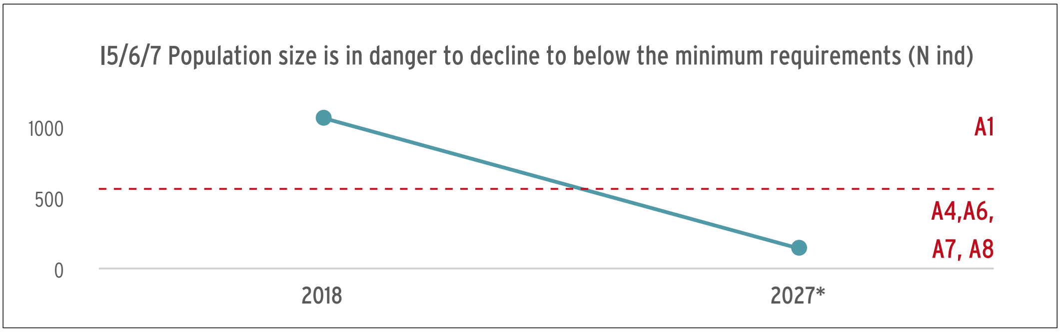
Aleppo pine population, seed stand, Kassandra, Chalkidiki, Greece (starting with assumed data 2018)		Monitoring values			Verifier values			Management action		
Indicator & verifier		2018	2027*(2030)	2040	2018	2027*(2030)	2040	2018	2027*(2030)	2040
I6	**Population size is in great danger to decline to below the minimum requirements due to a natural or anthropogenic event of high probability**									
I6a	Below the threshold for widely occurring and stand-forming species	18000	trend 100		>500	<500		A1	A4 or A6	
I6b	Below the threshold for marginal or scattered tree populations									
I6c	Below the threshold for remaining populations of rare or endangered tree species									
I7	**Population size is in danger to decline to below the minimum requirements due a natural or anthropogenic event of low probability**									
I7a	Below the threshold for widely occurring and stand-forming species									
I7b	Below the threshold for marginal or scattered tree populations									
I7c	Below the threshold for remaining populations of rare or endangered tree species									
I8	**Decline in genetic variation (genetic erosion)**									
I8a	Decline in number of alleles (Na) or allelic richness (Ar)									
I8b	Decline in expected heterozygosity (He)									
I8c	Decline in allele and genotype frequencies									
I8d	Decline in effective population size (Ne)									
Recommended management action								**A1**	**A1, A4, A6**	

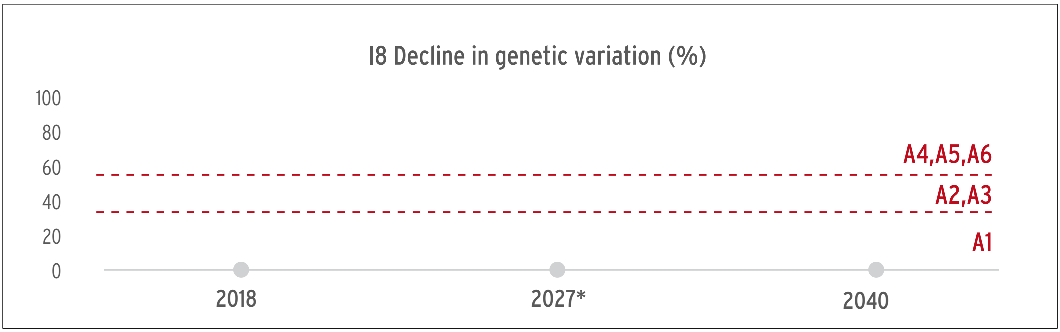

I1 Decline of population size (N prt)
100
80
60
40
20
0
A5,A6
A3
A2
A1
2018
2027*


I2 Lack of natural regeneration (no/yes)
1
0
A2
A1
2018
2027*
2040


I3 Expected decline of population size due to immediate biotic factor (%)
100
80
60
40
20
0
A7
A5,A6
A3
A2
A1
2018
2027*
2040


I4 Number of potentially reproducing trees declining below the minimum requirements (N prt)
1000
500
0
A1
2018
2027*


I5/6/7 Population size is in danger to decline to below the minimum requirements (N ind)
1000
500
0
A1
A4,A6,
A7, A8
2018
2027*


I8 Decline in genetic variation (%)
100
80
60
40
20
0
A4,A5,A6
A2,A3
A1
2018
2027*
2040

EUFORGEN