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**Evolution-based approach needed for the conservation and silviculture of peripheral forest tree populations**

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1 Evolution-based approach needed for the conservation and silviculture

2 of peripheral forest tree populations

3 Bruno Fady\*(1), Filippos A. Aravanopoulos \*(2), Paraskevi Alizoti (2)\*, Csaba Mátyás  
4 (3)\*, Georg von Wühlisch (4)\*, Marjana Westergren (5)\*, Piero Belletti (6), Branislav  
5 Cvjetkovic (7), Fulvio Ducci (8), Gerhard Huber (9), Colin T. Kelleher(10), Abdelhamid  
6 Khaldi (11), Magda Bou Dagher Kharrat (12), Hojka Kraigher (5), Koen Kramer (13), Urs  
7 Mühlethaler (14), Sanja Peric (15), Annika Perry (16), Matti Rousi (17), Hassan Sbay (18),  
8 Srdjan Stojnic (19), Martina Tijardovic (15), Ivaylo Tsvetkov (20), Maria Carolina Varela  
9 (21), Giovanni G. Vendramin (22), Tzvetan Zlatanov (23).

10

11 (1) INRA, UR629, Ecologie des forêts méditerranéennes (URFM), Avignon, France (author  
12 for correspondence)

13 (2) Faculty of Agriculture, Forest Science & Natural Environment, Aristotle University of  
14 Thessaloniki, Thessaloniki, Greece

15 (3) University of West Hungary, Inst. of Environmental and Earth Sciences, Sopron, ,  
16 Hungary

17 (4) Johann Heinrich von Thünen Institute, Institute of Forest Genetics, Großhansdorf,  
18 Germany

19 (5) Slovenian Forestry Institute, Ljubljana, Slovenia

20 (6) University of Torino, DISAFA Agricultural Genetics, Grugliasco, Italy

21 (7) University of Banja Luka, Faculty of Forestry, Banja Luka, Bosnia and Herzegovina

22 (8) CREA SEL, Consiglio per la ricerca in agricoltura e l'analisi dell'economia agraria,  
23 Forestry research centre, Arezzo. Italy

24 (9) Bavarian Institute for Forest Seeding and Planting, Teisendorf, Germany

25 (10) DBN Plant Molecular Laboratory, National Botanic Gardens of Ireland, Dublin, Ireland

26 (11) National Research Institute of Rural Engineering, Water and Forests (INRGREF),

- 27 University of Carthage, Tunis, Tunisia
- 28 (12) Laboratoire Caractérisation Génomique des Plantes, Faculty of Science, Saint Joseph  
29 University, Beirut, Lebanon
- 30 (13) Alterra – Green World Research, Vegetation, Forest, and Landscape Ecology, and  
31 Wageningen University, Wageningen, The Netherlands
- 32 (14) Burgersriedstrasse 11, Bruegg, Switzerland
- 33 (15) Croatian Forest Research Institute, Jastrebarsko, Croatia
- 34 (16) Centre for Ecology and Hydrology, Penicuik, United Kingdom
- 35 (17) Natural Resources Institute Finland (Luke), Vantaa, Finland
- 36 (18) Forest Research Centre, Agdal Rabat, Morocco
- 37 (19) University of Novi Sad, Institute of Lowland Forestry and Environment, Novi Sad, Serbia
- 38 (20) Forest Research Institute, Sofia, Bulgaria
- 39 (21) Instituto Nacional de Investigação Agrária e Veterinária, Oeiras, Portugal
- 40 (22) Institute of Biosciences and Bioresources, National Research Council, Sesto Fiorentino  
41 (FI), Italy

42 \*: equal contribution

43

44 ABSTRACT:

45 The fate of marginal and peripheral forest tree populations is of particular interest in the  
46 context of climate change. These populations may concurrently be those where the most  
47 significant evolutionary changes will occur; those most facing increasing extinction risk; the  
48 source of migrants for the colonization of new areas at leading edges; or the source of genetic  
49 novelty for reinforcing standing genetic variation in various parts of the range. Deciding  
50 which strategy to implement for conserving and sustainably using the genetic resources of  
51 marginal and peripheral forest tree populations is a challenge. Here, we review the genetic  
52 and ecological processes acting on different types of marginal and peripheral populations and  
53 indicate why these processes may be of general interest for adapting forests and forest  
54 management to climate change. We particularly focus on marginal and peripheral populations

55 at the rear edge of species distributions and at ecological margins therein, where  
56 environmental challenges are or will become most acute. We argue that marginal and  
57 peripheral forest tree populations are natural laboratories for resolving priority research  
58 questions such as how the complex interaction between gene flow, selection, genetic drift,  
59 immigration and intrinsic population growth rate shape local adaptation and whether genetic  
60 adaptation will be sufficient to allow the long-term persistence of species within their current  
61 distribution. Simultaneously, they are key assets for adaptive forestry which need specific  
62 measures for their preservation. We suggest approaches and principles which may be used for  
63 the management and conservation of these unusual yet valuable populations, in order to  
64 maintain active genetic and ecological processes that have sustained them over time. The  
65 traditionally opposing views of conservation planning and sustainable forestry need to be  
66 reconciled and harmonized for managing marginal and peripheral populations.

67

68 Key words: geographic range; forest tree genetics; ecology; climate change; forest  
69 management; conservation.

70

71

## 72 I. INTRODUCTION

73 Ecologically marginal and geographically peripheral forest tree populations are at risk,  
74 now more than ever. Global environmental change, particularly climate change, challenges  
75 the sustainability of these potentially useful populations that also often carry a societal, ethical  
76 or recreational value. This is especially true at the rear edge of species geographic  
77 distributions where populations have often persisted over long periods of geological time and  
78 experienced a complex evolutionary history (for Europe, see Hampe and Petit 2005). There,  
79 marginal and peripheral populations may contain traits of high potential value for adapting  
80 forests and forest management to new environmental conditions, locally as well as range-wide  
81 (Holliday et al. 2012). Because of local adaptation effects, valuable resources may also be  
82 found at ecological margins within the core of species distribution areas, for example at low

83 elevation along mountain slopes. Without proper management, severe erosion of this unique  
84 and potentially useful genetic diversity is likely to occur under climate change (Mátyás et al.  
85 2009). Comparatively, threats may appear less severe at the leading edges of species  
86 distributions where marginal and peripheral populations may benefit from gene flow from  
87 pre-adapted populations that will replenish their potentially low genetic diversity during  
88 migration (Lenormand 2002).

89 Foresters have often planted economically valuable tree species outside of the natural  
90 distribution range at low-latitude or low elevation sites, thereby creating artificial margins. In  
91 Europe, these include Scots pine (*Pinus sylvestris*), black pine (*Pinus nigra*), silver fir (*Abies*  
92 *alba*), chestnut (*Castanea sativa*), wild cherry (*Prunus avium*), sessile oak (*Quercus petraea*)  
93 and especially Norway spruce (*Picea abies*). Many of these forests, which have naturalized  
94 and expanded (e.g. *Pinus nigra* in the Apennines in Italy, Piermattei et al. 2012), are today  
95 challenged by changing climate and land uses.

96 Marginal and peripheral populations have regularly attracted the attention of ecologists  
97 and geneticists who have sought to understand processes that limit geographical ranges  
98 (Gaston 2009, Kawecki 2008, Lenormand 2002). Marginal and peripheral populations are  
99 natural laboratories for understanding how demography and selection shape local adaptation  
100 and prevent or facilitate colonization of new habitats. Whether marginal and peripheral  
101 populations are evolutionary “dead-ends” or “hot-spots” depends on complex interaction  
102 between gene flow, selection, genetic drift, immigration and intrinsic population growth rate.  
103 The relative contribution of each depends on local and historic conditions as well as on life  
104 history traits (Abeli et al. 2014, Alberto et al. 2013, Alleaume-Benharira et al. 2006,  
105 Benavides et al. 2013, Eckert et al. 2008, Lira-Noriega and Manthey 2014, Peterman et al.  
106 2013, Ursenbacher et al. 2015).

107 Whereas ecologists and geneticists tend to agree with Lesica and Allendorf (1995) that  
108 marginal and peripheral populations are valuable for conservation, conservationists and  
109 conservation planning often do not put a high value on marginal and peripheral populations  
110 unless they belong to species that are themselves threatened (e.g. Leppig and White, 2006,

111 Steen and Barrett 2015). Because of their often slower growth, poorer wood quality and lower  
112 economic value, marginal and peripheral forest populations are usually not recognized and  
113 managed as valuable forestry assets either (Lindner et al. 2010). This is unfortunate because  
114 marginal and peripheral populations can constitute climate warming refugia and ultimately  
115 may prevent species to go extinct altogether (Channell and Lomolino 2000). Also, marginal  
116 and peripheral populations may likely contain unique genetic resources (Kawecki 2008),  
117 useful in a range of natural and management settings.

118 The recognition of the value of marginal and peripheral populations is, however, starting  
119 to change as global change is now being placed at the forefront of many habitat management  
120 plans, while national and international forest adaptation strategies are emerging. For example,  
121 genetic resources found at low latitude in Europe and around the Mediterranean are currently  
122 receiving renewed interest as forest reproductive material in Europe (Konnert et al. 2015).

123 The fate of marginal and peripheral populations is of particular interest in the context of  
124 climate change (Mátyás et al. 2009, Valladarès et al. 2014, Allen et al. 2015). These  
125 populations may (a) be the place where the most significant evolutionary change will occur,  
126 (b) face increasing extinction risk, or (c) be the source of migrants for the colonization of new  
127 areas at leading edges or for reinforcing standing genetic variation in various parts of the  
128 range (Alleaume-Benharira et al. 2006). Deciding which strategy to implement for conserving  
129 and sustainably using the genetic resources of marginal and peripheral populations is a  
130 challenge. Conservation, on the one hand, and, on the other, sustainable use of forest tree  
131 species and of their genetic resources are often driven by different societal goals. Opposing  
132 views need to be reconciled and harmonized for managing marginal and peripheral  
133 populations.

134 Here, we review the genetic and ecological processes acting on different types of marginal  
135 and peripheral populations and indicate why these processes may be of general interest for  
136 adapting forests and forest management to climate c 136 hange. We particularly focus on marginal  
137 and peripheral populations at the rear edge of species distributions and at ecological margins  
138 therein, where environmental challenges are or will become most acute. We suggest

139 approaches and principles which may be used for the management and conservation of these  
140 unusual yet valuable populations, in order to maintain active genetic and ecological processes  
141 that have sustained them over time.

142

143 II. THE EVOLUTIONARY POTENTIAL OF MARGINAL AND

144 PERIPHERAL FOREST TREE POPULATIONS AND THEIR VALUE

145 FOR ADAPTING FORESTS TO CLIMATE CHANGE

146 1. The evolutionary potential of marginal and peripheral populations is driven by

147 unique demographic and genetic processes

148 We make a distinction between marginal and peripheral populations because they arise as

149 a result of different demographic and evolutionary processes and thus, may need to be

150 managed differently. Peripheral populations are those furthest away from the core geographic

151 distribution of a species. The periphery (i.e. edge) of a distribution area is often classified as

152 either a leading (or expanding, or colonizing) or a rear (or trailing) edge, based on Holocene

153 post-glacial migration history. Leading edge populations are situated at the front of presently

154 expanding or advancing distribution areas (e.g. for temperate forests, at high latitudes and

155 altitudes). At the leading edge, the standing genetic variation of marginal and peripheral

156 populations may be currently too low to contribute efficiently to colonization unless there is

157 significant gene flow from core populations.

158 Rear edge populations, conversely, are situated at the retreating front of a shifting range

159 (e.g. in the Mediterranean region, Hampe and Petit 2005). Isolated populations not connected

160 by gene flow to the core of the distribution area qualify as disjunct irrespective of their

161 situation at the leading or the rear edge.

162 Ecological margins can be present throughout the geographic range and appear when the

163 species reaches the limits of its ecological niche, thus forming marginal populations. The

164 habitat of species is sub-optimal at ecological margins (Kawecki 2008).

165

166

167 Figure 1. Some demographic and genetic processes affecting populations across their  
168 distribution range. Here, the species range is shown as being divided into two geographic  
169 entities, separated by a mountain. While peripheral populations occur at the edges of the range  
170 of the species, ecological margins can be found throughout the range wherever ecological  
171 conditions become sub-optimal. Ecological marginality and geography can influence genetic  
172 and demographic processes in variable ways across the species distribution range, as depicted  
173 by the grey shapes (source: Hampe and Petit 2005, Ohsawa and Ide 2008).

174

175 Demographic and evolutionary processes shape marginal and peripheral populations  
176 differently compared to populations at the core of the distribution, depending on their  
177 situation in the geographic and ecological space (Figure 1). Leading edge disjunct populations  
178 establish via long distance dispersal and may suffer from founder effect, reduced fitness  
179 because of genetic drift and inbreeding depression 179 due to reduced mate availability (Restoux  
180 et al. 2008). These populations are not necessarily ecologically marginal, as colonization  
181 speed of forest trees is much lower than the contemporary climatic shifts, especially on plains  
182 (Jump et al. 2009). Leading edge populations may have increased adaptation to long distance  
183 dispersal (Cwynar and MacDonald 1987).

184 Rear edge disjunct populations are not necessarily ecologically marginal either, although  
185 they might be small and potentially prone to extinction. Their main features may be their  
186 persistence over long periods of geological time (for example as climate refugia) and thus  
187 their genetic uniqueness results from long-term divergence (e.g. Liepelt et al. 2009 for *Abies*  
188 *alba*). Non-disjunct leading and rear edge populations are characterized by asymmetric gene  
189 flow from the core of the distribution area, which can be either maladaptive (rear edge) or  
190 adaptive (leading edge) under climate change range shifts.

191 At ecological margins, throughout the geographic range, selection pressure (with or  
192 without the occurrence of maladaptive gene flow) will drive the evolutionary trajectory and  
193 ability of populations to persist (Alleaume-Benharira et al. 2006, Borovics and Mátyás 2013,  
194 Gaston 2009, Hampe and Petit 2005, Kawecki 2008, Kremer et al. 2012, Kubisch et al. 2014,



195 Lenormand 2002). Under climate change, rear edge peripheral populations and low elevation  
196 marginal populations, are particularly and increasingly at risk (Figure 2).

197

198

199 Figure 2. Beaumont-de-Ventoux in the southeastern French Alps is a rear-edge, disjunct  
200 *Abies alba* population growing under sub-Mediterranean climate conditions where evidence  
201 of dieback (grey trees) is widespread since the summer heat wave of 2003.

202

203 2. The evolutionary potential of marginal and peripheral populations

204 Whether or not marginal populations are adaptable to changing conditions remains  
205 theoretically debatable and evidence from short- or long-lived plant and animal data is often  
206 conflicting (Kawecki 2008). Local adaptation is not as widespread as commonly thought and  
207 that small populations, particularly, rarely demonstrate evidence of local adaptation (Leimu  
208 and Fischer 2008, and, for forest trees, see St Clair and Howe 2007).

209 Few common garden experiments of forest trees actually test marginal and peripheral  
210 populations and sites. When data are available, marginal populations demonstrate phenotypic  
211 trait values (mean and variance) different from those found in core populations for a range of  
212 traits (Rehfeldt et al. 2002). Marginal and peripheral populations are possibly under much  
213 higher selection pressure than others and could thus be well adapted to extreme or fluctuating  
214 conditions (Borovics and Mátyás 2013), while their adaptability might be lower than often  
215 presumed. Populations from the trailing or xeric limit often display slower growth in more  
216 favorable ecological conditions. For example, Rehfeldt et al. (2002) showed that xeric margin  
217 populations generally lagged behind core populations in terms of phenotypic plasticity for  
218 height growth. Similar results are available 218 for jack pine (*Pinus banksiana*; Mátyás and  
219 Yeatman 1992) and Scots pine (*Pinus sylvestris*; Shutjaev and Giertych 2003). At the leading  
220 edge, strong selection for resistance to cold and photoperiod may limit the ability of trees to  
221 adapt to warming conditions (Savolainen et al. 2011).

222 These results do not support the hypothesis that marginal populations always have high

223 adaptability and phenotypic stability because extreme selection can negatively influence  
224 plastic responses (Valladarès et al. 2007). The importance of genetic diversity and phenotypic  
225 plasticity in determining adaptive potential has been shown to be a key issue when predicting  
226 species distributions using climate envelop modelling (Benito-Garzón et al. 2011).  
227 Much experimental evidence (e.g. part of the studies in Eckert et al. 2008) challenges the  
228 idea that there is a decrease of genetic diversity from core to periphery (Lenormand 2002,  
229 Kawecki 2008) and thus the reality of the “abundant center theory” (Sagarin and Gaines  
230 2002) which states that core populations are more abundant than marginal and peripheral  
231 populations where the balance between gene flow and selection limits population adaptation  
232 and thus, species range. First, and from a methodological perspective, geographical margins  
233 are not necessarily ecological margins, which can confuse issues (Lira-Noriega and Manthey  
234 2014). All peripheral habitats are not sub-optimal and range edges may in fact harbor high  
235 quality habitats (Channell and Lomolino 2000). Also, marginal and peripheral populations are  
236 not necessarily evolutionary dead-ends. Given sufficient population size and/or high enough  
237 levels of gene flow (which is not exceptional in forest trees, e.g. Kremer et al. 2012), their  
238 fitness can be high in their own environment (Alleaume-Benharira et al. 2006, Ganopoulos et  
239 al. 2011, Restoux et al. 2008) as well as in alien environments (Kreyling et al. 2014, Thiel et  
240 al. 2013). This is particularly the case of rear edge populations with a complex evolutionary  
241 history (Hampe and Petit 2005).

242

243 3. The importance of marginal and peripheral populations for adapting forests to  
244 global change

245 The occurrence of extreme climatic events coupled with high intensity and frequent  
246 ecological stress, likely increases vulnerability and limits adaptive capacity. At the rear edge  
247 and at low elevation margins, drought and heat waves in interaction with the spread of new  
248 and invasive pests and diseases will be major constraining factors. At the leading edge and at  
249 high elevation margins, persisting cold events and photoperiod limitations as well as pests and  
250 diseases spreading from the core 250 distribution or from lower elevations may remain strong

251 challenges for adaptation and hence reduce the geographic extent of suitable areas at leading  
252 edges (Rehm et al. 2015).

253 Deciding which peripheral and marginal populations will be able to resist, survive and  
254 evolve is a challenge when prioritizing and adapting management for these populations. For  
255 one thing, understanding which biotic and abiotic factors form rear- and leading-edges is far  
256 from trivial (Slaton 2015). Despite some knowledge gaps, innovative ecological and genetic  
257 tools have been developed to support such prioritization in forest trees and these efforts need  
258 to be continued (Konnert et al. 2015).

259 In the next two chapters, principles and examples of management of marginal and  
260 peripheral forest tree populations are discussed, in view of changing climatic conditions. We  
261 discuss silviculture and conservation separately, although in most cases the two are or need to  
262 be combined and balanced depending on management priorities.

263

### 264 III. SILVICULTURE IN MARGINAL AND PERIPHERAL POPULATIONS

265

266 1. Principles of management of marginal and peripheral populations: maintaining the  
267 stability and increasing the resilience

268 Forest tree species are best adapted to the disturbance regimes under which they have  
269 evolved (Bergeron et al. 1999). Therefore, forest ecosystem management based on an  
270 understanding of natural disturbance regimes is also a sound silvicultural approach in  
271 marginal and peripheral populations (Alfaro et al. 2014, Allen et al. 2015). However, novel  
272 forms of disturbance, or combinations of disturbances, may soon emerge (Lindenmayer and  
273 McCarthy, 2002) and seriously impact marginal and peripheral forest populations. Therefore,  
274 management methods should be adjusted to take into account the effect of silvicultural  
275 interventions on genetic diversity and, consequently, on adaptability. This type of  
276 management simultaneously accelerates genetic adaptation by facilitating tree populations to  
277 track environmental changes and preserves genetic diversity as a main source of adaptability  
278 to unknown disturbance cycles (evolution-oriented forestry, Lefèvre et al. 2014).

279 Marginal and peripheral populations, as well as their genetic resources, need to be  
280 identified and included as a priority in national forest strategies and climate adaptation plans  
281 where they could serve as “climate change” in-situ conservation units (Kelleher et al. 2015).  
282 They need to be recognized as specific 282 management units in forest management plans and  
283 identified as high conservation value stands. Maintaining stable, mixed, variably structured  
284 forest stands, as well as supporting and protecting long-term natural regeneration (Sagnard et  
285 al. 2011), safeguarding vital, isolated trees either at the fore-front of colonization or at the rear  
286 limits, are all desirable goals for marginal and peripheral populations. In specific cases,  
287 unconventional interventions must be developed to protect the survival of populations, e.g.  
288 partial removal of competing shrubs, or planting a provisory nursing stand. Box 1 provides an  
289 example for management practices in central Europe. In the Mediterranean where most rear  
290 edge populations of European tree species are located, a fire prevention strategy should also  
291 be an integral part of management plans.

292

293 Box 1: Examples of management practices adapted to ecologically marginal beech (*Fagus*  
294 *sylvatica*) populations in central Europe.

295

296 Using over 30 year-long regeneration periods with as many seed trees as possible is standard  
297 practice at the upper tree limit and on steep slopes in marginal beech forest of the Dinaric  
298 region and in the northern Alps in Bavaria. Long-term regeneration periods are particularly  
299 suitable to create mosaic- and uneven-aged structures, increasing the future stability of these  
300 marginal stands. Removal of trees that have reached harvest size is usually postponed until  
301 these trees have regenerated naturally. Regeneration aimed at group structure is small-scaled  
302 using an irregular shelterwood method, and several carefully applied regeneration cuts. This  
303 guarantees minimal impact on soils as these marginal populations often grow on steep slopes.  
304 In the Dinaric region, overstory removal is avoided as it negatively influences stability and  
305 quality of regeneration (Matic et al. 2003). If necessary during low seed crop years, natural  
306 regeneration is supplemented by stored seeds collected in- situ to strengthen local adaptation

307 as local genetic diversity is considered large enough. During regeneration, strong measures  
308 are taken to avoid overgrowing weeds, soil degradation, forest fires and grazing. At the lower  
309 limit of its distribution in the Dinaric Alps, beech becomes ecologically marginal and is found  
310 in mixed stands with pedunculate oak (*Quercus robur*). There, groups or individually  
311 admixed beech trees are favored to promote fructification and improve their vitality (Klepac  
312 et al. 1996). Overall, forest management operates at the level of trees and groups of trees,  
313 particularly because securing regeneration is a major concern in these often overly degraded  
314 marginal populations (Zlatanov 2006).

315

316 Regeneration, a specific silvicultural task in marginal and peripheral populations  
317 At the leading edge of species distributions, low dispersal rate, inbreeding due to small  
318 population size, increased browsing and unsuitable soils may hamper regeneration and  
319 population establishment and persistence under climate change. For example, browsing  
320 hinders the regeneration of partially inbred marginal populations of English yew at high  
321 latitudes (Myking et al. 2009). Management options for facilitating and securing population  
322 expansion at the leading edge include the use of genetically diverse reproductive material and  
323 assisted gene flow (Aitken and Whitlock 2013, see below for a discussion on assisted gene  
324 flow), and, more than elsewhere, herbivore deterrents.

325 At the rear edge of species distributions, climate may become increasingly unfavorable  
326 and thus many populations will become ecologically marginal, with drastic consequences for  
327 their survival. Rising temperatures and land use change were found to be responsible, despite  
328 some evidence of an adaptive response, to the gradual extinction over the last half-century of  
329 low elevation, rear edge populations of European beech in the Catalan mountains (Jump et al.  
330 2006, Peñuelas et al. 2007). Rising temperatures will also affect natural regeneration in many  
331 rear edge marginal populations. The negative effect of climatic extremes on flowering and  
332 seed set in populations at the rear edge may become a serious obstacle. For example,  
333 dormancy requirements of many broadleaved tree species may be not met by increased  
334 temperatures (e.g. Afroze and O'Reilly 2013 for *Sorbus aucuparia*, and Doody and O'Reilly

335 2011 for *Fraxinus excelsior*), which may stop germination altogether as demonstrated for  
336 beech (Krawiarz and Szczotka 2008). However, beyond sporadic reports, there are yet  
337 insufficient investigations on this subject.

338 Management options available to counteract extinction, decline of natural regeneration  
339 and reduction of genetic diversity in rear-edge marginal populations, depend on prevailing  
340 local ecological conditions and may include: (i) partial removal of herbaceous species to  
341 reduce competition with natural regeneration; (ii) retention of shrubs as facilitators for  
342 provision of shade (Benavides et al. 2013, Castro et al. 2004); (iii) soil and mycorrhiza  
343 abundance improvement (Smith and Read 2008) and (iv) fostering and increasing flowering  
344 and seed set (Box 2). In view of declining seed yields, the damage to seed crops caused by  
345 foraging game and, in some regions by grazing, should be curtailed.

346

347

348 Box 2: Flowering and seed set at the leading- and 348 rear-edges of natural distributions

349

350 Leading edge: Flowering and seed production are annually highly variable in most tree  
351 species. However, insufficient or lacking flowering and low seed set are of particular concern  
352 at the leading edge, for example in Scots pine (*Pinus sylvestris*) and birch (*Betula pendula*).  
353 While trees in plantations successfully acclimate to colder conditions, seed production and  
354 migration are probably limiting the northward expansion, as several consecutive warm years  
355 are needed for successful regeneration. In addition, only a small proportion of trees is  
356 responsible for most of the seed production. As experiments in Finland show no clear genetic  
357 correlation between flowering, growth and acclimation capacity, the only guideline for  
358 management of marginal birch populations is to favor individuals showing highest capacity  
359 for seed production (Rousi et al. 2011).

360

361 Rear edge: In Portugal, rear edge populations of *Quercus suber* and *Quercus ilex* /

362 *rotundifolia* demonstrate low and highly variable flower and seed production, as well as a

363 declining number of reproductive trees over the years. On suitable sites, with deep soil that  
364 can compensate for lack of rainfall, the proportion of fruiting cork oak trees varies between  
365 40-80 % depending on mast year, while on a poor site it varies between 10-20%. Such deep  
366 soil stands with reduced drought stress constitute excellent candidates for in-situ conservation  
367 as well as quality habitats for assisted migration schemes when threatened populations need to  
368 be transferred to safer places (sensu Richardson et al. 2009). In holm oak (*Quercus ilex*) stands  
369 that have been declining for a prolonged period of time, density decreases to less than 15 trees  
370 per ha. At such low density and with declining flowering and fructification, the quantity and  
371 the genetic quality of seedlings can be seriously jeopardized (see simulations in Sagnard et al.  
372 2011).

373

374 3. Marginal and peripheral populations: valuable resources for forest reproductive  
375 material

376 Economic, ecological and/or conservation interests justify active silvicultural intervention  
377 in marginal and peripheral populations to support their own survival and regeneration. The  
378 genetic resources of marginal and peripheral populations may also be a valuable contribution  
379 for securing the stability or resilience of threatened core distribution populations under  
380 assisted gene flow schemes. Although still debated, the forest reproductive material (FRM) of  
381 these populations could be directly used for enrichment planting and also for tree breeding  
382 purposes.

383 Assisted gene flow consists of mixing non-native pre-adapted genotypes into local,  
384 potentially threatened populations (Aitken and Whitlock 2013). There are few risks associated  
385 with using marginal and peripheral in assisted gene flow schemes: outbreeding depression has  
386 rarely been demonstrated in forest trees 386 and, although there is evidence that adaptation to  
387 drought is not present in all dry site ecotypes (e.g. for beech, Peuke et al. 2002), several  
388 studies have shown that marginal drought-resistant populations exhibit better drought  
389 adaptation than core populations (e.g. for beech, Rose et al. 2009; Ivojevic et al. 2012;  
390 Robson et al. 2012). Therefore, Thiel et al. (2013) suggest to use intermixtures of marginal

391 and drought-adapted populations with local populations, adapted to different environmental  
392 factors. Suggestions for using marginal populations need to be recognized as general  
393 guidelines and tested species by species and according to management objectives.  
394 Marginal and peripheral populations can thus contribute significantly to assisted gene  
395 flow. The legal framework in the European Union for the production and marketing of FRM  
396 (Council Directive 1999/105/EC) does not restrict the commercial use of genetic resources  
397 from marginal and peripheral populations (Konnert et al. 2015). Identification of seed stands  
398 located in marginal environments and the use of their FRM in reforestations when appropriate  
399 (i.e. as part of assisted gene flow strategies) and as a source of genetic novelty in breeding and  
400 conservation programs (and ex-situ collections) should be encouraged.

#### 401 IV. CONSERVATION OF THE GENETIC RESOURCES OF MARGINAL 402 AND PERIPHERAL POPULATIONS

403 The in-situ and ex-situ conservation of genetic resources has been well defined by  
404 international regulatory bodies such as the United Nations Convention on Biological Diversity  
405 (CBD) and the International Treaty on Plant Genetic Resource for Food and Agriculture  
406 (ITPGRFA). In-situ conservation builds on the idea that changing environmental conditions  
407 are key for evolving new adaptive traits in populations while not putting the long-term  
408 persistence of the population at risk. Dynamic in-situ conservation of forest genetic resources  
409 involves a natural system in which the evolutionary forces which give rise to genetic  
410 diversity, are allowed to act and modify allele and gene frequencies (Lefèvre et al. 2013).  
411 With ex-situ conservation, populations and individuals are conserved as copies in field,  
412 storage vault or cryopreserved collections. Ex-situ collections are at the root of breeding  
413 activities, although they are far from containing all genotypes that may be of importance to  
414 conservation as their primary goal is the selection of a few individuals with desired  
415 phenotypes or of known pedigrees. Field collections allowing spontaneous mating and  
416 reproduction (dynamic ex-situ conservation; Eriksson et al. 1993) may provide conditions in  
417 which evolutionary forces are allowed to act and modify allele and gene frequencies (Lefèvre  
418 et al. 2013) and offer an alternative to standard in-situ and 418 ex-situ strategies. With raising



419 extinction threats worldwide, particularly at rear edges and at low elevations (Hampe and  
420 Petit 2005), cryopreservation is increasingly perceived as a complementary system to  
421 conservation strategies (Li and Pritchard 2009). However, its advantages are doubtful for  
422 forest trees and their highly complex genetic system and long life cycle.

423

424 Box 3: Legal aspects linked to the conservation of the genetic resources of marginal and  
425 peripheral populations in Europe

426 In Europe, several legal frameworks and programs deal with the identification and the  
427 monitoring of components of biological diversity (as defined by the 1992 Convention on  
428 Biological Diversity) and can be used to support the conservation of marginal and peripheral  
429 populations.

430 • FOREST EUROPE (former Ministerial Conferences on the Protection of Forests in  
431 Europe, MCPFE);

432 • The Council Directive Nr. 92/43/EEC on the conservation of natural habitats and of  
433 wild fauna and flora (Habitats Directive);

434 • The European Forest Genetic Resources Programme (EUFORGEN).

435 In particular, the Habitats-Directive and EUFORGEN promote the development and  
436 implementation of dynamic in-situ conservation strategies across country borders through  
437 concrete objectives. At the national level, objectives for marginal and peripheral populations  
438 should be integrated within Forest and Conservation Acts, forest management practices and  
439 silvicultural concepts of each country.

440

441 1. Habitat conservation and genetic conservation: not necessarily incompatible

442 management targets

443 Conservation of all levels of diversity, from genes to species and communities, can be  
444 implemented simultaneously on the same site if target species for gene conservation are also  
445 keystone species in a particular habitat, ensuring similar conservation objectives, and if some  
446 level of silviculture or habitat management is allowed (Box 4). Protected habitats must be

447 sufficiently large and include significant landscape heterogeneity to maintain evolutionary  
448 processes in different target species (Fady et al. 2015). When this is not the case, specific gene  
449 conservation measures, such as dynamic in-situ conservation units or ex-situ collections, need  
450 to be adopted and decoupled from other species conservation measures (Koskela et al. 2013).

451

452

453 Box 4: Conserving the genetic resources of cork oak at the rear edge in a National Park in  
454 Tunisia.

455 In Tunisia, cork oak has seen its range reduced by half over the last 80 years. This reduction is  
456 due to different causes, both man-made and not. Social, climatic and technical constraints are  
457 major stumbling blocks to restoration efforts of cork oak forests in Tunisia. Under climate  
458 change, drought and pest and disease resistance, such as that found in marginal populations  
459 geographically distant from the central cork oak area, offer renewed opportunities for  
460 conservation, restoration and breeding.

461 The marginal population of Jebel Serj (Siliana), located more than 120 km south of the core  
462 area, is an excellent example of successful management. Until 2010, it suffered the same  
463 extinction risk as other marginal populations as it did not benefit from any special protection  
464 measures. Following a campaign to raise awareness, forest authorities decided to include this  
465 population within the just established Jebel Serj National Park by extending the area of this  
466 nature reserve dedicated to the protection of the Montpellier maple (*Acer monspessulanum*  
467 L.), another very rare species in Tunisia. This change of status has already provided better  
468 visibility to the marginal cork oak of Jebel Serj, has raised conservation awareness among  
469 local people and has definitely increased the interest of policymakers. The effectiveness of  
470 this conservation measure is well illustrated by the fact that natural regeneration, although  
471 absent before 2010, is now beginning to be visible in this population.

472

473 At the rear edge, marginal and peripheral populations often harbor a keystone species of  
474 interest for habitat conservation (e.g. sub-Mediterranean endemic *Pinus nigra* Salzmanni pine

475 habitats in southern France). Thus, they may be particularly suited for simultaneous in-situ  
476 conservation combined with habitat preservation. However, many of these populations will  
477 risk extirpation and may also become prime candidates for managed relocation (“the  
478 intentional movement of biological units from current areas of occupancy to locations where  
479 the probability of future persistence is predicted to be higher”, Richardson et al. 2009) and ex480  
situ conservation under climate change. At the leading edge, migrants may modify the  
481 composition of local keystone and dominant species and bring about conflicting views  
482 between habitat conservation and gene conservation strategies. The same conflicting views  
483 may arise if mortality increases in populations at the core of the geographical range. Whereas  
484 high adult tree mortality may be acceptable for dynamic in-situ conservation if gene flow is  
485 significant (as an efficient way to speed up evolutionary processes, Lefèvre et al. 2014), it  
486 might not be so for habitat conservation.

487 Conservation at high elevation ecological margins in the core of the distribution range  
488 may have similarities with that proposed for leading edge populations. The availability of  
489 sites necessary for potential population expansion 489 is vital, if an endangered population has  
490 reached mountain ridges or peaks, or if soil, moisture or vegetation cover conditions above  
491 the present distribution limit are unsuitable for colonization; then ex-situ conservation will be  
492 the only option. This calls for a timely and careful examination of the site conditions beyond  
493 present leading edges.

494

495 2. Planning and monitoring conservation in marginal and peripheral populations

496 Conservation planning needs to recognize the value of marginal and peripheral  
497 populations of widespread species, not just of rare and endangered ones (Leppig and White  
498 2006, Pressey et al. 2007). Genetic-oriented conservation planning is a process of: (i)  
499 recognition of specific targets (delineation of conservation areas), (ii) identification of  
500 endangering demographic and genetic processes (iii) instigation of specific measures, for  
501 capturing and sustaining a high level of genetic diversity.

502 The essence of genetic conservation planning is to avoid extinction of identified and

503 endangered marginal and peripheral populations by maintaining their natural reproduction  
504 capacity. Of specific importance are characteristics of the genetic/reproductive system (first of  
505 all mating, dispersal and regeneration features). There are only few species where reliable  
506 genetic information is available to support the selection of priority populations and to  
507 formulate proper measures. In most cases species level data may serve as proxies (pattern of  
508 natural distribution; social status, i.e. stand-forming/scattered; level of threats; tolerance to  
509 biotic and abiotic stress etc.).

510 The maintenance of conservation units needs active management interference, monitoring  
511 of results of management and, when these fail, ex-situ conservation measures (Figure 3). A  
512 decision cascade approach has been suggested as a method of prioritizing and subsequently  
513 managing target populations (Kelleher et al. 2015). The decision cascade can include criteria  
514 to assess population decline (such as in IUCN 2012) or the risk of genetic depletion (e.g.  
515 Potter and Crane 2010), with the subsequent mitigation measures.

516

517

518 Figure 3. Example of a decision cascade process for selecting genetic conservation actions  
519 in marginal and peripheral populations. The first step of the process is to identify threats to  
520 marginal and peripheral populations, i.e. using monitoring, particularly 'target (or focused)  
521 monitoring', which is based on existing hypotheses and associated models of system  
522 responses to management (adapted from Nichols and Williams 2006).

523

524 Genetic monitoring is an efficient tool to control how marginal and peripheral populations  
525 are adapting to changes in the environment. It provides an early warning system for  
526 supporting management decisions regarding silvicultural practices, securing the stability of  
527 marginal and peripheral populations and safeguarding an undisrupted supply of FRM. An  
528 assessment of the status of marginal and peripheral populations will: (i) make possible the  
529 identification of marginal and peripheral populations most valuable for production of FRM  
530 and for conservation and (ii) enable focusing available resources on their management and

531 monitoring. Priority should be given to populations showing significant adaptation to one or  
532 more desirable traits. At the leading edge, the likelihood that populations can contribute to the  
533 colonization of new habitats should be assessed (e.g. growth plasticity, sufficient fecundity,  
534 high dispersal). At the rear edge, populations displaying long term persistence (Hampe and  
535 Petit 2005) or showing growth plasticity and tolerance to drought should be prime candidates.  
536 Regular genetic monitoring of ongoing conservation 536 activities (Figure 3) enables the  
537 quantification of temporal changes in genetics and dynamics of populations, using appropriate  
538 and inexpensive parameters (Frankham 2010, Aravanopoulos 2011). It is based on assessing  
539 indicators (genetic diversity, genetic drift, gene flow, selection) stemming from the  
540 conceptual framework of the gene-ecological approach, through a set of verifiers (Graudal et  
541 al. 2014). Some of these verifiers should be estimated on a regular basis (demographic  
542 parameters), while others may be recorded at longer time intervals such as per decade or  
543 longer (genetic parameters). This is a species-independent method with a prognostic value  
544 applicable to any population of interest in order to enhance the conservation effort  
545 (Aravanopoulos 2011). In addition, health conditions, recruitment patterns and environmental  
546 parameters of marginal and peripheral populations should also be monitored. The intensity of  
547 monitoring depends on the features of the genetic/reproductive system of the species, on the  
548 actual threats and social interests.

549

550 3. Deciding when marginal and peripheral populations need to be conserved ex-situ  
551 With the decline of the ecological quality of the habitat in which the species of interest is  
552 growing, in-situ conservation may no longer be sustainable. However, ex-situ conservation  
553 may form an evolutionary dead-end that could be detrimental to marginal and peripheral  
554 population conservation, particularly in forest trees with very long generation times. Dynamic  
555 ex-situ conservation, therefore, should remain a last resort option to be decided case-by-case,  
556 e.g. when specific indicators point to severe extirpation risks (Figure 3).

557 In some fortunate instances, ex-situ conservation efforts may be shared with the aims of  
558 forest tree breeding. Ex-situ conservation has long been practiced by forest tree breeders and

559 the archived material may be an irreplaceable element of conservation (e.g. in case of  
560 European black poplar, wild cherry and some conifers). However, breeders' archives rarely  
561 include material from marginal and peripheral populations, although, with breeding programs  
562 required to consider climate change, this is starting to change (Fady et al. 2015).

563

564 V. CONCLUSIONS AND PERSPECTIVES: 564 MARGINAL AND  
565 PERIPHERAL POPULATIONS - A RESOURCE WORTH PROTECTING  
566 AND USING!

567 Future uncertainty in environmental conditions due to global climate change is a major  
568 issue for developing sound, long-term forest management strategies (Lasch et al. 2005,  
569 Garcia-Gonzalo et al. 2007, Lefèvre et al. 2014, Lindner et al. 2014). This uncertainty needs  
570 to be taken into consideration even more for marginal and peripheral populations where  
571 environmental and, consequently, demographic and genetic stochasticity is high compared to  
572 core populations.

573 Marginal and peripheral populations contain very valuable genetic resources for the  
574 maintenance of the adaptive potential of species. Habitat conservation and gene conservation  
575 strategies, especially in marginal and peripheral populations, are often carried out separately,  
576 uncoordinatedly, or in conflict with one another (Fady et al. 2015). However, both are  
577 concerned with threats, such as environmental change, habitat fragmentation, land use change,  
578 inappropriate forest management, and others, which simultaneously impact species,  
579 populations and gene diversity. It is our opinion that the different resource management views  
580 and strategies, concerning conservation on the one hand and utilization on the other, need to  
581 be reconciled in marginal and peripheral populations, particularly at the rear edge and at  
582 ecological margins.

583 We propose that sustainable forestry practices encompass conservation aspects in a more  
584 comprehensive manner by endorsing an evolution-oriented forestry (Lefèvre et al. 2014),  
585 especially in regions where marginal and peripheral populations are found. Conservation  
586 practices include the need to manage via silvicultural techniques when keystone species are

587 declining. We believe that in exceptional circumstances, either assisted gene flow or managed  
588 relocation of certain marginal and peripheral populations should be employed and endorsed  
589 by both the habitat conservation and the forest management communities. Without this  
590 option, many rear-edge populations will face extinction and their pre-adapted genetic  
591 resources will be lost. Their ability to strengthen potentially declining forests elsewhere in  
592 their range will also vanish. Under uncertain environmental conditions, marginal and  
593 peripheral populations, particularly at the rear-edge and at ecological margins, have an option  
594 value that no forest and habitat manager should want to see disappear. They are one of the key  
595 assets for adaptive forestry (i.e. the ability of forestry to adapt to changes in climate, Lindner  
596 et al. 2010) and are recognized as a strategic priority by the Global Plan of Action for the  
597 Conservation, Sustainable Use and Development of Forest Genetic Resources of the Food and  
598 Agriculture Organization of the United Nations (FAO 2014).

599 We would also like to draw attention to the importance of regular monitoring, for which  
600 we propose solutions. Particularly, marginal and peripheral populations, including those  
601 planted artificially, constitute early warning signals for dieback that should be recognized as  
602 outstandingly useful. An inventory of both natural and planted/naturalized marginal and  
603 peripheral populations must be a priority, in order to implement meaningful long-term genetic  
604 monitoring.

605 Whether genetic adaptation will be sufficient to allow the long-term persistence of forest  
606 trees within their current distribution and how changes in biotic interactions will affect this  
607 process, is currently one of the research priorities for forest management and conservation. In  
608 this area of research, marginal and peripheral populations (particularly at the rear-edge and at  
609 ecological margins) are “natural laboratories” that have a particular role to play. Given the  
610 complexity of ecological and demographic conditions found in marginal and peripheral  
611 populations, and how they interplay, using complex models that consider demographic,  
612 genetic and ecophysiological processes jointly in forest dynamics are needed (Kramer et al.  
613 2015, Oddou-Muratorio and Davi, 2014).

614 In the words of Alleaume-Benharira et al. (2006): “The fate of such marginal populations

615 is also very important in the context of climatic change as they might be the theatre of  
616 evolutionary change, face increasing extinction risk, or be the source of migrants to colonize  
617 new areas at expanding margins. It is therefore critical to identify the different sources of  
618 maladaptation in such populations and to propose efficient conservation measures”.

619

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630

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