CHAPTER 1

The context for reforestation and restoration guidelines

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Introduction

The ecological and economic importance of forests is uncontested, and forest functions are irreplaceable. Forests cover about 30% of the land and host about 80% of the world's biodiversity. They provide subsistence, employment opportunities, and income to a quarter of the world's population—not to mention storing vast amounts of carbon (FAO, 2022b). The protective role of forests, one of the ecosystem services they freely provide, is of tremendous value (Costanza et al., 2017). For example, trees and woodlands provide people in the UK with protection from flooding worth €450 million each year (Broadmeadow et al., 2023).

Humanity is facing triple threats from the loss and degradation of natural systems such as forests, declining biodiversity, and the warming and less predictable climate (Bergstrom et al., 2021). The growing demands on public- and private-sector resources will affect efforts to address the climate crisis, reducing the speed and scale of mitigation and adaptation responses for the immediate future. Adding to the immediate needs is the prospect of providing for a doubling of the human population to 10–14 billion by the end of the century.

Forests are part of important short-term and long-term strategies for addressing the triple threats, including climate change (Solomon et al., 2007; Deng et al., 2023). Five strategies summarize the numerous ways that forests can contribute to mitigating climate change: (1) maintain and (2) increase the area covered by forests, (3) increase the carbon taken up by forests, (4) maintain, and (5) increase the carbon stored in forests (Stanturf et al., 2015). Active forest management, restoring deforested and degraded forests, and setting forests aside under protection (passive management) are differing ways of implementing these strategies. One modeled comparison of the three approaches found that the global potential for increased carbon storage was greater by maintaining and sustainably managing forests than by restoring or protecting forests. In fact, over half (158.4 PgC) of the unrealized potential could be realized on land suitable for forests (Walker et al., 2022). Restoration of similarly suitable land could add another 22.7 PgC in storage. In every type of forest (boreal, temperate, and subtropical and tropical), the greatest potential additional storage was in maintaining and managing forests. These values are

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optimistic estimates because climate change feedback, changes in plant physiology, or natural disturbance regimes were not included, but the trends are realistic. A rational mitigation and adaptation strategy would be to deploy all three methods, where each was the most appropriate.

Deforestation and land degradation globally threaten ecosystem integrity, diminish the services and benefits forests provide, and deprive forest-dependent communities of livelihood provisions (Hosonuma et al., 2012; FAO, 2022a). Estimates of the current need for forest restoration vary widely, from 1 to 2 billion hectares (ha) globally (Minnemayer et al., 2011; Bastin et al., 2019), depending on definitions, survey methods, and data acquisition technologies. In the Tropics, for example, degraded forests and mosaic landscapes with restoration potential have been estimated at 863 million ha (Brancalion et al., 2019) to 930 million ha (ITTO, 2020). Besides the need to restore degraded land worldwide, timely reforestation following harvests, disturbances, and afforestation following land abandonment is lagging in many countries (e.g., Lieffers et al., 2020; del Campo et al., 2021; Fargione et al., 2021). Forest management could be sustainably intensified to sequester more carbon and, at the same time, promote biodiversity (Nabuurs et al., 2017; Seddon, 2020; Verkerk et al., 2020).

An altered future climate poses new challenges to ecosystem stability and amplifies old threats. In temperate forests of the Northern Hemisphere, disturbances caused by strong winds, heat- and drought-induced physiological stress, fires, bark-beetle outbreaks, and other detrimental factors (often interacting synergistically) have significantly exceeded historic frequencies and documented impacts (Senf and Seidl, 2018; Cook et al., 2022; Patacca et al., 2023). In managed forests of Europe, salvage cutting is routinely used in these disturbed areas. Natural regeneration may be impossible due to limiting environmental conditions. Even vigorous natural regeneration may require intervention to diversify the tree species portfolio in times of uncertain future climatic conditions.

Massive tree planting campaigns have been promoted, for example, the 3 billion additional trees to be planted in the EU by 2030 under the European Green Deal[1] that emphasizes the use of native species and biodiversity benefits. Restoring more natural conditions is also a way to address the critical loss of biodiversity. Increasingly, there is a recognition that the trees planted should be fit for purpose: The right tree, planted in the right place, for the right reasons (Bateman et al., 2023; Daley, 2024).

[1] Commission Staff Working Document 52021SC0651. 16 July 2021. The 3 Billion Tree Planting Pledge For 2030, accompanying the document communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee, and the Committee of the Regions, New EU Forest Strategy for 2030. Available at https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021SC0651&qid=1696330072891.

Objectives, scope, audience

Whether the motivation is to restore forests to increase biodiversity or to increase or maintain productivity of managed forests in the face of climate change, there clearly is a need to produce climate-adapted forest reproductive material (FRM) and to develop silvicultural systems appropriate under a changing climate. Our purpose in authoring this book is to provide forestry professionals with a tool to navigate the challenges of planting forests under climate change. As climate impacts intensify, there is an urgent need for guidelines that empower those on the frontlines of producing seedlings, planting, and managing the post-planting phase to grow and manage healthy new forests. This book fills that gap, offering insights, best practices, and evidence-based solutions to lay the foundation for fostering resilient and thriving forests.

The scope of this book primarily covers European conditions (boreal, temperate, and Mediterranean biomes) but draws on relevant knowledge elsewhere of forest restoration and reforestation practices. Our main focus is on biophysical aspects; while we recognize the importance of the social and economic dimensions of forest restoration and reforestation projects, in particular stakeholder engagement, a full treatment of these important topics is beyond the scope of the book, and other resources are available (e.g., Mansourian et al. 2024). Similarly, we do not attempt to cover in depth the full spectrum of issues around the impacts of climate change on forests.

The audience for this book is forestry professionals who grapple with the need to adapt forest management practices to the changing climate while preserving biodiversity and maintaining sustainable ecosystems. They must select the right tree species, produce FRM, and navigate the complex world of site preparation and silviculture without certain knowledge of the climatic conditions under which the forest will develop. Furthermore, these professionals often need to demonstrate the environmental and economic benefits of their projects to stakeholders. Our book addresses these challenges by providing evidence-based guidelines, practical solutions, and insights from experts, all tailored to the specific needs of forestry professionals.

The European forest context

Forests in Europe are extremely varied, from the boreal in the north to the temperate, Mediterranean biome in the south. From west to east, the climate varies from maritime to continental. Climate, soils, and vegetation, as well as past and current land use history and management, create a mosaic of forest types and management regimes. Thus any attempt at generalizing forest conditions will overlook important exceptions and local variants. Nevertheless, the following overview follows the five European biogeographical regions used by IIASA (Egger et al., 2024): North, Central-West, Central-East, South-West, and South-East Europe. In the tables that follow, data for land area, forest area, and areas of naturally regenerated and planted forest are from the 2020 Forest Resource Assessment (FAO, 2020). The data for public and private ownership reflect the situation in 2010 (UNECE/FAO, 2015). Although the current situation in individual nations may have changed, these are the most consistent available data for comparison.

Forest management regulation and practices in Europe vary considerably by country, particularly in the freedom a private landowner has to make management decisions, including which species to plant. Survey results for some countries were presented by Nichiforel et al. (2020). They used 37 indicators that were analyzed for 28 countries, comparing the legal framework for property rights in the mid-1990s with 2015. They compiled 37 indicators into a Property Rights Index in Forestry (PRIF). There were 13 indicators for the broad category of Management Rights, covering land use, planning, and operations. The following tables show the rating for one indicator (i25), "Scope of decision on the type of species to be used for reforestation," scaled from low to high (0–100) to indicate greater freedom of choice. In general, private forest owners in western Europe had greater freedom of choice than those in eastern Europe (Nichiforel et al., 2020).

Another indicator chosen to show the decision space available to forest managers of both public and private lands is the option to plant nonnative tree species (NNT). Pötzelsberger et al. (2020) reviewed the legal and regulatory environment in place in June/July 2019 regarding NNT in 40 European countries. Not surprisingly, the conditions ranged from very few restrictions on species choice to the complete banning of the use of NNT species in forests. They synthesized their findings into five categories of "Intensity" of legal restrictions on the practical use of NNT in forestry, from I = low, essentially a forest owner is free to decide where and what to plant, except for locally defined "invasive" or "harmful" species may be prohibited, to V = very severe, implying a complete or almost complete ban of the use of NNT in forestry. Their synthesis values are shown in the following tables; the numbers in parentheses indicate regional differences within a country.

North Europe

The countries in Northern Europe (Denmark, Estonia, Finland, Iceland, Latvia, Lithuania, Norway, and Sweden) are primarily in the boreal and hemiboreal biomes. Forest area comprises a relatively large share of the land area in several of these countries (Table 1.1), from Norway (33%) to Finland (74%), as contrasted to low forest cover in Iceland and Denmark (respectively 1% and 16%). The economic importance of the forest sector is great except in Denmark and Iceland. Forests provide a range of ecosystem services and economic benefits, including wood production from managed semi-natural forests and recreation and biodiversity, primarily in protected areas (Egger et al., 2024).

Table 1.1 Forest land in North Europe by country, showing forest area, forest cover as a percentage of land area, and area of naturally regenerated versus planted forest.

Country		Land area	Forest area	Naturally regenerated	Planted
	% Forest		X 1000 ha		
Denmark	16	4000	628	216	412
Estonia	57	4275	2438	2223	215
Finland	74	30,395	22,409	15,041	7368
Iceland	1	10,083	51	12	39
Latvia	55	6223	3411	2945	466
Lithuania	35	6261	2201	1590	611
Norway	33	36,427	12,180	12,072	108
Sweden	69	40,728	27,980	14,068	13,912

Of the three countries with the most forest land, the forests in Finland and Norway are mostly naturally regenerated, but in Sweden, the planted area is almost equal to the naturally regenerated forest area (Table 1.1). Over the period 2000–17, extreme weather was the most damaging agent reported in North Europe (almost 60% of reported damage). Insects and diseases accounted for about 20% of each reported damage; wildfire was a very minor factor in the region (Koch et al., 2024).

In these northern European countries, only Latvia and Lithuania have less than 50% of the forest area in private ownership (Table 1.2). The freedom of private forest owners to make management decisions is great, according to a survey reported by Nichiforel et al. (2020). Estonia and Latvia recently expanded the choice of species allowed for afforestation. Most countries, except for Denmark and Estonia, have restrictions on the use of nonnative forest tree species (Pötzelsberger et al., 2020).

Table 1.2 Ownership of forest land in North Europe by country, showing percentages of private versus public ownership, relative freedom of private forest owners to make management decisions on species to plant, and relative constraints on use of nonnative trees.

Country	% Private forest land ownership	% Public forest land ownership	Private forest owners' management freedom	Nonnative plants regulation
Denmark	76	24%	76	I
Estonia	53	47%	65*	II
Finland	70	30%	79	III
Iceland	67	33%	n.a.	III
Latvia	48	52%	53*	(III)
Lithuania	39	61%	n.a.	III
Norway	87	13%	77	IV
Sweden	76	24%	73	III

Table 1.3 Forest land in Central-West Europe by country, showing forest area, forest cover as a percentage of land area, and area of naturally regenerated versus planted forest.

Country		Land area	Forest area	Naturally regenerated	Planted
	% Forest	X 1000 ha			
Austria	47	8252	3899	2228	1671
Belgium	23	3028	689	251	438
France	32	54,756	17,353	14,819	2534
Germany	33	34,939	11,419	5710	5709
Ireland	11	6889	782	108	674
Liechtenstein	44	16	7	6	1
Luxembourg	35	257	89	59	30
Netherlands	11	3367	370	38	332
Switzerland	30	4128	1235	1074	161
United Kingdom	13	24,193	3190	344	2846

Central-West Europe

In the Central-West European countries (Austria, Belgium, France, Germany, Ireland, Liechtenstein, Luxembourg, Netherlands, Switzerland, and the United Kingdom), forest land area is relatively low, and forest cover varies from 11% in Ireland and the Netherlands to 44% in Luxembourg (Table 1.3). Forests are of moderate economic importance in Austria, France, and Germany (Egger et al., 2024) and are greatly valued for recreation and biodiversity in all countries (Egger et al., 2024). Forests in most countries were naturally regenerated, except in Germany, where planted and naturally regenerated were about equal, and in Belgium, Ireland, and the Netherlands, where more forest area was planted (Table 1.3). Over the period 2000–17, diseases and insects were the most damaging agents reported in Central-West Europe (over 70% of reported damage). Extreme weather accounted for slightly more than 20% of reported damage; wildfire was a very minor factor in the region (Koch et al., 2024). Because the report was based on data through 2017, it does not include the significant effect of drought and the large-scale bark-beetle outbreaks in Central and Eastern Europe since 2018 (Koch et al., 2024).

Land ownership in Austria, France, Switzerland, and the UK in Central-West Europe was mostly private (Table 1.4), and about equally in private and public ownership in the rest of the countries, except Liechtenstein, where public ownership greatly exceeded private ownership. Private forest owners had wide freedom to make management decisions in all countries except the Netherlands, but only in Ireland were forest owners able to freely plant nonnative tree species (Table 1.4).

Central-East Europe

The Central-East European countries (Belarus, Czechia, Hungary, Poland, Romania, Slovakia, Slovenia, and Ukraine) are relatively well forested (Table 1.5), but forests

Table 1.4 Ownership of forest land in Central-West Europe by country, showing percentages of private versus public ownership, relative freedom of private forest owners to make management decisions on species to plant, and relative constraints on use of nonnative trees.

Country	% Private forest land ownership	% Public forest land ownership	Private forest owners' management freedom	Nonnative plants regulation
Austria	74	26%	71	(II)
Belgium	53	47%	77x	(III, IV)
France	75	25%	61	II
Germany	48	52%	84x	(II, III, IV)
Ireland	47	53%	72	I
Liechtenstein	14	86%	n.a.	n.a.
Luxembourg	53	47%	n.a.	III
Netherlands	51	49%	29	(I, II)
Switzerland	73	27%	58	II
United Kingdom	72	28%	76	II

Table 1.5 Forest land in Central-East Europe by country, showing forest area, forest cover as a percentage of land area, and area of naturally regenerated versus planted forest.

Country		Land area	Forest area	Naturally regenerated	Planted
	% Forest	x 1000 ha			
Belarus	43	20,295	8768	6556	2212
Czechia	35	7719	2677	138	2539
Hungary	22	9126	2053	1264	789
Poland	31	30,610	9433	0	9433
Romania	30	23,008	6929	6034	895
Slovakia	40	4808	1926	1177	749
Slovenia	61	2014	1238	1192	46
Ukraine	17	57,940	9690	4842	4848

are less economically important than in Northern Europe. These countries are in the temperate biome. Forests cover varies, from about a third of the land area to almost two-thirds. The forest sector is moderately important in these countries, and wood production occurs in managed semi-natural forests (Egger et al., 2024). Most forests are naturally regenerated except for large areas of planted forests in Poland and Czechia; planted and naturally regenerated forests were about equal in Ukraine in 2010 (Table 1.5). Recreation and biodiversity are important services from managed semi-natural forests and protected areas. Over the period 2000–17, insects were the most damaging agent reported in Central-East Europe (almost 60% of reported damage). Extreme weather

Table 1.6 Ownership of forest land in Central-East Europe by country, showing percentages of private versus public ownership, relative freedom of private forest owners to make management decisions on species to plant, and relative constraints on use of nonnative trees.

Country	% Private forest land ownership	% Public forest land ownership	Private forest owners' management freedom	Nonnative plants regulation
Belarus	0	100%	n.a.	IV
Czechia	23	77%	47*	IV
Hungary	42	58%	18	III
Poland	18	82%	27	IV
Romania	33	67%	16	III
Slovakia	45	55%	24	IV
Slovenia	75	25%	33	III
Ukraine	0	100%	n.a.	I

accounted for slightly more than 30% of reported damage; wildfire was a very minor factor in the region (Koch et al., 2024). Because the report was based on data through 2017, it does not include the significant effect of drought and the large-scale bark-beetle outbreaks in Central and Eastern Europe since 2018 (Koch et al., 2024) or the war damage to Ukrainian forests (Pereira et al., 2022; Hartmane et al., 2024).

Ownership of forest land in Central-East Europe was predominantly public, including Belarus and Ukraine, where public ownership was total (100%). The exception that stands out is Slovenia, where three-fourths of the forests are privately owned. On the whole, private forest owners were restricted in their ability to make management decisions except in Czechia, where recent changes in legislation have allowed more freedom to choose species for afforestation (Nichiforel et al., 2020). Use of nonnative tree species is greatly restricted in all countries except Ukraine (Table 1.6).

South-West Europe

The South-West European countries (Andorra, Italy, Portugal, San Marino, and Spain) are well forested (17%–37%), but only Italy, Spain, and Portugal have large forest areas with sizable areas of planted forests. Nevertheless, forests in all countries are mostly naturally regenerated (Andorra and San Marino have no planted forest areas; Table 1.7). Fire was by far the most reported damaging agent (50%) in South-West Europe over the period 2000–17, followed by diseases (over 25% of reported damage). Insects and extreme weather were relatively minor damaging agents (about 10% each of reported damage) (Koch et al., 2024).

Information on private forest owners' management freedom (Nichiforel et al., 2020) and ability to use nonnative species (Pötzelsberger et al., 2020) was only available for Portugal and Spain. While these countries scored high on the landowner freedom scale,

Table 1.7 Forest land in South-West Europe by country, showing forest area, forest cover as a percentage of land area, and area of naturally regenerated versus planted forest.

Country		Land area	Forest area	Naturally regenerated	Planted
	% Forest		X 100 ha		
Andorra	34	47	16	16	0
Italy	32	29,572	9566	8921	645
Portugal	36	3312	1056	2256	700
San Marino	17	6	1	1	0
Spain	37	18,572	15,982	2590	1010

Table 1.8 Ownership of forest land in South-West Europe by country, showing percentages of private versus public ownership, relative freedom of private forest owners to make management decisions on species to plant, and relative constraints on use of nonnative trees.

Country	% Private forest land ownership	% Public forest land ownership	Private forest owners' management freedom	Nonnative plants regulation
Andorra	n.a.	n.a.	n.a.	n.a.
Italy	66%	34%	n.a.	n.a.
Portugal	97%	3%	68*	IV
San Marino	n.a.	n.a.	n.a.	n.a.
Spain	71%	29%	81	(II,III,IV)

and recent legislation in Portugal clarified the use of *Eucalyptus* spp., managers in both countries faced more restrictions on the use of nonnative tree species (Table 1.8).

South-East Europe

The South-East European countries (including Türkiye) are all well forested, from the low of Cyprus (19%) to a high of Montenegro (61%). Most forests in the region are naturally regenerated, except for Greece, which has by far more planted (3.9 million ha) than naturally regenerated forests (29,000 ha). Insects (50%) and extreme weather (30%) were the most reported damaging agents in South-East Europe over the period 2000–17, followed by wildfire (over 10% of reported damage). Diseases were a relatively minor damaging agent, accounting for less than 10% of reported damage (Koch et al., 2024) (Table 1.9).

Public ownership of forest land was typical of all countries in South-East Europe, from highs of 100% in Türkiye and 97% in Albania. On the contrary, ownership in Serbia and Montenegro was essentially equal between public and private. Private forest land owners were mostly constrained in their freedom to manage their forests, ranging from a score of 10 in North Macedonia to 42 in Greece (on a scale of 0–100).

Table 1.9 Forest land in South-East Europe by country, showing forest area, forest cover as a percentage of land area, and area of naturally regenerated versus planted forest.

Country		Land area	Forest area	Naturally regenerated	Planted
	% Forest	X 1000 ha			
Albania	29	2740	789	712	70
Bosnia Herzegovina	43	5120	2188	2185.8	2.2
Bulgaria	36	10,856	3893	3116	777
Croatia	35	5596	1939	1871	68
Cyprus	19	924	173	140	33
Greece	30	12,890	3902	29	3873
Montenegro	61	1345	827	819	8
North Macedonia	40	2522	1001	n.a.	n.a.
Serbia	32	8409	2723	2607	116
Türkiye	29	76,963	22,220	21,503	717

Table 1.10 Ownership of forest land in South-East Europe by country, showing percentages of private versus public ownership, relative freedom of private forest owners to make management decisions on species to plant, and relative constraints on use of nonnative trees.

Country	% Private forest land ownership	% Public forest land ownership	Private forest owners' management freedom	Nonnative plants regulation
Albania	3	97%	n.a.	I
Bosnia Herzegovina	20	80%	24	(III)
Bulgaria	12	88%	25	IV
Croatia	28	72%	33*	III
Cyprus	31	69%	n.a.	V
Greece	23	77%	42	I
Montenegro	52	48%	n.a.	III
North Macedonia	10	90%	10*	III
Serbia	47	53%	n.a.	III
Türkiye	0	100%	n.a.	II

Regulations on use of nonnative tree species were low (Category 1) in Albania and Greece, with more restrictions in the other countries (Table 1.10).

Climate change

Natural disturbances (wind, wildfire, drought, snow and ice, insects, and pathogens) are intrinsic ecological factors in European forests (Thom and Seidl, 2016; Sommerfeld et al., 2018). Disturbances have increased in many European countries since 1950, most importantly wind, bark beetles, and wildfire (Patacca et al., 2023). Climate change is expected to cause a significant increase in the frequency, intensity, and severity of natural disturbances in Europe (Seidl et al., 2017). Climate change impacts forests by higher annual average temperature, lower or more variable rainfall, less snowpack, or a combination of these factors (Acácio et al., 2009; Dai, 2011; Williams et al., 2013). Extreme events are projected to increase in frequency by more than an order of magnitude as climate change continues (IPCC, 2021). Heat-induced tree mortality, reduced moisture availability, and drought are already affecting tree growth worldwide (Ciais et al., 2005; Leuzinger et al., 2005; Allen et al., 2010; Babst et al., 2019; Cook et al., 2022).

Climate change projections depend on anticipated changes in key driving forces that produce different levels of greenhouse gas emissions that result in different representative concentration pathways (RCP) or trajectories of future greenhouse gas concentrations. The higher the RCP, the greater the expected impacts on global climate. The RCPs hypothesize that different mitigation efforts will be made to limit emissions. RCP 2.6 is a very stringent pathway, RCP 4.5 is an intermediate scenario, and RCP 8.5 is a scenario with few effective efforts made to lower emissions, which continue to rise throughout the 21st century (Meinshausen et al., 2011). The projected temperature and precipitation in the five European biogeographical regions are shown in Figs. 1.1 and 1.2 for two time periods, 2041–60 and 2061–80, compared to historical conditions (1979–2013) for RCP 2.6, 4.5, and 8.5.

Current global climate models are better at projecting temperature than precipitation, so the trends in temperature changes are more consistent across the three RCPs (F.. 1.1). Mean temperature is projected to increase by between 2°C in North, Central-West, and South-West Europe and 5°C in Central-East and South-East Europe under the most extreme projection (RCP 8.5). Trees planted today would be expected to live beyond the longer-term projection (2061–80); even under the intermediate RCP 4.5 scenario, trees, especially seedlings, will experience mean temperature increases between 2°C and 3°C throughout Europe (Fig. 1.1).

The picture for precipitation includes substantial uncertainty (Fig. 1.2), with slight gains or losses in the northern and western regions and losses of up to 400 mm/year in Central-East, Central-West, and South-West Europe in the 2061–81 period. The combination of higher temperatures and lower precipitation will significantly affect many species (Lindner et al., 2014; Leuschner et al., 2023), particularly the lowered suitability of Norway spruce (*Picea abies*) and better conditions for *Quercus* species (Hanewinkel et al., 2013). A common prescription for adapting silviculture to this altered future climate is to create mixtures of species in forests as a way of reducing risk (Bauhus et al., 2017; Verkerk et al., 2020; Yousefpour, 2022; Cooper and MacFarlane, 2023; Felton et al., 2023). This option may be limited, however, by the loss of climatically adapted native species by the end of the century (Wessely et al., 2024).

European forests are predominantly naturally regenerated; the planted area was half the naturally regenerated (70,425 ha vs. 151,955 ha; data for Bosnia and North

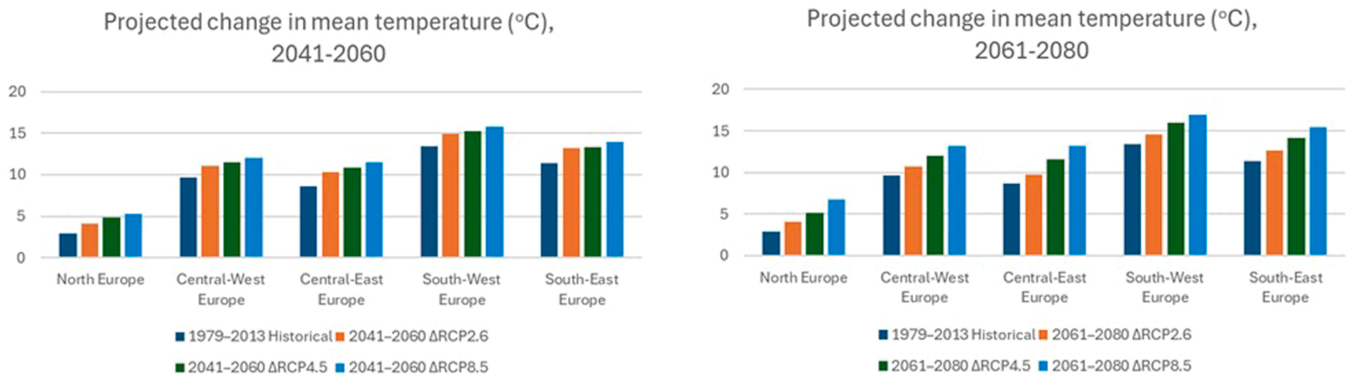

Figure 1.1 Projected change in mean temperature (°C) in two time periods (2041–60 and 2061–80) compared to historical (1979–2013) for three representative concentration pathways for five European biogeographical regions. *(Credit: (Source: Data from Brun et al. (2022) in Eggers et al. (2022)).)*

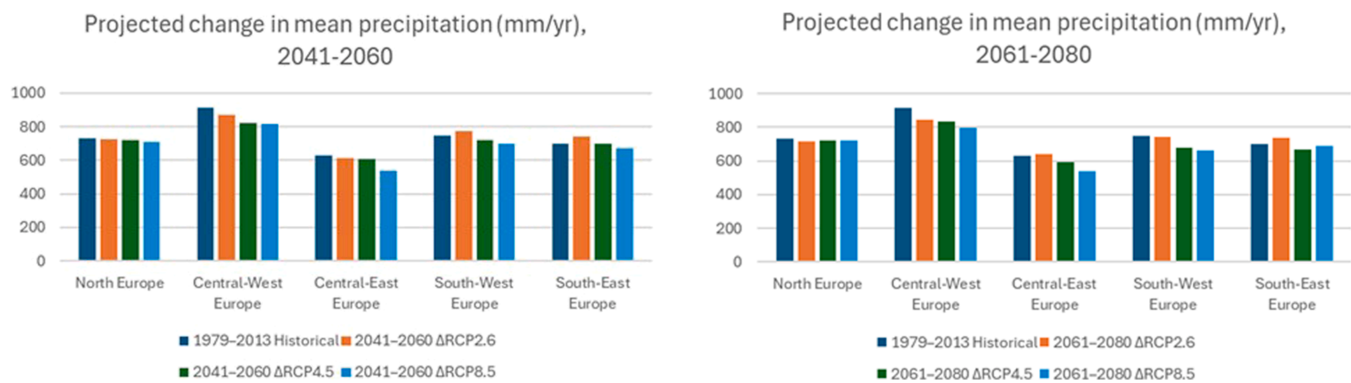

Figure 1.2 Projected change in mean precipitation (mm/yr) in two time periods (2041–60 and 2061–80) compared to historical (1979–2013) for three representative concentration pathways for five European biogeographical regions. *(Credit: (Source: Data from Brun et al. (2022) in Eggers et al. (2022)).)*

Macedonia not available). The current enthusiasm in many countries for close-to-nature or continuous cover forestry (Brang et al., 2014; O'Hara, 2016; Stiers et al., 2020), furthered by EU legislation (e.g., the EU Forest Strategy, Green Deal, Habitats Directive, and the Nature Restoration Law) could result in even more naturally regenerated forest land but the long-term benefits may be limited. A recent study by Rosa et al. (2023) determined that closer-to-nature management on up to 37.5% of forest land in the EU lowered extinction risks (extreme biodiversity losses). Species extinction would be lowered even more if more wood were produced by higher management intensity on other land, along with importing some wood from low-intensity managed areas outside of the EU. But even low-intensity practices could not prevent increased extinction risk under a future scenario with greater demand for energywood.

If more than 25% of the currently managed forestland in the EU is set aside for passive management, by 2100 the global extinction risk would be greater compared to the continuation of current practices. This is because the projected increase in demand for wood would be met by imports to compensate for a decrease in domestic harvest. And some of the imports would come from regions vulnerable to biodiversity losses (Rosa et al., 2023). This "leakage" effect, of locking up EU forests and buying wood products from overseas with an unclear chain of custody, in effect, is exporting our biodiversity impacts to other countries.

From forestry and biodiversity perspectives, natural regeneration may have important benefits, including lower cost and locally adapted genetic material. There are significant limitations, however, in terms of species composition and the inability to introduce species or provenances better adapted to the future climate. Assisted migration (AM) is an adaptation strategy for overcoming a climate that is changing faster than long-lived forest trees can adapt or migrate (Aitken et al., 2008; Aitken and Bemmels, 2016; Sang et al., 2021). AM is the intentional movement of tree species and populations to more hospitable habitats and to replace species unable to thrive under a rapidly altered climate (Dumroese et al., 2015; Twardek et al., 2023; Stanturf et al., 2024). Using AM in European forestry faces significant barriers, with the emphasis in many countries on natural regeneration and constraints in the use of nonnative species.

Much of our present knowledge about forest regeneration developed under relatively stable climate regimes. As evidence accumulates that a changing climate is rendering many native European species maladapted in their current range, a critical awareness is emerging that new approaches to reforestation and restoration are needed. The current demand for reforesting harvested forests, afforesting marginal farmland, and restoring degraded land will only increase as disturbances become more frequent, of greater intensity, and severity. Adaptive and innovative approaches to producing and deploying climate-adapted FRM are of greater importance than ever before to overcome these limitations and guide tree species composition to increase forest resilience and resistance. The following chapters are an attempt to facilitate efforts to adapt to future conditions.

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