Food and Agriculture Organization of the United Nations

International Commission on Poplars and Other Fast-Growing Trees Sustaining People and the Environment

Innovative practices in the sustainable management of fast-growing trees

Lessons learned from poplars and willows and other experiences with fast-growing trees around the world

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Food and Agriculture Organization of the United Nations
Rome, 2025

Required citation:
Zalesny, R.S.Jr., Barzagli, A., Caldwell, B., Minotta, G., Nervo, G., Paris, P., Rogers, E.R. & Salbitano, F., eds. 2025. *Innovative practices in the sustainable management of fast-growing trees – Lessons learned from poplars and willows and other experiences with fast-growing trees around the world.* Rome, FAO. https://doi.org/10.4060/cd4104en

ISBN 978-92-5-139579-0

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Acknowledgements

This publication is the result of a long-term collaborative effort under the auspices of the IPC and benefited from the contributions of the multiple practitioners, technical experts, and leading scientists in the field of fast-growing trees that are listed here below, who generously contributed their time and knowledge to give birth to this publication.

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Finally, this publication benefited from the strategic guidance and support from the IPC Executive Committee members, who demonstrated their continued support and enabled its preparation: Martin Weih (Swedish University of Agricultural Sciences, Sweden) ; Barb Thomas (University of Alberta, Canada) ; Esteban Borodowski (Ministerio de Agricultura, Ganadería y Pesca de la Nación, Argentina) ; Mariya Chambova (Executive Forest Agency, Bulgaria) ; Meng-Zhu Lu (Zhejiang A&F University, China) ; Eric Paillassa (Centre National de la Propriété Forestière, France) ; Mirko Liesebach (Thünen Institute of Forest Genetics, Germany) ; Dinesh Kumar (Forest Research Institute, India) ; Giuseppe Nervo (Council for Agricultural Research and Economics, Casale Monferrato, Alessandria, Italy) ; Kyu-Suk Kang (Seoul National University, Republic of Korea) ; Yasar Selim Bostanci (Poplar and Fast Growing Forest Trees Research Institute, Türkiye) ; Ronald S. Zalesny Jr. (United States Department of Agriculture, Forest Service, Rhinelander, Wisconsin, United States of America) ; Cristian Espinosa Ackerknecht (Cristian Espinosa Ackerknecht, Chile) ; Judson G. Isebrands (Environmental Forestry Consultants, LLC, United States of America) ; Tshimangadzo Cyril Ndou (Department of Forestry, Fisheries, and Environment, South Africa) ; Marzena Niemczyk (Forest Research Institute, Poland) and Patrick Worms (World Agroforestry Centre (CIFOR-ICRAF), Belgium).

Summary

Planted forests account for 7 percent of the global forest area, covering 290 million hectares (ha) of land. About 131 million ha of planted forests are intensively cultivated for productive purposes with fast-growing trees (FGTs). Fast-growing trees have been developed and used for millennia to provide wood and non-wood products to rural communities and other direct and non-direct benefits to urban societies. Globally, FGT plantations comprise a variety of tree species in temperate, subtropical and tropical biomes. These belong to genera such as *Populus*, *Salix*, *Paulownia*, *Pinus*, *Acacia*, *Casuarina*, *Eucalyptus* and *Tectona* with diverse applications ranging from forest farming to plantations for biomass production. Many FGTs are pioneer species that can colonize bare or degraded lands, and for this reason they are often used to provide a wide range of ecosystem services beyond contributing to wood security.

Today, FGTs represent an important economic sector for many countries. They are key to the industrial bioeconomy as well as the livelihoods of local communities. Fast-growing trees also have huge potential for combating climate change and providing other ecosystem services, thanks to their fast growth, high efficiency in functional ecophysiology, and ability to adapt to poor ecological conditions. However, to obtain the greatest economic and environmental benefits from FGTs, knowledge on the genetics, physiology and ecology of FGTs must be advanced further, and the understanding of socioeconomic factors contributing to the success of FGTs must be strengthened. The objective of this publication, *Innovative practices in the sustainable management of fast-growing trees: lessons learned from poplars and willows and experiences with other fast-growing trees around the world*, is to address knowledge gaps and the current and potential development of FGTs at the global scale by highlighting successful, innovative FGT practices that can help sustain people and the environment. Further, the book aims to make this information relevant and accessible to a diverse range of stakeholders involved in the agriculture and forest sectors, including researchers, landowners, technical operators and planners, and policymakers. In this context, the authors propose a comprehensive list of references as part of the methodology.

In total, 43 authors from nine countries contributed to this book, bringing their ideas, experience and expertise to advance innovation in FGT science, management and policy. Multiple themes within these broad categories are discussed. First, the FGT genera and species deemed most common across varied climatic zones are introduced. This is followed by a discussion on the adverse biotic, abiotic and anthropogenic factors affecting FGT plantations, and the management actions that can be taken to mitigate these. The genetic resources and genetic improvement of FGTs are described, with a focus on conservation strategies for maintaining genetic integrity, and the potential for developing and deploying superior forest reproductive material (FRM) for FGT plantations. Next, the environmental dimensions of FGTs are discussed (with aspects such as climate-change resilience, enhanced biodiversity, improved water quality and soil health, and pollution mitigation), followed by their societal dimensions (i.e. enhanced livelihoods, non-wood products, landscape restoration and landscape design, and trees in cities) and their productive dimensions (i.e. raw materials for primary production). Finally, a path forward is presented for innovations in FGT management practices, and models for economic sustainability of FGTs are suggested.

1 Introduction

With contributions by Stefano Bisoffi,[1] Pierluigi Paris,[2] Piermaria Corona[3]

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Fast-growing trees (FGTs) are light-demanding pioneer species capable of relatively rapid growth in suitable site conditions (Whitmore, 1989). These types of trees are natural colonizers of gaps that open in the forest due to disturbances such as stand-replacing fire, windthrow, landslides and floods. A survey was conducted in 2020 among the 38 member countries of the International Commission on Poplars and Other Fast-Growing Trees Sustaining People and the Environment (IPC). Fifteen countries identified alder (*Alnus* Mill.), ash (*Fraxinus* Tourn. ex L.), locust (*Robinia* L.), birch (*Betula* L.), cherry (*Prunus* L.), Douglas fir (*Pseudotsuga* Carr.), eucalyptus (*Eucalyptus* L'Hér), larch (*Larix* Mill.), linden (*Tilia* L.), maple (*Acer* L.), mulberry (*Morus* L.), oak (*Quercus* L.), pine (*Pinus* L.), poplar (*Populus* L.), paulownia (*Paulownia* Sieb. & Zucc.), spruce (*Picea* A. Dietr.), walnut (*Juglans* L.) and willow (*Salix* L.) as the most common FGT genera of interest in their countries. Global statistics on the cultivation of FGTs are not readily available. However, some inferences can be made from the *Global Forest Resources Assessment 2020* report of the Food and Agriculture Organization of the United Nations (FAO), which identifies two broad categories of forest, naturally regenerating forest and planted forest. According to this report, 7 percent of the world's forest area is planted forest, of which nearly half (45 percent) is plantation forest, which is intensively managed planted forest that at maturity is composed of one or two species and has one age class and regular tree spacing (FAO, 2020). Globally, the area of planted forest, and within this, the area of plantation forest, increased between 1990 and 2020. Of the 131 million hectares (ha) of global plantation forest, most is in Asia (79 million ha) and South America (20 million ha). Most, if not all, forest plantations are established with FGTs, but some planted forests that are not plantation forests still contain FGTs. In addition, 71 countries reported an overall 45 million ha of agroforestry (FAO, 2020), though only some of this area is cultivated with FGTs. Besides their use in planted forests, including forest plantations, FGTs also remain an important component of naturally regenerating forests worldwide.

Due to their potential to establish and grow rapidly in open conditions, FGTs have been widely cultivated worldwide for applications in planted forests, including forest plantations, agroforestry systems, urban forestry and phytotechnologies. They can produce a relatively large amount of biomass in a relatively short space of time. Building on that advantage, management objectives have focused on the production of timber, fibre, energy and non-wood products (NWPs). However, well-designed and sustainably managed FGT plantations can also provide a wider range of ecosystem services, such as soil conservation and restoration, watershed protection, climate regulation and aesthetic values, that may benefit livelihoods on a global scale, for both market and subsistence economies in evolving socioeconomic scenarios. Long-term investments to improve FGT genetic material and management methods have translated into increased success in meeting designated management goals. As a result, FGTs are an important component of forestry and agricultural systems worldwide, often owned by small-scale farmers, whose livelihoods they support. Fast-growing trees are also a major part of the production systems and business models of large timber companies and are a key component of global wood-based value chains. In the context of good planning and governance, FGTs can efficiently produce wood to spare land for conservation.

The important environmental applications of FGTs include their use for rapid restoration of degraded or contaminated land and stabilization of soils, due to their accelerated growth. However, monoculture has been the dominant FGT cultivation model, with extensive applications in monoclonal plantations for species like poplar (*Populus* L.) and eucalypt (*Eucalyptus* L'Hér), and FGT monoculture plantations are rarely able to provide the same ecosystem services as naturally regenerating forests, especially in terms of biodiversity and resilience to climate change.

With the world's total forest area declining, new avenues are needed to restore and sustainably manage healthy, productive ecosystems. Deforestation has accelerated dramatically in the last few centuries, though the rate of decline of net forest loss has slowed in the last three decades. Current rates of afforestation and reforestation are not sufficient to counterbalance deforestation. The average annual rate of plantation forest gain was 1.48 million ha per year in 2010–2020. Climate change is increasingly impacting forests globally. In Europe, recent findings have shown an increased vulnerability of forests to fires, windthrow and insect outbreaks between 1979 and 2018 (Forzieri *et al*., 2021). At this pace, all the world's forests could disappear in approximately 100–200 years. At the same time, global needs for wood will continue increasing sharply, putting further pressure on the world's depleted forests. A study by Carle, Duval and Ashfordc (2020) compared outlook studies of industrial roundwood production from planted forest resources, with projected values varying between 1 400 million cubic metres (m^3) and 1 900 million m^3 in 2030. FAO estimated that global demand for wood products – primary processed wood, industrial roundwood, and woodfuel – will grow by an average of one-third by the year 2050 (FAO, 2022). The primary sector needs to adopt innovative approaches to increase sustainable production of raw materials for food, energy and industrial purposes (Ramankutty *et al*., 2018; Corona, 2019).

The sound use of FGTs in plantation forestry and agroforestry systems can help reverse the deforestation trend while supporting a transition towards sustainable and productive agrifood systems. Establishing forests and planting trees must be further implemented to counterbalance deforestation, but this must be done in such a way that it ensures strategic ecological services, especially to mitigate and adapt to climate change, conserve biodiversity, and avoid further land degradation. Planning and establishment of well-managed, multispecies FGT systems involving participatory decision-making can facilitate the management and protection of natural forests while allowing increased wood production for traditional and innovative biobased productive value chains.

FGTs can be rapidly planted and managed for the temporary or permanent establishment of:

- productive plantations for industrial roundwood;
- energy plantations for the production of both fuelwood and wood chips for energy conversion, according to flexible cultivation models;
- mixed plantations of FGTs and slow-growing trees to increase plantation biodiversity; and
- agroforestry systems that mix trees and woody species with crops – many such systems have balanced biodiversity conservation and the production of goods necessary for human subsistence, such as food and wood, for centuries, thereby benefiting agroecosystems while producing multiple wood products.

Research is rediscovering agroforestry systems, in which FGTs may be established as fertilizer trees in the case of nitrogen-fixing FGTs, shelterbelts or buffer strips (Wolz and DeLucia, 2018).

This book on the management and utilization of FGTs was produced by the IPC as a contribution to the United Nations decade of action to achieve the Sustainable Development Goals (2020–2030). When sustainably managed, FGTs contribute to global international goals to mitigate and adapt to climate change, reduce poverty and conserve soils and water. The book is not meant to be read as a comprehensive catalogue of established best practices. Its purpose is to highlight successful FGT practices that can make contributions to sustaining people and the environment, for applied scientists, land managers and policymakers, linking technological innovations, traditional practices and environmental stewardship for the benefit of people worldwide and the planet. The goal in producing the book is also to enhance uptake, adaptation, innovation and additional investment in promising practices regarding FGTs.

The editors and the IPC hope that this book will help foster the innovation, partnerships and cooperation that will be necessary to scale up good practices in the management of FGTs in the years to come.

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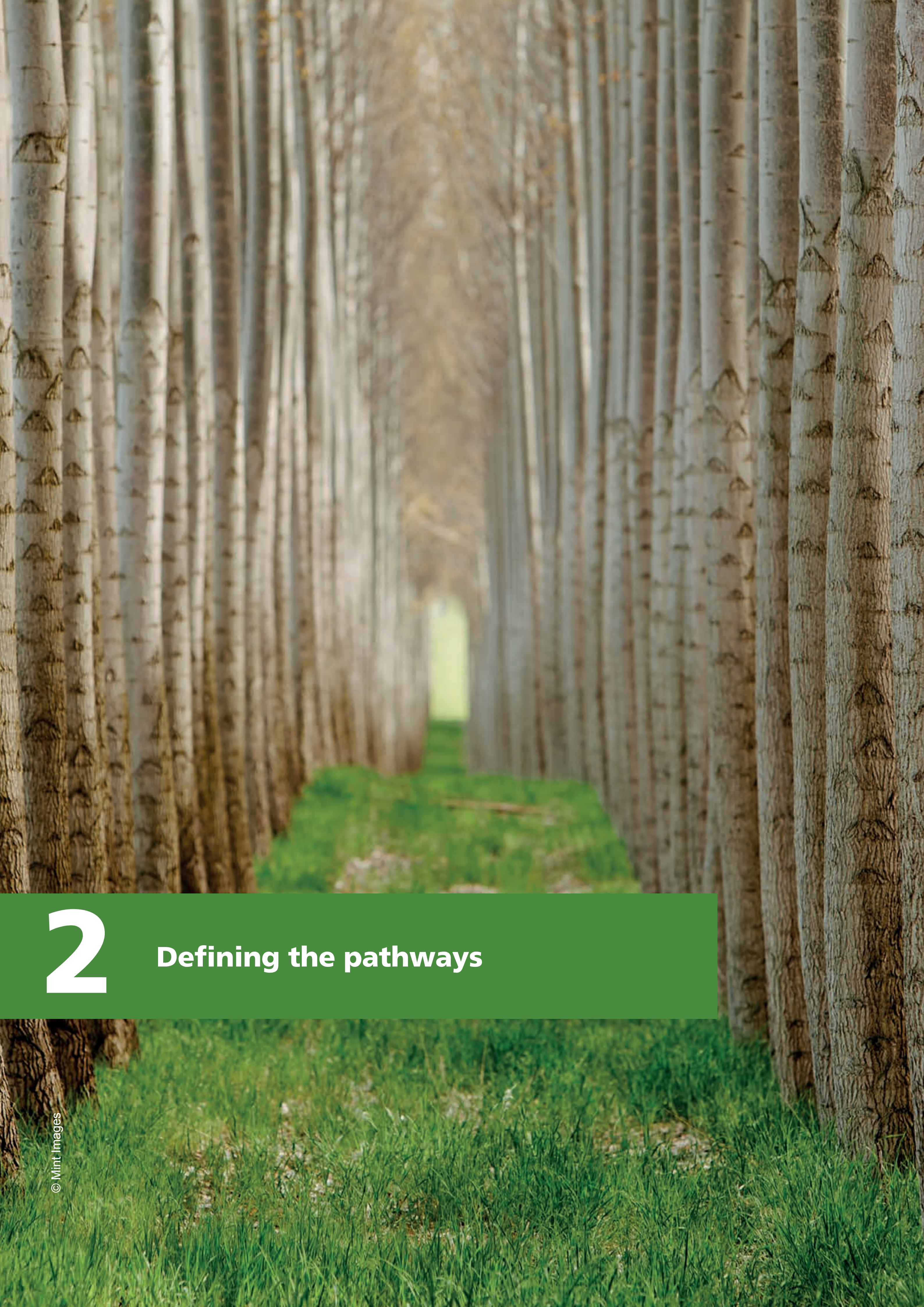

2 Defining the pathways

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2.1 Objectives, scope, methodology and limitations of this synthesis

This book focuses on the cultivation of fast-growing trees (FGTs) worldwide. Research on this topic in the global literature is still limited, and studies addressing their different dimensions even more so. The book approaches the topic of FGTs from a scientific and technical perspective while also examining some social and economic implications of the cultivation of these species on a global and local level, and their contribution to the industrial bioeconomy. Our goal is to highlight strategies for optimizing the sustainable use of FGTs to enhance the livelihoods and well-being of local communities who depend on agriculture and forestry. It aims to support a wide range of stakeholders involved in the agriculture sector, be they researchers, landowners, technical operators and planners or decision-makers. Many different aspects are presented, including the management and use of the ecosystem services that FGTs can produce when sustainably managed. There is a particular focus on innovation in these areas. The contribution of FGTs both to the bioeconomy on a global scale and to the livelihoods of local communities is discussed. The large number of species, environments and technical solutions involved on a global scale makes it impossible to conduct a comprehensive review of FGTs, while the strategic and policy issues discussed in some chapters will bear universal relevance.

Methodology

To facilitate the scoping of the main topics covered in this book and objectivize current trends in knowledge related to FGTs, a bibliographic analysis was developed on the topics of innovation and livelihoods in FGT cultivation systems, as follows:

- The first step was to perform a literature search on documents cited as references in the chapters of the publication. A literature search was then conducted using the Google Scholar search facility on a set of themes, i.e. tree farming OR FGTs OR poplars AND willows + livelihoods AND/OR innovation. The Google Scholar references database was used to include grey literature on topics that may not have been included in the book's references. By choosing to include non-scientific documents in this analysis, the authors got a better understanding of the world of FGTs in respect of innovation, income generation and livelihoods, as well as sustainable management and the ecosystem services that FGTs could provide. Based on the Google Scholar search, 556 documents were identified. These documents were filtered to avoid duplicates and exclude abstracts, annotations or other kinds of popular documents, resulting in 478 documents. The final 478 documents include: (1) scientific peer-reviewed articles (339 documents); (2) papers published in non-indexed journals (26 documents); (3) book chapters (40 documents); (4) proceedings of international and regional conferences (35 documents); and (5) project reports, technical books and monographs (38 documents). A references database was built that includes title, authors, country and region, year of publication, source, main topics covered and developed, and self-reported keywords for each document. The bibliographic database was constructed by taking into consideration all the materials that have been published, produced and disclosed on the topic of interest.
- The second step aimed to analyse the types of papers contributed by different regions of the world (Table 1). The number of documents produced by North American countries (particularly the United States of America) and European countries was much larger than those produced in other regions of the world. This is mainly due to the higher importance of poplar and willow cultivation in these regions. Documents written in languages other than English were also considered in the review, particularly French, Italian, Portuguese

and Spanish. Most of the documents examined deal with issues relating to "tree farming" (Figure 1) and specifically to tree cultivation methods. Specific topics include rotation periods, pruning, the need for fertilization and irrigation, and resistance to drought and nutrient deficiency. These topics are linked to the possibility of improving and increasing the production of biomass and wood as a central issue. The other topic extensively covered in the articles is the importance of plant microbiomes, and plant–soil and plant–microorganism interactions, followed by genetic resources. On the other hand, topics involving opportunities for improving livelihoods for farmers and local communities, and social aspects of the cultivation of FGTs, are underrepresented in the references database.

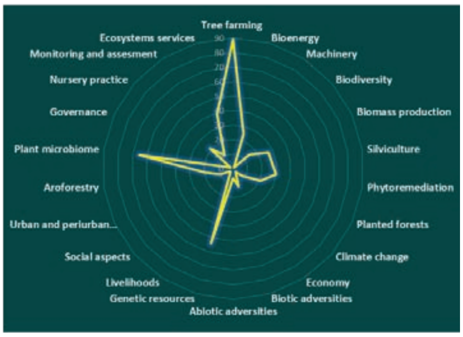
Table 1. Types of documents by country

Country	IJ	N-S J	BC	R	R	Total
United States of America	100	1	6	7	4	**118**
Italy	28	20	1	13	6	**68**
Brazil	22	0	0	0	0	**22**
Germany	16	0	1	1	0	**18**
Spain	11	0	0	1	4	**16**
United Kingdom of Great Britain and Northern Ireland	13	0	2	1	0	**16**
Canada	13	0	0	0	2	**15**
Sweden	12	0	1	0	0	**13**
France	9	3	0	0	0	**12**
China	8	2	1	1	0	**12**
India	8	0	2	0	0	**11**
Australia	6	0	0	1	0	**7**
Netherlands (Kingdom of the)	4	0	1	0	0	**5**
Belgium	4	0	0	1	0	**5**
New Zealand	4	0	0	1	0	**5**
Serbia	3	0	2	0	0	**5**
Argentina	2	0	0	3	0	**5**
Poland	4	0	0	0	0	**4**
Finland	4	0	0	0	0	**4**
Hungary	3	0	0	0	0	**3**
Egypt	2	0	0	1	0	**3**
Republic of Korea	2	0	0	0	0	**2**
Türkiye	2	0	0	0	0	**2**
Greece	2	0	0	0	0	**2**
Russian Federation	2	0	0	0	0	**2**
Chile	2	0	0	0	0	**2**
Ukraine	2	0	0	0	0	**2**
Ireland	1	0	0	0	1	**2**
Czech Republic	1	0	0	0	1	**2**
Niger	1	0	0	0	1	**2**
Japan	1	0	0	0	0	**1**
Ethiopia	1	0	0	0	0	**1**
Iran (Islamic Republic of)		0	0	0	0	**1**
Slovakia		0	0	0	0	**1**
Viet Nam	1	0	0	0	0	**1**
South Africa	1	0	0	0	0	**1**
Pakistan	1	0	0	0	0	**1**
Portugal	1	0	0	0	0	**1**
Estonia	1	0	0	0	0	**1**
Micronesia (Federated States of)	1	0	0	0	0	**1**
Mexico	1	0	0	0	0	**1**
Switzerland	0	0	1	0	0	**1**
Bulgaria	0	0	0	1	0	**1**
Indonesia	0	0	0	0	1	**1**
Bhutan	0	0	0	0	1	**1**

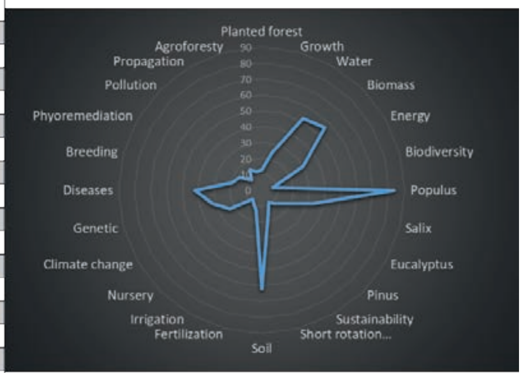
Note: IJ= Indexed journals; N-SJ= Non-scientific journals; BC= Book chapters; P= Proceedings; R= Project reports, technical books and monographies.

Figure 1. Breakdown of the main themes and keywords in the documents analysed

Main themes	N
Tree farming	89
Plant microbiome	65
Genetic resources	54
Ecosystems services	39
Phytoremediation	30
Biomass production	27
Silviculture	27
Bioenergy	25
Planted forests	21
Nursery practice	21
Aroforestry	20
Biodiversity	15
Biotic adversities	13
Monitoring and assesment	11
Urban and periurban forestry	10
Climate change	8
Abiotic adversities	7
Economy	3
Livelihoods	3
Social aspects	3
Governance	2
Machinery	1



Keywords	N
Populus	83
Soil	62
Biomass	56
Water	52
Diseases	42
Salix	33
Genetic	32
Energy	30
Growth	24
Climate change	23
Breeding	19
Eucalyptus	17
Short rotation coppice	16
Phyoremediation	16
Propagation	15
Planted forest	13
Fertilization	13
Pinus	12
Agroforesty	12
Irrigation	10
Sustainability	9
Pollution	9
Nursery	8
Biodiversity	7



2.2 Summary of the state-of-the-art in sustainable management of fast-growing trees

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Summary

In this section, several new practices for the sustainable management of fast-growing trees (FGTs) are reported. The primary focus is on techniques used in Italy and the southern European Union in short-rotation forestry and poplar cultivation. Specific techniques discussed include site choice and preparation, transplanting, weed control, irrigation, fertilization and pruning. Many of the cultivation practices reported concern poplars (*Populus* L.) or Salicaceae in general. However, several techniques related to soil preparation and establishment are common to most FGTs. Notes are also made for locusts (*Robinia* L.), eucalypts (*Eucalyptus* L'Hér) and pines (*Pinus* L.).

Keywords: Short-rotation forestry; short-rotation crops; cultivation; tending

Introduction

Fast-growing tree species have been cultivated for millennia to provide wood for multiple uses in rural communities and, in the last century, to provide timber, fibre and biomass for industrial and energy uses. Planted forests account for 7 percent of the global forest area, covering 290 million hectares (ha). About 131 million ha of these are intensively cultivated for productive purposes, mostly with FGTs (FAO, 2020). A global overview of poplar (*Populus* L.) and willow (*Salix* L.) cultivation is given in Chapter 5 of the FAO and CABI book *Poplars and willows: trees for society and environment* (Stanturf and van Ooosten, 2014). In this section, new techniques for plantations using FGTs are reported, specifically those applied in Italy and the southern European Union in short-rotation forestry (SRF) using poplars.

Site choice and preparation

For cultivation to be economically sustainable, it is necessary to invest in at least a few hectares (3–5 ha) of the farm to make the resulting goods and services attractive to users. After choosing an appropriate species to grow considering the climatic conditions and soil characteristics of the site or farm (Table 2), management aspects related to mechanized tending and harvesting must be considered.

Fields should be long and large enough to maximize machine efficiency, particularly for harvesting operations. Headlands sufficiently wide at both ends of the planting rows are required to facilitate machine access and turning. This is particularly important for foragers with modified headers used to harvest young trees in short-rotation coppice (SRC) (FAO, 2008). Easy access to the site is essential to facilitate removal of the harvested material. The access track should lead to an unloading area where the harvested material can be handled (Caslin, Finnan and McCracken, 2010).

Site preparation commonly involves mechanical and chemical treatments. The field should be cleared of perennial weeds, and subsoiling should be implemented to a depth of 60–70 centimetres (cm), followed by ploughing to a depth of 30 cm or more, and then cross-disking before planting (Colorio *et al*., 1996; Stanturf and van Ooosten, 2014). As part of the Scientific Support for Agricultural Conversion to Energy Crops (SUSCACE) project, funded by the Italian Ministry of Agricultural, Food and Forestry Policies, the Council for Agricultural Research and Economics (CREA) Research Centre for Engineering and Agrifood Processing developed a prototype that carries out deep subsoiling (80 cm) in a single pass and primary and secondary tillage on a 54 cm strip where the seedlings or cuttings will be planted. In this way, it is possible to reduce the cost of soil preparation by more than 65 percent when compared to traditional SRF plantations, and this also allows for rapid development of the roots of young trees. The best results, especially with regard to rooting, were obtained with poplar cuttings transplanted in late winter (Pari and Assirelli, 2009). In coarse soil, with the usual site preparation tillage, soil organic carbon (SOC) content may decrease by 8–40 percent, down to a depth of 50 cm. A consistent decrease in SOC was observed with the conversion from forest to poplar plantation (Ferré *et al.*, 2014). A no-till method can be applied only on well-drained sites with deep, coarse soil to minimize soil erosion and conserve soil moisture and SOC.

Careful planning is required for the successful establishment of SRF. Precision management is therefore increasingly implemented for SRF, especially for poplar stands. A consistent set of steps is followed in precision management applications. First, the perimeter coordinates of the planting area are acquired with a global positioning system (GPS) to better delineate the actual field conditions. Once these data are acquired, and squaring of the land has been completed, plantation planning is carried out, considering the following factors: row orientation (usually north to south); spacing; and the distance between field borders and rows (which in Italy varies among municipalities), and from roads. Data collected in the field are transferred onto a computer, processed and used by a tractor operator to mark the rows or to open holes directly with auger planting poles. In this way, the use of manpower is greatly reduced, and the available surface is exploited in an efficient manner (Manzone and Balsari, 2011).

In the southern European Union, tree cultivation outside forests is undergoing a differentiation process towards numerous cultivation models, each specific to an industrial product, such as veneer, packaging, paper, energy or panels, or an environmental service, such as phytoremediation or landscape restoration (Padoan *et al.*, 2019). Therefore, different cultivation techniques are being studied. Densities of about 240 trees/ha or less for poplar plantations are used to produce logs of higher quality. For poplar, willow, *Robinia pseudoacacia* L. and eucalypts (*Eucalyptus* L'Hér), densities of 1 000–1 300 trees/ha are used in SRC to produce logs for packaging, paper, oriented strand board (OSB) and energy applications, while higher densities (5 500–20 000 trees/ha) are used for particle board and energy applications (Facciotto *et al.*, 2020). Each planting density corresponds to a different harvesting cycle (low density: 10–20 years; medium density: 4–8 years; high-density: 2–4 years).

Table 2. Main site factors to consider when selecting fast-growing trees for short-rotation forestry

	Topography		Soil pH			Prevailing soil texture		
Species	P	H/M	<6	6–8	>8	C	L	S
Acacia saligna	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Acer pseudoplatanus	Moderate limitation	Favourable	Moderate limitation	Favourable	Favourable	Moderate limitation	Favourable	Serious limitation
Alnus cordata	Favourable	Favourable	Favourable	Moderate limitation	Moderate limitation	Moderate limitation	Favourable	Favourable
Alnus glutinosa	Favourable	Favourable	Moderate limitation	Favourable	Moderate limitation	Favourable	Favourable	Moderate limitation
Castanea sativa	Serious limitation	Favourable	Favourable	Favourable	Serious limitation	Favourable	Favourable	Favourable
Cedrus spp.	Favourable	Favourable	Favourable	Favourable	Moderate limitation	Moderate limitation	Favourable	Favourable
Eucalyptus spp.	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Fraxinus excelsior	Moderate limitation	Favourable	Moderate limitation	Favourable	Favourable	Moderate limitation	Favourable	Moderate limitation
Paulownia tomentosa	Favourable	Favourable	Favourable	Favourable	Favourable	Serious limitation	Favourable	Favourable
Platanus spp.	Favourable	Favourable	Moderate limitation	Favourable	Favourable	Moderate limitation	Favourable	Moderate limitation
Robinia pseudoacacia	Favourable	Favourable	Favourable	Favourable	Moderate limitation	Moderate limitation	Favourable	Favourable
Ulmus pumila	Favourable	Favourable	Moderate limitation	Favourable	Favourable	Moderate limitation	Favourable	Favourable

Key:

Serious limitation (red) Moderate limitation (yellow) Favourable (green)

Note: P=plain, H/M = hill or mountain; C=clay, L= loam, S=sand.

Source: Modified from **Buresti Lattes, E. & Mori, P.** 2016. *Progettazione, realizzazione e gestione delle Piantagioni di legno Policicliche di tipo Naturalistico*. Arezzo, Italy, Compagnia delle Foreste.

Transplanting

The planting material varies depending on species and density per hectare. For poplar and willow, different planting materials are used for different applications. Cuttings (20–30 cm or more) are used in high-density plantations, long cuttings (80–100 cm), sets or 1-year-old poles in medium-density plantations, and 1-to-2-year-old poles in low-density stands (Camp, Rousseau and Gardiner, 2012; Bergante, Manzone and Facciotto, 2016). Seedlings or rooted cuttings grown in pots for 2 to 3 months are used for eucalypts and paulownia (*Paulownia* Siebold & Zucc.), while 1-year-old bare root seedlings are used for locusts and acacias (*Acacia* Mill). For other species, 2-to-3-year-old seedlings are used. It is important to ensure that good-quality material is used by checking for the following characteristics: straight and well lignified stem, intact apical bud, no mechanical damage, balanced height/diameter transplant ratio (between 50 and 80 for broadleaves, excluding poplar poles), and properly developed and intact roots (Buresti Lattes and Mori, 2016).

The planting period is the end of winter or early spring. Planting stock, prepared during winter, should be stored in cold conditions at temperatures between -4 °C and 0 °C; shoots and roots must not have time to develop before the cuttings are planted (Johansson, 1996). Poplar and willow cuttings are hydrated for 2–3 days before planting while long cuttings and 1-to-2-year-old poles are hydrated for 7–10 days prior to planting. Cuttings are planted with a transplanting machine. A variety of such machines are available on the European market. Semi-automatic machines are a valid choice technically and economically, especially when utilized in small areas (2–7 ha), while fully automatic machines are suited for planting whole sets or long cuttings, both in vertical or horizontal positions (at 5 cm depth), on areas larger than 7 ha (Balsari, Airoldi and Facciotto, 2004; Pari, 2005; Bergante, Manzone and Facciotto, 2016).

Tractor with GPS

Holes for planting seedlings opened at the intersection points of lines tracked on the ground with a GPS

The photos were taken by the chapter authors during machine trials in the "Mezzi" farm of CREA Forestry and Wood Centre in Casale Monteferrato, Italy

Weed control

Weed control is an essential operation for the successful establishment of SRC and SRF plantations (Buhler *et al.*, 1998). Weed control by mechanical and chemical means, or a combination of both, can be used, particularly during the establishment phase, and in the spring after harvesting for SRC, to avoid competition between weeds and trees for nutrients and water (Dickmann, 2006). On sites with dry summers and winters with temperatures above freezing, such as in Mediterranean countries, weed control must be carried out immediately after harvest to avoid losses of coppiced stumps. Cultivation practices are reduced during the second and third year after establishment or after coppicing in very short-rotation coppice (VSRC), after the third year in SRC and after the fourth year in SRF; disc harrowing can then be done only once in late spring. After this period, weeds can be controlled effectively by simply cutting them down with a mower, string trimmer or forestry mulcher before seed production to prevent them from returning the following year. In SRC, when the canopy is sufficiently developed to shade the soil, it is possible to stop mechanical weed control without reducing tree growth (Facciotto, 1998). Reduced soil cultivation increases SOC, contributing to the mitigation of carbon dioxide (CO_2) emissions (Ceotto, Librenti and Di Candilo, 2010). Each combination of species or clones, soil and weed population requires a different kind of herbicide (Buhler *et al.*, 1998). Herbicide availability changes over time (new formulations appear on a continuing basis, and older ones are withdrawn from the market), so keeping up to date is recommended.

To reduce the use of herbicides or manual hoeing, the CREA Research Centre for Engineering and Agrifood Processing studied an automatic system based on tree detection and weed recognition to remove weeds within the rows of poplar grown in nurseries or in SRC. In the first month after planting, the growth of poplar is rather slow; the control of intrarow weeds is therefore critical to avoid high yield losses. A simplified detection system consisting of a photoelectric sensor and a capacitive sensor was designed and then tested to assess its accuracy in detecting poplar cuttings along the row. The detection system was found to work best at low speeds, regardless of the distance from the row. Bearing in mind that the system is intended to be used on a machine operating in the interrow, it was found to be particularly useful, since the detection of poplar cuttings can take place at a safe distance to avoid any damage from accidental impacts (Assirelli *et al.*, 2014). The structural simplicity of this detection system should allow its application on the most common machines.

Irrigation

Most FGT species and clones require large quantities of water (Shock *et al.,* 2002; Paris *et al.*, 2018). Water has a very strong influence on accumulation and allocation of photosynthesis products. When soil water content decreases, the shoot/root ratio is reduced (Yin and Zhai, 2008; Chaturvedi and Raghubanshi, 2018). Water consumption of trees can be estimated as the quantity of water transpired to produce 1 kilogram (kg) of dry matter. In Italy, this value has been determined experimentally for the clone, I-214, (*P. ×canadensis*) as approximately 350 litres of water per kg of dry matter (Frison, Negro and Bardelli, 1982). This value will likely vary among clones. In Spain, poplars need 6–7 cubic centimetres (cm^3) water/day to produce 1 gram (g) of dry matter (Padró Simarro and Orensanz, 1987). Irrigation is not essential in most parts of Europe and North America, but for the Mediterranean region and other parts of the world (South America, Africa and Asia), it is required to obtain adequate yields (Achinelli *et al.*, 2008, 2018; Jia *et al.*, 2008; González-González *et al.*, 2017). In northern Italy, where poplars can be grown without irrigation, biomass production increases by 12–100 percent if the plantation is irrigated with 150–200 millimetres (mm) of water over the course of the summer (Facciotto, 2011; Paris *et al.*, 2018).

Various types of irrigation techniques can be used. Widespread methods include surface (flood) irrigation, sprinkler (overhead) irrigation and drip (trickle) irrigation. Though surface irrigation does not require high energy levels as water moves over land by gravity, it does require high volumes of water, up to 800–1000 cubic metres (m^3) per hectare per irrigation treatment. In sprinkler irrigation, groundwater or water from channels is distributed by overhead high-pressure sprinklers. This method requires less water at each treatment (300–500 m^3/ha), but irrigation treatments must be repeated every 2–3 weeks during the dry season. In addition, much of the water sprayed evaporates or is blown away by the wind before it hits the ground. Finally, in the drip irrigation method, and particularly with subsurface drip irrigation, water is delivered at or near the root zone, drop by drop. This is considered the most water-efficient method of irrigation because evaporation and runoff are minimized (Paris *et al*., 2018). For energy crops, it is also possible to use wastewater for irrigation, with especially good results in water-scarce locations (Leffert *et al*., 2008; Bustamante *et al*., 2011).

All aspects of poplar response to drought have been extensively studied in the last few decades. Drought resistance appears to be a very complex and multigenic property resulting from a combination of various mechanisms (Marron *et al*., 2008; Navarro *et al*., 2014; Viger *et al.,* 2016). The sensitivity of poplars to drought represents a limitation to the future development of poplar cultivation in dry conditions.

Fertilization

Fertilization is an expensive operation from an energy and economic point of view (Bergante, *et al*., 2023), particularly for SRC in which the wood produced has low economic value. At the University of Washington in the United States of America, Professor Sharon Doty and her team recently demonstrated that poplars grown on riparian soil (cobble and sand) along the Snoqualmie River in the State of Washington have colonies of endophytic diazotrophic bacteria (Doty *et al*., 2016). These microorganisms are mutualistic symbionts that improve growth and health of poplar and other species under nutrient-limited conditions. The studies conducted by Doty and colleagues lay the foundation for a future in which agriculture and forestry will be able to thrive without chemical fertilizers.

However, to avoid soil impoverishment, it is still currently necessary to periodically apply fertilization in organic (manure, digestate or green manure) or mineral forms in such quantities that the nutrients removed from the plantation site can be replenished. The need for fertilizer will depend on the initial nutrient availability of the soil and the quantity of dry biomass being removed. The quantity of nutrients absorbed by the plants is correlated with the species or clone, growth rates, and tree/shoot age at harvest. On land previously used for agricultural crops, fertilization does not usually significantly increase biomass production in the initial years of the first rotation. Only plantations established on infertile sites (e.g. containing soils characterized by a sandy texture, highly acidic pH or highly alkaline pH) may require the addition of fertilizer (Frison and Facciotto, 1992). Nutrition is linked to water availability during the growing season; nitrogen (N) fertilization may make poplars more susceptible to cavitation on dry sites, but phosphorus (P) fertilization may reduce this effect (Harvey and van den Driessche, 1997). Poplar and plane trees (*Platanus* L.) receiving irrigation with fertilization treatments showed greater above- and belowground biomass than those receiving only irrigation or only fertilization treatments (Coyle and Coleman, 2005).

Based on tests carried out in Italy, the quantities of nutrients necessary to avoid fertility decrease are 350–600 kg/ha of molecular nitrogen (N_2), 150–200 kg/ha of phophorus pentoxide (P_2O_5), and 350–420 kg/ha of potassium oxide (K_2O), depending on the densities and rotation period adopted. The addition of P and potassium (K) is usually done during soil preparation. Nitrogen can be spread every 2 years in coppices with biennial rotation, in the year after the harvest or at the beginning of the second growing season of each rotation to avoid weed fertilization. In SRC with 5-to-7-year rotations, fertilizers can be spread in the spring of the first 3 or 4 years after establishment. For biological and environmental reasons in particular, N fertilizer should be divided into two or more applications in the spring through early summer. High soil nutrient content can result in luxury consumption and consequently high nutrient concentrations in plant tissues. Enhanced nutrient content in plant tissues may then contribute to increased wood ash content and NOx emissions during combustion in power plants (Ericsson, 1994). Instead of following a single fertilization plan for the entire stand, accurate spatial data (e.g. GPS data) on tree growth or foliar nutrient concentration values (precision forestry) allow plantation managers to vary nutrient inputs according to site-specific needs (Fernandez-Moya *et al*., 2014).

Recently, the use of substances referred to as "biostimulants" has been proposed as an alternative and sustainable solution for increasing productivity and reducing the application of conventional fertilizers (Le Mire *et al*., 2016; De Pascale, Rouphael and Colla, 2018). Ozyhar, Mughini and Marchi (2020) found that a biostimulant treatment applied to containerized *Eucalyptus globulus* Labill. resulted in increased survival by reducing transplanting stress and increased growth after transplanting to the field.

Pruning

The objective of pruning is to produce clear, knot-free wood. It is essential if high-value logs are desired. In poplar stands with 10-year rotations where the goal is production of veneer logs, pruning should begin during the first growing season and be repeated every year until the fifth year. Double apices should be removed in the first year but, thereafter, pruning should target only lateral branches. Branches must be removed before they exceed a diameter of 6 cm and where the bole diameter reaches about 10–12 cm. Pruning must be carried out to a height of 5–7 m; the effort required to go higher is not economically viable (Facciotto, 1999). The lower 3.2 m of the bole will produce veneer of high quality, while the remaining logs are of a lower quality. The logs up to 7 m are used for other solid wood products, such as packaging, pulp and paper.

Fast-growing conifers

Pine plantations are the principal softwood resource for industry in mountainous regions or temperate climates of the southern hemisphere, and in southern parts of North America and Europe. Commonly, pines are grown in pure stands that reach commercial size within 30 years. The southern United States of America, the Iberian Peninsula, the Caribbean, Chile, New Zealand and Australia are the most important plantation regions for fast-growing exotic pine species, as a result of the restructuring and globalization of the forest industry (Marchak, 1995). Plantations in southern Europe benefit from mild Mediterranean climatic conditions and are established in areas with little forest cover and minor interest in grazing or other agricultural uses. Intensive interventions using mechanical equipment for site preparation do not spare native vegetation present at the time of planting, and sometimes attract criticisms about their sustainability. *Pinus radiata* D. Don plantations in Sardinia, Italy, are established with spacings of 2 m × 2 m or 2 m × 3 m, which change to 5 m × 5 m or 6 m ×5 m after systematic thinnings. These pine plantations are fire sensitive, and clear-felling management systems may exacerbate negative effects on soil erosion and native biodiversity conservation. Even for the exotic *P. radiata*, foresters today are faced with the need to ensure wider benefits from plantations while minimizing negative effects in order to balance social, cultural, environmental and economic values (Mead, 2013). Continuous forest cover management systems may represent a more sustainable way of achieving multiple benefits from plantations of exotic conifer species (Mason, 2015; Pignatti *et al*., 2020).

Other tree species of tropical and subtropical environments

In warm climates, hardwoods other than eucalypts, such as acacias (e.g. *Acacia auriculiformis* A.Cunn. ex Benth., *A. mangium* Willdenow, *A. mearnsii* De Wild., *A. saligna* (Labill.) H. L. Wendl.), teaks (*Tectona* L. f) and casuarinas (*Casuarina* L.), have similar commercial attractivity. From an ecological point of view, they may represent a sustainable way of restoring land degraded by logging and clearing of the original native forests. Modern techniques of forest and landscape restoration increase profitability and ecosystem services (e.g. carbon sequestration and water resource management) in these plantations (Marshall *et al*., 2020), whereas economic factors and new challenges (e.g. ecological issues, land availability and mechanization) affect plantation establishment and management (Krishnapillay, 2002).

Conclusion

The cultivation of FGTs, especially poplars, willows and eucalypts, began in the last century to meet the high demand for timber for industrial uses (furniture and paper), and has evolved over the years to adapt to new demand for energy uses and phytoremediation. Today, out-of-forest plantations with different species are being established all over the world to reduce the use of wood from natural forests and contribute to climate-change mitigation. To achieve the latter objective, cultivation techniques must be increasingly environmentally friendly. Thus, fertilization should involve the use of natural fertilizers (e.g. residual digestate of biogas production) or alternative methods based on biostimulants or endophytic diazotrophic bacteria, for example. Irrigation should be done using low-consumption methods such as drip irrigation or subirrigation while using as much wastewater as possible. Soil preparation should be less impactful, and weed control should be mainly mechanical and limited to the first few years after planting to avoid the reduction of SOC. The use of chemical herbicides should be avoided using new smart operating machines. Some of these techniques have been mentioned, but much work remains to be done in coming years.

Take-home messages

- Cultivation techniques can be more environmentally friendly by increasing SOC conservation and reducing energy consumption and pollution.
- For species with medium to long growing cycles, as with conifers compared to SRF species, sustainable management relates to plantations with multifunctional purposes.
- Precision forestry can be applied for certain techniques (e.g. establishment and fertilization).

Case study 1

USE OF ERECT TREE GENOTYPES IN SHORT-ROTATION COPPICE FOR INCREASING WOODY BIOMASS YIELD

Matthias Fladung

The use of upright-grown (“erect”) tree species in short-rotation coppice is a very simple strategy to increase woody biomass production; if already available, erect genotypes are selected and no breeding efforts are required. Besides physiological advantages (e.g. increased photosynthetic potential), the use of erect trees allows for denser planting and thus a higher number of trees per unit of land area. Elite clones from intensive poplar (*Populus* L.) breeding can also be selected for short-rotation coppice, though the induction of erect phenotypes (e.g. by genome editing with CRISPR/Cas9) will take a few years.

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3 The world of fast-growing trees

3.1 Poplars, willows and other fast-growing trees: a baseline of the species commonly in use

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Summary

The fast-growing trees (FGTs) cultivated in the world belong to genera typical of temperate regions, such as poplars (*Populus* L.), willows (*Salix* L.), plane trees (*Platanus* L.), elms (*Ulmus* L.), paulownias (*Paulownia* Siebold & Zucc.), pines (*Pinus* L.), spruces (*Picea* A. Dietr.), Douglas firs (*Pseudotsuga* Carrière) and larches (*Larix* Mill.), and subtropical and tropical areas, such as acacias (*Acacia* Mill.), casuarinas (*Casuarina* L.) and eucalypts (*Eucalyptus* L'Hér). They are grown to provide wood in a relatively short space of time, and the wood produced can be used for many industrial and local purposes, including woodfuel, sawnwood, veneer and pulp wood. Some eucalypts and pines (e.g. *Pinus radiata* D. Don) are among the most cultivated trees for wood production in the world. As pioneer species able to colonize bare or degraded lands, many FGTs are often used for the provision of ecosystem services, such as restoration of degraded areas, soil consolidation and urban greening, and are therefore established in windbreaks and buffer strips. Fast-growing trees are commonly grown outside their natural ranges, where, due to their adaptability and rapid growth, they can assume invasive behaviours. Thus, FGTs are a resource that must be managed wisely. Fast-growing tree systems must be designed and maintained to be sustainable and to ensure positive environmental and economic performance, both in global terms and for the livelihoods of local communities.

Keywords: Fast-growing tree genera and species; mean annual increment; wood production; ecological services; invasive ability; sustainable systems

Introduction

In the international literature, fast-growing trees (FGTs) are those capable of reaching defined growth levels in a specified time. Some authors have proposed mean annual increment (MAI) as a reference for FGTs, which, by convention, must be at least 10 cubic metres per hectare (m^3/ha) (FAO, 1965; Dwivedi, 1993; Le Quoc Huy, 2004; Badalamenti *et al*., 2020). To express their growth potential, species must be established in suitable environmental conditions, and appropriate planting and tending techniques must be applied. Generally, FGTs are light-demanding pioneer species that can rapidly colonize bare or degraded lands. Today, various FGT species are cultivated on different continents using different cultivation systems to obtain (1) wood products for industrial or local use and (2) non-wood products and ecosystem services, such as soil protection, windbreaks, reclamation of polluted sites, restoration of forest habitats, water conservation and urban greening. As already noted in

Chapter 1, this book is not intended to cover all the species used for these purposes in the world; rather, only the genera and species deemed most common in the various climatic zones found in IPC member countries will be considered here (Table 3).

Fast-growing tree genera and species

Table 3. The fast-growing tree genera and species selected for discussion in Section 3.1

Genus/species	Bioclimatic domain of native range and cultivation area
Broadleaves	
Acacia Mill.	Tropical, subtropical
Alnus Mill.	Temperate, subtropical
Casuarina L.	Tropical
Eucalyptus L'Hér	Tropical, subtropical
Populus L.	Temperate, subtropical
Paulownia Siebold & Zucc.	Temperate, tropical, subtropical
Robinia pseudoacacia L.	Temperate, subtropical
Salix L.	Temperate, subtropical
Ulmus L.	Temperate, subtropical
Conifers	
Pinus radiata D. Don	Temperate, subtropical
Pinus taeda L.	Temperate, subtropical
Picea sitchensis (Bongard) Carrière	Temperate
Pseudotsuga menziesii (Mirb.) Franco	Temperate, subtropical
Larix ×eurolepis Henry	Temperate

Note: Bioclimatic domains are provided sensu **FAO**. 2012. *Global ecological zones for FAO forest reporting: 2010 update*. Forest Resources Assessment Working Paper 179. Rome. https://openknowledge.fao.org/handle/20.500.14283/ap861e

Poplars (*Populus* L.) and willows (*Salix* L.), which have quite similar ecophysiological needs, are suitable for lowland, hilly and valley areas. They require adequate water availability; the production of poplars and willows is maximized with an annual precipitation of 700–800 millimetres (mm) (Bergante, Facciotto and Minotta, 2010). In Europe, numerous poplar clones are selected to produce biomass and for use as parent trees in both intra- and intersectional hybridization. Among the species used, *Populus alba* L., *P. nigra* L. and *P. tremula* L. are native to Europe, while *P. deltoides* Bartr. ex Marsh., *P. tremuloides* Michx. and *P. trichocarpa* Torr. & Gray ex Hook. are native to North America and *P. maximowiczii* A. Henry is native to Asia. In addition, hybrids are also used: *P.* ×canadensis Moench (intrasectional hybrid *P. deltoides* × *P. nigra*); *P. ×wettsteinii* Hämet-Ahti (intrasectional hybrid *P. tremula* × *P. tremuloides*); and *P. ×generosa* A. Henry (intersectional hybrid *P. deltoides* × *P. trichocarpa*). While poplars of the section *Populus* can grow well on sites low in nutrients in central and northern Europe, poplars of the sections *Aigeiros* and *Tacamahaca* and their intersectional hybrids require better nutrient supplies. Test criteria in poplar breeding include growth performance (especially in youth), suitability for a wide amplitude of sites, resistance to diseases and frost, straight and cylindrical trunks, and wood quality. There are additional breeding goals within short-rotation management: juvenile growth, regenerative capacity (the ability to resprout from suckers and rootstock), density tolerance, long-living rootstocks and resistance to leaf diseases.

Willows, with about 300 species spread throughout the globe, are extremely versatile and are also suitable for cultivation in a short-rotation model for energy use. Though they are more water demanding than poplars, they are tolerant of high densities and repeated coppicing. In northern Europe, *Salix viminalis* L. clones and hybrids are well established. In southern Europe, particularly Italy, *S. alba* L. and *S. caprea* L. clones and hybrids obtained from open pollination of *S. babylonica* L. (formerly *S. matsudana* Koidz) are used and have high production. In Argentina, hybrids obtained from controlled crossings of *S. matsudana* × *S. alba* and from open pollination of *S. matsudana*, *S. alba* and *S. nigra* are used in forest plantations for wood production (Cerrillo *et al*., 2021), while *S. viminalis* clones are used for basket-making (Cerrillo *et al*., 2019). More recently, willows are being applied for phytoremediation and environmental uses in Argentina, particularly in northern Patagonia (Romagnoli *et al*., 2021).

Eucalypts (*Eucalyptus* L'Hér), native to Oceania and now a widespread industrial crop all over the world, have rather high thermal needs and therefore can only be cultivated in the hottest areas of southern Europe and in Mediterranean countries. Promising results are obtained with the species *Eucalyptus globulus* ssp. *bicostata* (Maiden, Blakely & Simmonds) J.B. Kirkp. and *E. camaldulensis* Dehnh. The *E. camaldulensis* provenance, 'Lake Albacutya', in particular, can thrive in areas with low rainfall and saline soils (Mughini, Gras and Facciotto, 2007). In more demanding conditions, eucalypt production is quite scarce.

About 15 eucalypt clones have been selected in Italy by the Council for Agricultural Research and Economics (CREA), containing crosses between *E. camaldulensis* and *E. globulus* Labill. ssp. *globulus*, *E. globulus* ssp. *bicostata*, *E. viminalis* Labill. and *E. grandis* W. Hill ex Maiden (Mughini, Gras and Salvati, 2014). These clones have better performance than pure parental species and also show promise for the phytoextraction of heavy metals, but they are not yet available on the market (Mughini, Gras and Facciotto, 2007).

Only *E. occidentalis* Endl. and *E. gomphocephala* DC. have been resistant to galligenic insects that have recently spread throughout the Mediterranean basin. Both species have thermal needs higher than *E. camaldulensis*. Between 2007 and 2008, *E. gomphocephala* was established in short-rotation forestry (SRF) plantations in Sardinia since its growth was higher than that of the *E. camaldulensis* trees attacked by pests.

Robinia pseudoacacia L., native to North America and now naturalized in Europe, is a self-sufficient legume for nitrogen thanks to its symbiosis with *Rhizobium* Frank. More tolerant than poplars and willows, *R. pseudoacacia* can be grown in non-irrigated, permeable soils with a pH of around 6, and on plains and in hilly and mountainous areas up to 1 000 metres (m) above sea level (in the southern Alps) and higher (the Apennines). At present, Hungarian sources of *R. pseudoacacia* are used for European plantations as there is a long tradition of its cultivation in Hungary. However, genotype selection is underway in other countries. *R. pseudoacacia* does not tolerate stagnant water or poor soil oxygenation, nor does it adapt to environmental conditions characterized by long dry periods in summer (e.g. Mediterranean countries). However, *R. pseudoacacia* tolerates different slopes and exposures, as well as very coarse soils rich in rock fragments.

Locusts *(Robinia* L.) belong to the *Leguminosae* family and therefore are nitrogen-fixing and soil-enhancing trees. The overall energy balance of locust cultivation is better than that of other more demanding species as little or no fertilization is required. Locusts can be grown in SRF, with a harvest cycle of 2 to 4 years, but require lower densities than poplars or willows. In addition, locusts are melliferous so, if grown with harvesting intervals that allow flowering (i.e. 5 to 7 years), they can make an important contribution to honey production and the development of pollinators.

Paulownias (*Paulownia* Siebold & Zucc.), native to Asia, need coarse-textured soil and sufficient water availability during the growing season. Further, paulownias can be grown in soils with groundwater accessible at the roots or in lowland areas close to foothills that are rich in water and have an annual rainfall of around 1 000 mm. Winter frost limits cultivation options as paulownias cannot stand in compact soils or flooded areas. In Italy, *Paulownia tomentosa* (Thunb.) Siebold & Zucc. is grown with good results. The most cultivated in the world is the hybrid CV 'Octagenia' of the species *P. fortunei* (Seemann) Hemsley, which is more demanding from a thermal point of view than others. In Australia and China, clone varieties with higher production performances are available (Chinese Academy of Forestry, 1986).

Alders, particularly *Alnus glutinosa* (L.) Gaertn. and *A. cordata* (Loisel.) Duby, can be considered FGTs. They need a lot of water, but *A. cordata* tolerates dry periods better than *A. glutinosa*. Both can withstand periods of flooding or water stagnation and have slower growth rates than the previous species described but are self-sufficient for nitrogen due to symbiosis with nitrogen-fixing bacteria. These species can be grown at moderate densities of up to 2 000 trees/ha and can then be coppiced.

Among the elms, *Ulmus pumila* L., native to the Far East, is resistant to Dutch elm disease and is not too water demanding, which means that it can also be used in Mediterranean environments (Fernández, 2009). *U. pumila* can give good production in fertile lowland soils, especially after coppicing. There are also two hybrid elm clones resistant to Dutch elm disease derived from crossings of the Dutch cultivar 'Plantyn' with *U. pumila*: 'S. Zanobi' and 'Plinio', which were selected by the Institute for Sustainable Plant Protection (IPSP) of the National Research Council of Italy (CNR) and patented in 1997. These clones may be used mainly in the formation of coppice rows or in medium-rotation plantations.

Regarding plane trees (*Platanus* L.), *Platanus ×hispanica* Mill. ex Münchh. (formerly *P. ×acerifolia* [Aiton] Willd.) and *P. occidentalis* L. have traditionally been coppiced in rows along waterways for woodfuel production. These species can also be grown at moderate densities and with a harvesting cycle of 5 to 6 years.

The *Acacia* genus includes numerous shrub or tree species native to the African continent and Australasia. Acacias (*Acacia* Mill.) are found in diversified habitats, including alpine settings, rainforests, woodlands, grasslands, coastal dunes and deserts. *Acacia saligna* (Labill.) H. L. Wendl. is a shrub or small tree native to Australia that is proving to be the most tolerant species in terms of soil type and water stress resistance (it can tolerate annual precipitations as low as 250 mm). On the other hand, *A. saligna* is very demanding from a thermal point of view; it does not withstand minimum winter temperatures below 4.5 °C. *A. saligna* is highly suitable for coastal areas in Mediterranean countries that are well exposed, sheltered from cold winds and up to 200–300 m above sea level. In some parts of the world, particularly South Africa, *A. saligna* is considered an invasive species. To avoid problems, this species must be cultivated away from protected environmental sites.

Acacia melanoxylon R. Br., a species native to southeastern Australia, can have a shrub or tree habit with heights of up to 45 m. This acacia can be grown in warm temperate or subtropical areas. In tropical climates, it can also be introduced at relatively high altitudes. *A. melanoxylon* can produce good quality wood, considered to be one of the most valuable among Australian timbers (Fern, n.d.). In the juvenile phase, it shows rapid growth with annual increases of 1.5–2 m in height and 1.5–1.9 centimetres (cm) in stem diameter. This acacia is also used for soil consolidation and the creation of windbreaks. However, *A. melanoxylon* shows great invasive ability in many countries where it was introduced, and specific interventions are required to prevent its expansion (Arán *et al*., 2017).

Acacia mangium Willd. is a large tree that can reach a height of 30 m. It is native to northeastern Queensland in Australia, the western province of Papua New Guinea, Papua and the East Moluccas. *A. mangium* was introduced for wood production in several Asian countries, and large plantations were established in Indonesia and Malaysia to produce paper pulp (Logan, 1987). Commercial plantations of *A. mangium* have also been established in other Asian countries such as China, the Philippines, Thailand and Viet Nam (Awang and Taylor, 1993). This species also has potential for cultivation in some African countries and in Central and South America, though it can be invasive outside its native range. *A. mangium* prefers acidic soils but tolerates heavy and infertile soils. In South and Southeast Asia, it can reach an MAI of 20–25 m^3/ha, with peaks of up to 40 m^3/ha (Del Lungo, Ball and Carle, 2006). The wood of *A. mangium* can have different uses in the paper industry, for construction, and as fuelwood and charcoal. *A. mangium* can provide forage for animals and is used in agroforestry systems for soil improvement and the reclamation of degraded land.

Vachellia nilotica (L.) Hurter & Mabb. (formerly *Acacia nilotica* [L.] Willd. ex Delile) is widespread in Africa, the Arabian Peninsula and the Indian subcontinent. *V. nilotica* can appear as a shrub with a wide crown or as a tree capable of reaching 15–20 m in height, depending on the subspecies. *V. nilotica* grows spontaneously in many African countries (Algeria, Angola, Botswana, Egypt, Ethiopia, the Gambia, Ghana, Guinea-Bissau, Kenya, Libya, Malawi, Mali, Mozambique, the Niger, Nigeria, Senegal, Somalia, South Africa, Sudan, Togo, Uganda, United Republic of Tanzania, Zambia and Zimbabwe), the Arabian Peninsula (Oman, Saudi Arabia and Yemen) and the Indian subcontinent (India, Nepal, Pakistan, Myanmar and Sri Lanka). *V. nilotica* has been introduced to many other countries, including Australia, where it is considered an invasive species (Carter, 1994), Cabo Verde, Indonesia, Iraq, Iran (Islamic Republic of), Israel, Syrian Arab Republic, United Republic of Tanzania and Viet Nam. A gum (Indian gum Arabic) extracted from its bark is used as a traditional medicine to treat dysentery among various African and Asian populations, as well as injured skin, sores and ulcers. Pods and leaves can be used as feed for cattle and poultry. The wood of *V. nilotica* is very strong and durable and is used for house construction, tools and fuel (Troup and Joshi, 1983). In North Africa, this species can reach an MAI of 15–20 m^3/ha in fertile soils with good water availability (Del Lungo, Ball and Carle, 2006). *V. nilotica* is capable of colonizing alkaline soils and has been used extensively in agroforestry systems in India for the recovery of degraded areas due to its nitrogen-fixing capacity.

The *Casuarina* genus includes evergreen shrub or tree species native to Australia, the Indian subcontinent, Southeast Asia, the islands of the western Pacific Ocean and East Africa. One of the most cultivated species for wood production is *Casuarina equisetifolia* L., a species with a tree habit that can reach a height of 35 m, with stem diameters of up to 100 cm. *C. equisetifolia* is widely cultivated in tropical areas for wood production and as a windbreak for soil protection in coastal areas. Typically found among coastal dunes (rarely in internal, hilly areas), *C. equisetifolia* is a sun-demanding, nitrogen-fixing species that requires well-drained, sandy soils. Further, *C. equisetifolia* is resistant to marine aerosols and occasional submersion with seawater. However, it can be invasive, especially in the environments where it has been introduced. In favourable environments, it can reach an average annual productivity of 15 m^3/ha in 10 years. The most used rotations are 4 to 5 years for energy wood and 10 to 15 years for the production of poles. *Casuarina* wood has a high calorific value and can provide quality charcoal (Kondas, 1983). *C. equisetifolia* is one of the few, if not the only, tree species capable of growing over a cover of herbaceous halophytes and is therefore used for soil rehabilitation (Thaiutsa, 1990).

Pinus taeda L. is a conifer species native to the southeastern United States of America, where it is the main tree species used for timber and pulpwood production (Langdon, 1979). Because of its rapid growth, *P. taeda* is also established for soil stabilization in the United States of America (Burns and Honkala, 1990). Often, this pine is grown in plantations subject to natural or artificial regeneration. Natural regeneration of even-aged stands can be achieved using different silvicultural systems such as seed-tree, shelterwood or clearcut systems (Langdon, 1979). *P. taeda* is an FGT that can annually produce 10–15 m^3/ha of merchantable timber with a 36-year cutting cycle. It grows well on moderately acidic soils, even with imperfect drainage and fine texture.

Pinus radiata D. Don is a conifer with a natural range limited to three sites on the Californian coast in the United States of America and two sites located on two Mexican islands (Millar, 1986). *P. radiata* finds favourable conditions under oceanic climates where the humidity remains high throughout the year, the winter is mild and the summer is not too hot. The most suitable soils are deep sandy loams with acidic or subacidic pH (McDonald and Laacke, 1990). *P radiata* is one of the species most cultivated for wood production outside its native range. Worldwide, the total area of *P. radiata* plantations is estimated to be more than 4 million ha (Mead, 2013). It is widespread in Australia, Chile, New Zealand, South Africa and Spain. In these countries, *P. radiata* wood is used for various purposes, including construction, panels, furniture, poles and pulp. Cultivation generally takes place in even-aged plantations subject to artificial regeneration and, more rarely, to natural regeneration. Generally, *P. radiata* is cultivated in pure stands, but in Spain there are also sites where it grows mixed with other pines as well as broadleaved species (Mead, 2013). *P. radiata* is a typical fast-growing species; in New Zealand, in plantations older than 25 years, MAIs of 25–30 m^3/ha are common, with peaks of up to 50 m^3/ha.

Picea sitchensis (Bong.) Carrière is a conifer native to a narrow strip of land from Alaska to northern California in northwestern North America (Taylor, 1990). It is one of the largest species of the *Picea* A. Dietr. genus and can reach heights of 100 m in its indigenous areas. *P. sitchensis* can produce good-quality wood and exhibits rapid growth at a young age. These characteristics have led to the introduction and cultivation of *P. sitchensis* in northern

European countries in coastal environments similar to those of its natural range. Young plants can show height increments of 1.0–1.5 m/year outside their natural range, if planted in suitable site conditions. Today in Ireland and the United Kingdom of Great Britain and Northern Ireland, planted *P. sitchensis* stands represent 52 percent and 25 percent of national forest area, respectively. To a lesser extent, *P. sitchensis* is also grown in Denmark and France. Even-aged *P. sitchensis* plantations are traditionally subject to artificial regeneration, but several studies on natural regeneration of these stands are underway (Bianchi, Hale and Gibbons, 2019). The wood of *P. sitchensis* has an excellent strength/weight ratio and is suitable for various uses (e.g. paper, poles and construction). Furthermore, its good sound transmission properties mean that is suitable for musical instruments.

Pseudotsuga menziesii (Mirb.) Franco is a conifer native to the western part of North America, from British Columbia to central California, along the Rocky Mountains. This species can reach large dimensions of up to 60–80 m in height and 2 m in stem diameter. In its natural range, *P. menziesii* grows under different climatic conditions, from a maritime climate in the Pacific Northwest to a continental climate in the central Rocky Mountains and at altitudes ranging from 0 to 3 200 m above sea level. It prefers well-aerated, well-drained, deep soils with a pH of 5–6. *P. menziesii* was introduced in Europe in the nineteenth century, where it is now frequently cultivated, especially in even-aged stands subject to artificial or natural regeneration (Spiecker, Lindner and Schuler, 2019). The European countries where *P. menziesii* is most common are France, Germany and the United Kingdom of Great Britain and Northern Ireland. Today, it is the most cultivated exotic conifer in Central Europe. *P. menziesii* has also been introduced in non-European countries such as South Africa, some South American countries, New Zealand and Australia, though it is reported as an invasive species in Argentina, Chile and New Zealand (Da Ronch, Caudullo and de Rigo, 2016). *P. menziesii* is a fast-growing species; in Italy, annual production of 10–20 m^3/ha was observed in plantations aged 20 to 50 years. The wood is of excellent quality (moderately heavy, but very durable), has excellent mechanical properties and is highly suitable for structural uses. It can also be used for veneer and by the pulpwood industry. Further, since *P. menziesii* is less drought-sensitive than *P. abies* (L.) H. Karst, it could be a valid alternative in Central Europe on plantations at lower altitudes or in response to climate change (Hanewinkel *et al*., 2013).

Larix ×eurolepis (*L. decidua* Mill. × *L. kaempferi* [Lamb.] Carrière) combines good growth of *L. decidua* and the canker resistance of *L. kaempferi*. L. ×*eurolepis* and shows better growth performance than the parent species in a wider range of locations. Although hybrid larches (*Larix* Mill.) have been commercially available for a long time, their cultivation potential is far from being exhausted. Currently, cultivation is limited to Atlantic, Central and northwestern Europe. In Central Europe, hybrid larches have room to grow in importance as they can supply softwood for construction in a short time. Larches are used in many different silvicultural situations, for afforestation and reforestation in pure or mixed stands, especially with *Fagus sylvatica* L. In addition, larches are used as nurse species on windy or frosty sites before the introduction of more delicate species (e.g. *Abies alba* Mill.), as well as for forest enrichment, afforestation of abandoned agricultural land and agroforestry applications (Pâques *et al*., 2013).

Conclusion

Today, multiple FGT species represent a widespread resource throughout the world. Not only can FGTs support the industrial bioeconomy and the livelihoods of local communities, but they also have huge potential for combating climate change and providing other ecosystem services. However, to obtain the greatest economic and environmental benefits, FGTs need to be managed in a prudent and sustainable way, avoiding the replacement of natural forests with FGT plantations and counteracting the invasive capacity of many of these species when introduced outside their natural ranges.

Take-home message

- Due to their rapid growth and high adaptability, FGTs can provide economic and environmental benefits on global and local scales. However, these trees must be managed within the scope of sustainable systems to avoid ecological damage.

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3.2 Vulnerability and resilience

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Summary

Several adverse factors, whether abiotic, biotic or anthropogenic, have increased the vulnerability of wood plantations over the last few decades. After a short description of the different types of damage to fast-growing trees (FGTs) by various pathogens or pests, the main present threats are outlined, with particular reference to introduced exotic parasites and the increasing risk that they pose with the effects of climate change. Methods adopted to increase the resilience of cultivated trees to adversities, and approaches for preventive protection, are also discussed.

Keywords: Introduced exotic pests; tree emerging parasites; plant protection; integrated pest management

Introduction

At the dawn of the new millennium, unprecedented challenges to tree cultivation and management came to the attention of cultivators, plant pathologists and lawmakers. The first challenge was brought about by an increase in trade in an increasingly interconnected world. From 1979 to 2019, the trade of forest products more than tripled, according to an estimation carried out in 2021 using FAOSTAT data. Such an increase in wood imports and exports, sometimes poorly stored and monitored, was likely associated with an increased probability of accidentally introducing allogeneic pathogens and exotic pests.

Another challenge was posed by international and national legislation, with two contradictory standpoints. On the one hand, inadequate quarantine legislation often led to delays compared to what could be achieved with advanced methods and tools for preventing the introduction of allogeneic pests. On the other hand, increasingly stringent phytosanitary legislation on chemical pesticides came into force. More and more active ingredients were prohibited or passed into conditional use in an effort to enhance integrated pest management.

A third challenge is now posed by climate change, the effects of which have become significantly more apparent since the 1990s. Climate change causes direct abiotic stress and exacerbates the impact of introduced pathogens and pests, thereby affecting tree plantations.

All these factors, in which anthropogenic contributions are evident, have coalesced to increase the vulnerability of wood arboriculture to diseases and infestations, emphasizing the need to exploit existing mechanisms of resilience among such simplified ecosystems. The vulnerability and resilience of fast-growing trees (FGTs) are summarized below, with examples and case studies.

Factors of vulnerability: biotic, abiotic and anthropogenic

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Fast-growing trees represent an important economic sector for many countries. One of the main objectives of FGT plantations is the production of high-quality wood. Carbon sequestration, bioenergy production and environmental improvement are other benefits of these plantations. Most FGT plantations are composed of trees of the same age and species and can even be monoclonal, which makes them more prone to abiotic, biotic and anthropogenic disturbances. These disturbances can cause widespread damage to plantations as all the plants are at the same developmental stage at the same moment and moreover are all genetically sensitive to a similar extent.

The productive and ecological features of FGT plantations are often impaired by phytosanitary problems of biotic or abiotic origin that are exacerbated, directly or indirectly, by human action. Interest in this type of arboriculture for economic, sociocultural and environmental reasons has encouraged the adoption of several species, both native and exotic (e.g. paulownias [*Paulownia* Sieb. & Zucc.] in European areas). These species may contribute to the spread of new infesting or parasitic species (pests and diseases, respectively) or worsen the spread of those already present. Inadequate management or adaptation may increase the incidence of weakness parasites. Finally, irresponsible cultivation of allogeneic species can lead to uncontrolled multiplication and consequent competition with native species in forest ecosystems (e.g. locusts [*Robinia* L.] in the past; tree-of-heaven [*Ailanthus* Desf.] more recently).

Some adversities damage production quantitatively by reducing tree growth and development, as is the case with many foliage diseases (e.g. leaf spots, anthracnoses, rusts, downy mildews, scabs and leaf blights) and leaf-infesting pests (e.g. sapsuckers, miners and phyllophagous pests). This damage can occur through shoot destruction (shoot-blight disease), compromised leaf function or reduced leaf area from pathogenic defoliation. Other adversities may prove ruinous for the entire plantation, such as fatal winter chill, root rot pathogens (*Phytophthora* de Bary, *Dematophora* R. Hartig, *Heterobasidion* Bref., etc.), wilting agents (e.g. *Verticillium* Nees and *Bursaphelencus* Fuchs) and bark xylophagous insects (e.g. *Ips* De Geer, *Tomicus* Latreille).

Other adversities induce qualitative damage by affecting wood appearance, integrity or structural properties, such as many bark canker agents (e.g. *Sphaerulina musiva* [Peck] Quaedvl., Verkley & Crous, *Entoleuca mammata* [Wahlenb.] J.D. Rogers & Y.M. Ju, *Cryptodiaporthe populea* [Sacc.] Butin, *Xanthomonas populi* pv. *populi* [Ridé] Ridé & Ridé and *Fusarium* Link spp. on poplar; *Xylodon flaviporus* [Berk. & M.A. Curtis ex Cooke] Riebesehl & Langer on willow; canker bacteria on walnut [*Juglans* L.] and ash [*Fraxinus* L.]; *Cronartium* Fr. spp. on pine [*Pinus* L.]; *Lachnellula willkommii* [R. Hartig] Dennis on larch [*Larix* Mill.], etc.) and xylophagous insects (e.g. *Phoracantha* Newman spp. on eucalypt [*Eucalyptus* L'Hér.]; *Saperda* Fabr. spp. on poplar; *Cossus cossus* [L.] and *Megaplatypus mutatus* [Chapuis] on broadleaves; *Cryphalus* Erichson spp. and *Trypodendron* Stephens spp. on conifers).

Indigenous parasites have evolved in antagonistic symbioses with their hosts, displaying a mild harmfulness, except when the environment is particularly favourable. By contrast, the damage induced by exotic parasites is much more severe since these did not co-evolve with their hosts. Consequently, hosts are exposed without proper defences or, in the case of exotic pests, cannot take advantage of the presence of parasitoids. Some pathogens may even increase their virulence as a result of hybridization between exotic and indigenous species (such as *Phytophthora alni* Brasier & S.A. Kirk).

Climate change is altering the dynamics of pests and pathogens, which poses a significant threat to the health of fast-growing plantations (Linnakoski *et al*., 2019). In addition, growing trade in propagation material because of globalization has frequently led to the introduction of new parasites or pests, including insects, nematodes, fungi, bacteria, viruses and phytoplasmas (Franić *et al*., 2019; Potter and Urquhart, 2017; Wingfield *et al*., 2013). Such parasites are easily transferred alive from continent to continent and have favoured the resurgence of indigenous parasites on new imported hosts. Recent changes in climatic conditions, including more frequent extreme weather events and modified temperature regimes, have promoted the acclimatization of allogeneic parasites and pests that were previously restrained by adverse environmental factors. The adaptation and incidence of such organisms vary significantly from one geographic area to another. Temperate regions are among the regions most at risk since they can be suitable for adaptation of subtropical species (Gullino *et al*., 2022). Heavy epidemics have impacted all continents. European countries have been greatly impacted by allogeneic parasites or pests because of the concentration of organisms originating from North American, South American and Asian countries.

Focusing on central and southern European countries, in comparison with the few exotic parasites or pests that arrived before the 1990s (e.g. *Marssonina brunnea* [Ellis & Everh] Magnus and *Melampsora medusae* Thüm. on poplar; *Sirococcus strobilinus* Preuss and *Matsucoccus feytaudi* Ducasse on pines), several alarming allogeneic agents have spread in the last three decades. Among pests, the gall-inducing eulophid *Ophelimus eucalypti* Gahan and the polyphagous Asian beetles *Anoplophora chinensis* Förster and *Anoplophora glabripennis* Motschulsky are particularly harmful to broadleaved trees in general. Other pests target specific tree species or genera, such as the brown marmorated stink bug *Halyomorpha halys* Stål and the ambrosia beetle *Megaplatypus mutatus* (especially harmful to poplars) (Tremblay *et al*., 2000), the pine tortoise scale *Toumeyella parvicornis* Cockerell and the western conifer seed bug *Leptoglossus occidentalis* Heidemann (affecting pines), and the black twig borer *Xylosandrus compactus* Eichhoff (affecting *Tilia* L.). Pathogens worth mentioning include *Hymenoscyphus fraxineus* (T. Kowalski) Baral, Queloz & Hosoya (particularly harmful to some species of ash), *Diplodia scrobiculata* J. de Wet, Slippers & M.J. Wingf. (on *Pinus radiata* D. Don) and *Phytophthora cinnamomi* Rands (on various tree species). Some pathogens, which have not significantly spread in Europe at present, must be kept under observation since they could become dangerous due to climate change (e.g. *Phytophthora ramorum* Werres, De Cock & Man in 't Veld. on oaks [*Quercus* L.]; *Heterobasidion irregulare* Garbel. & Otrosina and the nematode *Bursaphelenchus xylophilus* [Steiner & Buhrer] Nickle on pines). Over time, dozens of harmful parasites have been targeted by European quarantine measures, and many others could become a threat to trees with poor health.

South America has also experienced the spread of pests in FGT plantations. For example, in Argentina, where about 100 000 ha of poplar and willow plantations are cultivated (mainly in the Paranà Delta for pulp and particle board production), *Sphaerulina musiva*, a fungal pathogen, is present on poplars. *S. musiva* is an agent of leaf spot and shoot canker that was accidentally imported during the 1940s from the United States of America. On *Populus deltoides* Bartr. ex Marsh. trees native to North America, *S. musiva* only induces mild leaf spots, but, in Argentina, its contact with new hosts that have not co-evolved with it has caused severe outbreaks of the canker form among many locally cultivated clones. The disease has marked genetic control, and an intense poplar breeding programme has thus been carried out to mitigate its incidence (see Case study 2). Regarding introduced allogeneic pests in Argentinian willow plantations, the sawfly *Nematus oligospilus* Förster has had a heavy impact. *N. oligospilus* is a Holarctic species native to Europe and Asia that was first reported in South America in the 1980s. Its larvae feed on willow leaves, causing dieback that can be serious.

Another example of disease outbreaks due to the spread of a pathogen outside its original range is given by thousand cankers disease. Thousand cankers disease is induced by *Geosmithia morbida* M. Kolařík, Freeland, C. Utley & Tisserat and is actively dispersed by the scolytid *Pityophthorus juglandis* Blackman. The disease is native to the southwestern United States of America, where it survives on its tolerant host, *Juglans major* (Torr.) A. Heller. In the mid-1990s, thousand cankers disease spread onto *J. nigra* L. in the western United States of America, and subsequently to the native range of *J. nigra* (Tennessee, Virginia, Pennsylvania), causing heavy damage. Thousand cankers disease was reported in northern Italy in 2013, again on planted *J. nigra* and also on *J. regia* L.

In the context of climate change, milder winters associated with higher average temperatures in some geographic regions have not only promoted the acclimatization of allogeneic parasites and pests but have also encouraged the spread or resurgence of indigenous parasites with high potential for colonization. Such parasites, particularly *Phytopthora*, are becoming true phytosanitary emergencies in many countries; though practically negligible in Europe until the 1980s, the incidence of *Phytopthora* on *Acer* L., *Alnus* Mill., *Juglans*, *Pinus* and *Quercus* genera has increased greatly (Scanu *et al*., 2014).

Furthermore, the frequent and prolonged drought periods associated with climate change, together with higher temperatures, have often triggered high levels of stress in trees. Stressed trees are predisposed to colonization by parasites or pests, which then induce diffuse decline or die-off. Among such pests are several bark insects (*Ips typographus* L. on spruces [*Picea* Mill.]; *Tomicus piniperda* L. on pines; *Agrilus* Curtis spp. and *Melanophila* Eschscholtz spp. on poplars, willows and maples; *Phoracantha* Newman spp. on eucalypts), and polyphagous root rot and bark necrosis agents (e.g. *Botryosphaeria* Ces. & De Not. spp., *Cytospora* Ehrenb. spp., *Phomopsis* Sacc. & Roum. spp. on broadleaf trees; *Lachnellula* P. Karst. spp., *Sphaeropsis* Sacc. spp., *Nectria* (Fr.] Fr. spp. on conifers). Bark parasites are often already present asymptomatically in tissues of healthy trees but may be triggered as pathogens from latent conditions by modified stress metabolic parameters (Desprez-Loustau *et al*., 2006).

Anthropogenic factors play a central role in plantation health, largely through plantation management and site selection but also through the local and regional transport of parasites. Abiotic agents of damage, however, may also be enhanced by human activities. For example, iron chlorosis is associated with planting on calcareous soils (Anderson and Ladiges, 1978), and damage by winter frost observed on pines and especially on eucalypts (e.g. *Eucalyptus grandis* W. Hill, *E. globulus* Labill. and *E. camaldulensis* Dehnh.) occurs in plantations outside of the species' natural ranges.. Apart from inappropriate species or genotype selection, the most frequent negative human influence on plantation health derives from poor management practices, either during planting (e.g. parasite-infected propagation material, poor material quality, excessively dehydrated material, excessively dense spacing) or during the management phase (e.g. inappropriate or infrequent cultivation practices).

The importance of damage induced by different adversities varies according to plantation objectives. Leaf and root pathogens cause a lot of damage to plantations for phytoremediation or bioenergy. Short-rotation forestry plantations are prone to root rot and stump decay as the trees are susceptible to these diseases because of repeated cuts at their collars (Soularue *et al*., 2017).

Take-home messages

- The introduction of exotic species for FGT plantations in any given area must be carefully analysed, since some of their parasites may be introduced in a new habitat and on the other hand, the new species may be susceptible to local parasites in non-co-evolved conditions; moreover, the imported species could become invasive by escaping from cultivated stands.
- Altered atmospheric parameters in connection with climate change may enhance the pathogenicity of weakness parasites, such as root rot and bark necrosis agents, and increase the aggressiveness of pests able to overcome FGT genetic improvement due to their host non-specificity.

Case study 2

SPREAD OF DISEASES ON SALICACEAE IN ARGENTINA

The only species of Salicaceae native to Argentina is *Salix humboldtiana* Willd. ('sauce criollo'). The cultivated species are exotic poplars (*Populus deltoides* Bartr. ex Marsh., *P.* ×*canadensis* Moench. and *P. nigra* L.) and various willow hybrids.

Table 4. Area cultivated with poplars and willows in different regions of Argentina

Region or province	Willows (ha)	Poplars (ha)	Total (ha)
Deltas of the Paraná and Uruguay rivers (Buenos Aires, Entre Ríos)	68 862	14 508	83 370
Buenos Aires (continent)	-	5 000	5 000
Patagonia (Neuquén, Río Negro, Chubut and Santa Cruz)	-	1 744	1 744
Cuyo (Mendoza, San Juan and San Luis)	-	8 015	8 015
Centro (Santa Fe, Córdoba, La Pampa)	-	1 602	1 602
Noroeste (Jujuy, Salta and Tucumán)	-	114	114
TOTAL	68 862	30 983	99 845

Source: 2017 data from the Directorate of Forestry Production, Ministry of Agroindustry of Argentina.

The main regions where Salicaceae are cultivated in Argentina are the Paraná Delta region and the Cuyo region (Table 4). Each has different features that affect production cycles, planting techniques, harvesting and transport. The Paraná Delta is a large floodplain located in northeastern Buenos Aires and southern Entre Ríos, with an annual rainfall of 1 000 millimetres (mm). Transport to industrialization centres is mainly fluvial, in barges on waterways. In the Cuyo region, poplars are cultivated in a climate with a marked water deficit and loose soil, which means that water must be supplied by irrigation through a channelling system.

In the Delta region, cultivated *Populus* clones are *P. deltoides* ('A106-60', 'A129-60', 'Stoneville 66 Delta Gold' and 'Stoneville 67 Mississippi Slim'). Their good vegetative vigour and marked resistance to rusts (the most widespread disease in the area) mean that they are well suited to the area's ecological conditions. Some clones of hybrid *P.* × *canadensis* are cultivated as well and are resistant to *Septoria* canker by *Sphaerulina musiva* (Peck) Quaedvl., Verkley & Crous. Among willows, the most cultivated clones are *Salix babylonica* L. var. *sacramenta* Hortus (American willow) and the *S. babylonica* × *S. alba* L. hybrids 'A131-25' and 'A131-27'. *S. nigra* Marsh. 'nr. 4', the hybrid S. *matsudana* Koidz. × S. alba L. 'A13-44' and *S. viminalis* L. are cultivated to a lesser extent. The incidence of diseases in *Salix* is much lower, though *Marssonina* anthracnose is observed more frequently in summers with alternating drought and wet periods (Cerrillo, 2006).

The most common disease on poplars in the Paraná Delta region is *Melampsora* rust, so the use of resistant or tolerant clones is very important. Attacks of *Sphaerulina musiva* are not a serious problem in the region since the clones most cultivated belong to *P. deltoides*, a species with low susceptibility. Euro-American hybrids (*P.* ×*canadensis*) are not recommended as they can suffer severe attacks (Cerrillo, 2006). Although they frequently cause symptoms, other diseases reported in this region on Salicaceae do not result in significant economic damage.

In the Cuyo region, poplar is associated with few phytosanitary problems. The most damaging disease is caused by *Septoria* cankers, and where irrigation management is not appropriate, *Phytophthora* root rot is sometimes observed.

Diseases reported on Salicaceae in Argentina are as follows:

- rust induced by various *Melampsora* species: *M. alli-populina* Kleb., *M. larici-populina* Kleb., *M. medusae* Thüm., *M. populnea* (Pers.) P. Karst. on poplars; *M. amygdalinae* Kleb., *M. salicis-albae* Kleb., *M. coleosporioides* Dietel, *M. epitea* Thüm., *M. abietis-caprearum* Tubeuf on willows (Cortizo and Romero, 2000; Cortizo, 2005; Lucero *et al*., 2011b);
- poplar anthracnose, caused by *Elsinoe populi* (Sacc.) X.L. Fan & Crous, observed mainly on *P. nigra* 'Italica';
- *Septoria* stem canker and leaf spots, caused by *Sphaerulina musiva*. In the Paraná Delta region, this canker is almost absent, but symptoms on leaves are present, and the teleomorph has been reported only in southern Argentina. The greatest damage inflicted by this disease occurs in Cuyo. Studies carried out on the susceptibility of various *Populus* clones have stated that 'I-214', 'I-161', 'I-205', 'I-30', 'I-262', 'I-53', 'I-488', 'I-72', 'I-29', 'Longhi', 'Cima', 'Neva' and 'Stoneville 70' are very susceptible, whereas 'Conti 12', 'I-42', 'Triplo', *P. deltoides* 'INTA 71/67', 'Harvard', 'Australia 106/60', 'Catfish 5', 'INTA 369/69', 'INTA 88/69', 'Stoneville 81', *P. alba* '94/70' and *P. ×canescens* (Aiton) Sm. 'Spanish hybrid' show high resistance (Arreghini *et al*., 2001; Lucero *et al*., 2016). The management of this disease is mainly based on preventive measures, such as the use of resistant clones and the acquisition of healthy plants. Nurseries should be located in disease-free areas, and cuttings should be obtained from disease-free mother plants (Lucero *et al*., 2011a);
- phomopsis stem canker caused by *Phomopsis macrospora* Tak. Kobay. & Chiba is reported in the Paraná Delta region, mainly on *P. deltoides* '208-68';
- bark necrosis by *Cytospora chrysosperma* (Pers.) Fr. is reported in all regions where Salicaceae are cultivated, especially under water stress conditions, as in Cuyo and Patagonia;
- *Populus* leaf blister caused by *Taphrina populina* Fr;
- the "brown spots" physiologic disorder first appeared in the Cuyo region in 1996 (Anselmi *et al*., 1996). It is a non-parasitic disease that occurs at low intensity in plantations subjected to stress. It weakens trees but does not usually kill them;
- willow anthracnose induced by *Marssonina kriegeriana* (Bres.) Magnus (holomorph: *Drepanopeziza triandrae* Rimpau) and *M. salicicola* (Bres.) Magnus (holomorph: *D. sphaerioides* [Pers.] Höhn.) and whose sexual stage has not been reported in Argentina. This disease has been observed on *Salix alba* var. *calva* G.F.W. Mey. ('poplar-willow'), *S. babylonica* (weeping willow) and *S. ×argentinensis* Ragonese & Alberti cv. 'ibrido' (hybrid willow). The most susceptible clone is *S. alba* var. *calva*, and its cultivation in the Paraná Delta is decreasing for this reason. *S. nigra* (black willow), the hybrids of *S. babylonica* × *S. alba* 'A131-25' and 'A131-27', *Salix babylonica* var. *sacramenta* (American willow) and the hybrids of *S. matsudana* × *S. alba* are considered resistant; Toscani (1994) and Cerrillo (2006) reported that, although symptoms are common, they are not connected with significant economic losses due to their low incidence and late onset. The attack level is slightly higher and earlier on 'A 131-25' and 'A 131-27';
- willow cercospora caused by *Pseudocercospora salicina* (Ellis & Everh.) Deighton. It was reported on 'poplar-willow', weeping willow, American willow, hybrid willow, 'sauce criollo' (*S. humboldtiana*), twisted willow (*S.* ×erythro-*flexuosa* Ragonese & Alberti), goat willow (*S. caprea* L.), crack willow (*S. fragilis* L.) and basket willow (*S. viminalis* L.);
- stem rot caused by *Xylodon flaviporus* (Berk. & M.A. Curtis ex Cooke) Riebesehl & Langer. It was reported on *S. nigra* (Bakarcic, 1978; Larriera, 1989; Deschamps and Wright, 2000), with significant differential clonal susceptibility, according to Cerrillo (2006);
- cankers by *Neonectria ditissima* (Tul. & C. Tul.) Samuels & Rossman (anamorph: Fusarium mali Allesch.), reported on *S. alba* (Larriera, 1989; Cerrillo, 2006);
- dothichiza stem canker by *Cryptodiaporthe populea* (Sacc.) Butin, reported on *S. nigra* (Larriera, 1989); and
- dematophora root rot by *Dematophora necatrix* R. Hartig and *Phytophthora* root rot (Lucero *et al*., 2011a).

Case study 3

THE DEVELOPMENT AND APPLICATION OF INSECT-RESISTANT *POPULUS NIGRA* CLONES USING BIOTECHNOLOGY IN CHINA

Meng-Zhu Lu

China has some of the most extensive poplar plantations in the world (Fang, 2008; Hu *et al*., 2014). These plantations were established at scale in recent decades to prevent soil erosion and desertification, as well as for timber production. Poplar (*Populus* L.) is well suited to the local environmental conditions where they are established and can effectively meet management objectives. For a variety of reasons, however, these extensive plantations suffer from insect attack, with significant economic and ecological consequences (Wang *et al*., 2018).

A promising solution to this situation is the use of gene-edited poplars. A gene from *Bacillus thuringiensis* Berl. (Bt) is widely used in plant breeding for disease resistance. Using gene modification technology, *Populus nigra* L. was modified to express Bt genes. In a staged approach to deploying the modified *P. nigra*, clones were tested in the lab and then in field trials to select for those clones most resistant to insects while still offering good growth. Finally, biosafety of the modified Bt poplars was tested for traits like gene flow, gene transfer and impact on non-target insects. Based on these tests, the modified clones were approved by the National Forestry and Grasslands Administration of China, and large plantations were established.

The performance of these clones showed marked improvement compared to unmodified poplar. Application of pesticides could be significantly reduced in the modified stands, and insect densities remained at low levels. In addition, Bt clones performed better and grew faster than their conventional counterparts. Moreover, non-transgenic poplars were also afforded protection from defoliation if planted with Bt poplars. At present, about 1 000 ha of this modified poplar is planted out of around 7 million ha of poplar established in monoclonal plantations in China.

In the future, gene-editing technology may also provide a means to breed trees more efficiently; gene-editing can avoid some of the safeguards necessary for genetic modification as it does not necessarily entail inserting foreign DNA into the tree.

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Plant health

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The problems posed by various biotic, abiotic and anthropogenic adversities in FGT plantations are reported above. Careful monitoring and well-designed protection strategies are required to mitigate damage, both in new and existing nurseries and plantations. Preventive management is the most desirable form of protection from diseases and pests. The Committee on the Environment, Public Health and Food Safety of the European Parliament has adopted technical cultivation strategies to avoid or minimize the incidence of adverse events in tree plantations.

The use of material certified as healthy is key in maintaining plants free from parasites. This is particularly important in international exchanges of vegetative material, such as seeds and cuttings, and involves establishing quarantine strategies as a first step to prevent the introduction of undesired parasites (FAO, 2011). One of the most efficient preventive measures for pathogens and pests is exclusion. This is demonstrated by the current lack of damage in Europe from *Sphaerulina musiva* (Peck) Quaedvlieg, Verkley & Crous, despite the cultivation of susceptible poplar (*Populus* L.) clones (specifically, clones belonging to the hybrid *P.* × *canadensis* Moench obtained from crossing *P. deltoides* Bartr. ex Marsh. and *P. nigra* L.) in suitable environments.

To avoid the introduction and spread of potentially dangerous exotic pathogens, 15 European countries have established the European and Mediterranean Plant Protection Organization (EPPO), a regional plant protection organization now counting 52 members from the Euro-Mediterranean region. The EPPO follows the terms of the International Plant Protection Convention (IPPC), hosted by FAO. It sets standards that constitute recommendations that are issued to the national plant protection organizations of EPPO member countries and promotes the exchange of information between its member countries by maintaining information services and databases on plant pests and by organizing many conferences and workshops. At the national level, countries carry out checks at import customs points such as airports, railway stations and road borders. Despite the numerous controls an increasing number of parasites are escaping. Therefore, the IPPC and EPPO are seeking to strengthen customs monitoring through more effective diagnostic systems (Petter, Giovani and Trontin, 2023)

Genetic protection is the most effective preventive defence against pathogens and other adversities. The production and use of plant material resistant to pathogens, certain pests and abiotic factors has already given promising results in poplar, willow (*Salix* L.), walnut (*Juglans* L.) and cherry (*Prunus* L.) species. For the genetic improvement of FGTs, particular effort must be made to:

- highlight the genetic variability for parasite resistance within the natural populations of the host;
- prevent possible occurrence or introduction of biotypes of more virulent pathogens; and
- select resistant or tolerant genotypes for many potential adversities.

In poplar cultivation, genetic improvement has undoubtedly been the most efficient and effective way of reducing the damage caused to wood quality by pests and diseases. This strategy, refined at the beginning of the 1980s, follows a multistage programme based on semi-reciprocal recurrent selection that provides numerous cycles of crossing. Wide genetic variability is maintained, and improved populations of European (*P. nigra*) and American genotypes (*P. deltoides*) are obtained. The genetic improvement of FGTs in general is significantly hampered by their multiannual life cycle, with trees that do not flower for several years, which means that the detection of dendrological characters can take years. Resistance detection is therefore limited by the need to conduct separate inoculation or infection tests on a large number of offspring.

Modern study systems and new biotechnologies are very helpful in the resistance detection of poplars, especially in highlighting the mechanisms underlying resistance, both through early screening and possible genetic transformation. Recently, genetic engineering and other biotechnological approaches have been employed as means for circumventing some of the problems associated with genetic improvement in poplars. Micropropagation, selection of somaclonal and gametoclonal variants, and protoplast fusion all play an important role in these programmes. Increased availability of molecular markers for genetic loci associated with the expression of parasitic resistance would greatly facilitate and accelerate selection protocols. For example, loci of qualitative and quantitative resistance to *Melampsora larici-populina* Kleb. have been mapped, and molecular markers are already available for some of them. Similarly, loci of quantitative traits associated with resistance to poplar woolly aphid (*Phloeomyzus passerinii* [Sign.]) have been identified (Carletti *et al*., 2016) and markers are still under study for improvement programmes.

In addition to Salicaceae genera, several other genera of FGTs would benefit from the use of resistant species, ecotypes or varieties. In the genus *Juglans,* for instance, *J. nigra* L. is more tolerant of abiotic factors such as flooding and drought and biotic agents (e.g. *Ophiognomonia leptostyla* [Fries] Sogonov; *Xanthomonas arboricola* pv. *juglandis* [Pierce] Vauterin, Hoste, Kersters & Swings; and *Phytophthora* de Bary) than *J. regia* L. (Anselmi *et al*., 2005). The natural hybrid between *J. nigra* and *J. regia* shows increased vegetative vigour (heterosis), marked disease resistance, valuable wood quality and greater winter hardiness than *J. regia* (Fady *et al.,* 2003; Fernández-Moya *et al.,* 2019).

In any case, it is possible to reduce the damage from adversities within tree genera by avoiding the use of notoriously susceptible species. For example, *Pinus strobus* L. and *Quercus rubra* L. should not be planted in acidic soils. *Eucalyptus grandis* W. Hill*, E. globulus* Labill., *E. camaldulensis* Dehnh. and Mediterranean pines should be avoided in areas with cold winters. In areas where *Hymenoscyphus fraxineus* (T. Kowalski) Baral, Queloz & Hosoya (also know as *Hymenoscyphus pseudoalbidus* Queloz, Grünig, Berndt, T. Kowalski, T.N. Sieber & Holdenr.) is widespread, it is advisable to avoid implants of *Fraxinus excelsior* L. and *F. angustifolia* Vahl, which are known to be susceptible to the pathogen. In environments associated with oak (*Quercus* L.) decline, it is advisable to use *Q. pubescens* Willd. instead of *Q. cerris* L. as it is more tolerant of water stress.

It is worth emphasizing that it is not necessary to identify genotypes completely resistant to particular diseases. Rather, the emphasis should be on species with horizontal resistance: that is, species that are not completely resistant but tolerate the main diseases and thus have greater long-term reliability. Therefore, new European poplar clones are selected with the goal of improving general tolerance of the main abiotic factors and fungal diseases. Such general tolerance should promote suitable levels of production and low levels of damage, even in the presence of significant pathological outbreaks.

This approach is currently preferred for achieving parasite-specific resistance but not in preventing further evolution of the same agent or exposure to other adverse factors. Such a phenomenon has occurred in recent years with rust pathogens on poplar, which are also limiting from the standpoint of biomass production. In this case, high tolerance should permit moderate attacks without significant leaf fall or reduction of stump viability.

Biodiverse, multispecies plantations are resistant to many adversities due to dilution of both pathogenic pressure and specific endophytic pathogens on individual genotypes. Therefore, plantations with “clonal patchworks” should be promoted to mitigate possible parasitic outbreaks on susceptible clones. Multispecies plantations in which a very fast-growing species is complemented by a species with slower growth but more valuable wood (e.g. poplar and walnut) are another viable option. For example, in Italian intensive poplar plantations, public authorities have been fostering multiclonal stands where new multiresistant clones are combined with the well-established *P.* × *canadensis* ‘I-214’.

In new plantations, it is advisable to use nursery material that is healthy, in good condition and certified. From a practical point of view, transplanting risks could be reduced by:

- creating nurseries in areas with low inoculum pressure;
- minimizing water stress in the nursery; and
- avoiding the dehydration of transplanting material and promoting its hydration before planting.

Sufficiently wide spacing provides greater soil volume for trees while reducing potential nutritional deficiencies and lowering the risks associated with bark necrosis. Moreover, by modifying the microclimate, wide spacing reduces the probability of attacks by some fungal parasites or leaf-sucking insects.

Further, appropriate soil cultivation may:

- improve soil aeration, thereby increasing the reaction of radical root systems against root rot agents (e.g. *Dematophora* R. Hartig and *Armillaria* [Fr.] Staude);
- enhance tree resistance to attacks by weakness parasites (e.g. *Discosporium* Höhn., *Cytospora* Ehrenb. and *Phomopsis* (Sacc.] Bubák);
- reduce inoculum of some leaf diseases by burying infected leaves (e.g. *Marssonina* Magnus, *Venturia* Sacc.) and by eliminating possible alternate hosts of heteroecious fungi (rust agents); and
- limit the spread of weeds and, therefore, their competition with young trees.

Root rot agents are particularly influential in the developmental stages following stand establishment. From this perspective, soil cultural practices are significantly effective against *Dematophora*, especially if drainage is improved. In the case of limited attacks, the removal of healthy plants, or at least their isolation via ditches, should be considered. The parasite epiphytic phase can be kept at a low level by waiting 2 or 3 years in the transition between the original stand and the establishment of new trees, as well as by keeping new plantations at an adequate distance from *Dematophora*-susceptible crops.

The aforesaid prescriptions reduce but do not eliminate the effects of adversities that may negatively impact plantation production. Therefore, to limit the attacks and reduce damage, agronomic practices must be integrated with chemical control. Long considered the preferred tool for mitigating damage caused by biotic adversities, chemical control involves the use of often synthetic chemicals, such as pesticides, that can have serious ecological consequences (e.g. bioaccumulation; damage to wildlife; selective pressure on insects, fungi and bacteria; onset of resistance; increased incidence of secondary phytophagous insects; and acute and chronic toxicity). With the entry into force of Directive 2009/128/EC of the European Parliament and of the Council, limitations on chemical control of tree-related adversities are increasing. Chemical products should be used sparingly and selected and applied in a manner that minimizes negative impacts on human health and the environment.

In Europe, chemical protection is used to protect trees against adversities in several cases, such as on poplar trees (e.g. against *Marssonina brunnea* [Ell. et Ev.] P. Magn., *Cryptorhynchus lapathi* L. and *Saperda carcharias* L.) and in poplar nurseries (e.g. against *Melampsora laricis-populina*, *Gypsonoma aceriana* Duponchel and *Paranthrene tabaniformis* Rottenburg). Chemical control is also applied in nurseries of other genera, such as *Pinus* (e.g. against *Lophodermium seditiosum* Minter, Staley & Millar), *Prunus* (against *Blumeriella jaapii* [Rehm] Arx) and *Juglans* (e.g. against *Xanthomonas arboricola* pv. *juglandis*).

Biological protection is an unconventional, often underestimated alternative to traditional chemical-based treatments. Several methods for biological control exist, including treatments based on *Bacillus thuringiensis* Berliner or the spread of antagonists, as well as on the use of pheromones or various traps (Battisti and Masutti, 2014). In the defence of poplar plantations against *Hyphantria cunea* (Drury), the use of formulates based on *B. thuringiensis* has allowed cultivation to continue in sensitive areas such as river floodplains. Further, entomoparasitic nematodes can be applied to limit *Popillia japonica* Newman.

Lastly, worth mentioning is the emerging topic of pesticides based on RNA interference (RNAi). Such pesticides involve the introduction of formulates containing interfering RNA, which, after ingestion by the infesting insect, silences the expression of a gene necessary for some function of the insect. In this way, the pest genome is not directly modified; the pest is simply introduced to a molecule that blocks a specific fragment of RNA. RNAi-based pesticides are not toxic for the environment and, because they are very selective of the target species, they do not negatively affect beneficial insects.

The European Union has been promoting integrated pest management for several years (Lefebvre, Langrell and Gomez-y-Paloma, 2015), which involves implementing several protective measures together (e.g. legislative, genetic, agronomic, chemical and biological). Integrated management is based on improved biological and epidemiological knowledge of parasites or pests and deeper knowledge of resistance factors and climate conditions affecting the species of interest.

Take-home messages

Complete control of the adversities affecting tree growth and production is not feasible. However, significant improvements can be achieved by dedicating more research to the development of effective and innovative systems in the following areas:

- parasite identification (diagnosis) to prevent the introduction of allogeneic organisms and ensure that the propagation material is healthy;
- monitoring of parasitic outbreaks to limit or prevent the risk of plantation degradation;
- genetic improvement and selection methods for plant resistance; and
- the eco-compatible application of unavoidable biological or chemical protective treatments in nurseries or plantations.

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3.3 Genetics and conservation of fast-growing trees: adaptation, drift, selection, biotechnology, genetic pollution and habitat shrinkage

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Summary

The fast-growing trees (FGTs) used worldwide are the result of breeding and selection activities organized around base genetic resources of several tree species and hybrids. *In situ* characterization of FGTs has revealed high genetic variability of natural populations, while *ex situ* field trials have shed light on their gene ecology. Static and dynamic conservation strategies contribute to maintaining the integrity of genetic resources and sustaining the genetic improvement of FGTs. Recurrent intra- and interspecific breeding over generations have greatly improved the growth and yield of FGT plantations. Selection and deployment of superior forest reproductive material (FRM) will be accelerated by new high-throughput tools, including genomics, phenomics and modelling. International regulations apply to the production and trade of FRM, but more countries should participate, and barriers to trade and use of FRM need to be addressed.

Keywords: Breeding; dynamic gene conservation; reproductive material; genetic diversity; genetic improvement; static gene conservation

Introduction

In recent years, interest in FGTs to produce wood and biomass as renewable raw materials has risen greatly. Joint efforts by industry, stakeholders and scientists are required to achieve more sustainable production systems and reduce anthropogenic pressure on forest ecosystems. The sustainable management and economic exploitation of FGTs require in-depth knowledge of genetic resources in terms of their geographic distribution and their genetic, phenotypic and ecological diversity. Genetic resources refer to the heritable diversity and genetic material maintained within and among plant species that are of environmental, scientific, economic or societal value. The genetic resources of a given species include selected germplasm, natural wild populations and interfertile species of wild relatives. The exploration and characterization of genetic resources provide the knowledge base for their conservation and management. Information acquired on genetic and phenotypic diversity is essential for selection and breeding to improve FGT reproductive material and ensure adaptation to future climate scenarios. New technologies are empowering the basic research and breeding of FGTs, particularly in some model species, and are opening new horizons to improve the whole FGT value chain.

Characterization of fast-growing tree genetic resources

The diversity of genetic resources is fundamental for breeding, cultivation and adaptation to a changing environment (Jactel *et al*., 2017). Unlike crops, most FGTs belong to poorly domesticated forest species, and a wide genetic diversity is present in their natural populations (Neale and Kremer, 2011). The biological and ecological features of forest trees, such as their mating system, life history and gene flow, maintain a relatively high genetic diversity, despite the impact of climate change and anthropogenic disturbances (Savolainen and Pyhäjärvi, 2007). Breeding and propagation practices can affect the diversity and adaptation of genetic resources. Vegetative propagation is an efficient method for several purposes, but the genetically homogeneous plantations of FGTs increase vulnerability to abiotic and biotic stressors. Moreover, seed dispersal and pollination from plantations may affect the genetic diversity of surrounding natural forests (Ingvarsson and Dahlberg, 2019). This risk is relevant where cultivated exotic species can cross with local wild plants, as in the case of interspecific poplar (*Populus* L.) hybrids grown near natural stands (Vanden Broeck *et al*., 2021). Some globally spread FGT species may also become invasive alien species and alter the diversity and structure of forest ecosystems (da Silva, Bouillet and de Paula, 2016). The characterization of genetic resources requires two levels of investigation, *in situ* and *ex situ*.

In situ studies explore existing variations of plant populations in their ecological habitats. Natural stands adapted to specific sites represent precious genetic resources for plantations in similar environments. Basic characterization of natural genetic resources addresses the genetic diversity and structure of natural populations by analysing DNA variation. In the last decade, rapid progress has been made in the field of genomics, which analyses entire genomes using high-throughput technologies, such as next-generation sequencing (NGS) technology. Genomics tools are available for a few species with long research track records, such as poplars, eucalypts (*Eucalyptus* L'Hér) and pines (*Pinus* L.) (Street, 2019).

Ex situ studies investigate the genetic basis and plasticity of phenotypic traits, the "genotype × environment interaction" and the association between genetic variants and traits (Li *et al*., 2017). Common garden field trials are the most common experimental design in *ex situ* studies and are fundamental steps in the scientific analysis, domestication and breeding of trees (Sáenz-Romero *et al*., 2019). Multisite trials are essential for evaluating adaptation to different environments (Chakraborty *et al*., 2019). Some basic information on genetic resources of the main FGT species among hardwoods and softwoods is presented in this section.

Poplars have long played a role in human society as multipurpose trees for wood and specialty products (Pannucci *et al*., 2021). The *Populus* genus includes 32 fast-growing species, classified in six sections, encompassing a wide natural range throughout the northern hemisphere. The current status of domestication and conservation of poplar genetic resources has been reviewed by Stanton, Serapiglia and Smart (2014). Initial *in situ* studies focused on phenology in wild populations of *Populus trichocarpa* Hook. and *P. deltoides* Moen. from different latitudes of North America and showed the importance of bud set phenology for breeding and selection (Pauley and Perry, 1954). Common garden experiments were then established at several locations to study the quantitative genetics of adaptive traits in *P. deltoides* and *P. trichocarpa* (Farmer, 1996). DNA markers have enabled the genetic characterization of poplar germplasm and the identification of commercial genotypes (Fossati *et al*., 2005).

Moreover, *P. nigra* L. is a keystone species of European riparian ecosystems (Figure 2) and is a good example of how genetic resources are characterized by field and laboratory analyses. Genetic studies on *P. nigra* populations in Europe have shown high genetic diversity and a population structure consistent with the geographic separation of river basins (Faivre-Rampant *et al*., 2016). E*x situ* provenance trials have been conducted to study several characteristics, such as leaf functional traits (Guet *et al*., 2015), biomass and bioenergy (Allwright *et al*., 2016), and wood chemical properties (Gebreselassie *et al*., 2017).

Genetic mapping of full-sib poplar pedigrees has identified genome regions or quantitative trait loci (QTL) controlling complex adaptive traits, such as growth (Rae *et al*., 2008), bud phenology (Rohde *et al*., 2011; Fabbrini *et al*., 2012), disease resistance (Jorge *et al*., 2005) and response to elevated carbon dioxide (CO_2) (Rae *et al*.,

2007) and cadmium (Iori *et al*., 2016). A great breakthrough was the public release of the genome sequence of *P. trichocarpa*, the first among tree species (Tuskan *et al*., 2006). These genomic resources are now widely applied thanks to technological advances and decreasing costs. Genome-wide association studies have been carried out on large collections of unrelated plants and have identified candidate genes associated with productive traits, such as biomass and wood quality in *P. nigra* (Allwright *et al*., 2016) and *P. deltoides* (Fahrenkrog *et al*., 2017).
Eucalypts are the world's most widely planted hardwood trees (Myburg *et al.*, 2014). *Eucalyptus* species and hybrids are of great interest as FGTs, mostly the subtropical *Eucalyptus grandis* W. Hill, *E. urophylla* S.T. Blake and *E. camaldulensis* Dehnh., and the temperate *E. globulus* Labill. and *E. nitens* Maiden. Hybrid eucalypts are the result of crosses among *E. grandis*, *E. urophylla*, *E. tereticornis* Sm., *E. camaldulensis* and *E. pellita* F. Müller (FAO, 1979a; Doughty, 2000). Eucalypts are native to Australia and adjacent islands and have high diversity and adaptability and rapid growth, and they can easily be propagated vegetatively (FAO, 1979a).

A marked genetic differentiation between populations is common in *Eucalyptus* species, whereas quantitative traits display clinal gradients associated with environmental factors. *E. camaldulensis* is the only species widespread across the Australian continent with a major ecological role. In this species, populations within river basins represent metapopulations with significant inner diversity. The neutral genetic diversity is defined by large-scale variation in latitude and moisture index (Butcher, McDonald and Bell, 2009), but the functional diversity displays differentiation patterns associated with local environments (Dillon *et al*., 2014). The native genetic resources of *E. camaldulensis* should be considered as a panel of subspecies with high genetic diversity. *E. globulus* is a temperate species spread across South Australia and Tasmania. *In situ* genetic studies have found a genetic structure well correlated with geographic distribution, whereas the differentiation of quantitative phenotypic traits was driven by natural selection (Steane *et al*., 2006). *Eucalyptus* has been extensively studied as a model for tree genetics; the genome sequence is publicly available, together with advanced biotechnological resources (Myburg *et al*., 2014). Genome-wide analyses have been applied to high-density linkage maps for the identification of DNA markers associated with growth and wood traits (Silva-Junior and Grattapaglia, 2015).

Pinus radiata D. Don (radiata pine or Monterey pine) is native to North America and is the most planted softwood worldwide. It was introduced to Europe in the eighteenth century, then to Australia, and later to other continents, mainly in the southern hemisphere. *P. radiata* is widely planted as an exotic tree, but its native range is small and restricted to five populations of North America (Mead, 2013). As a consequence, its genetic diversity is lower than in other planted softwoods (Moran, Bell and Eldridge, 1988). The domestication and breeding of *P. radiata* started in Australia and New Zealand. Cultivated *P. radiata* germplasm mainly originates from the two northern provenances, Monterey and Año Nuevo, and represents a narrow fraction of the natural genetic diversity (Moran and Bell, 1987).

P. radiata can be vegetatively propagated by rooted cuttings, allowing the establishment of informative replicated experiments, accurate estimation of trait heritability, and selection of clonal varieties (Baltunis and Brawner, 2010). *Ex situ* studies have allowed significant progress in quantitative genetics, with the obtention of genetic linkage maps (Kuang *et al*., 1999). Progeny tests and multisite common garden trials have investigated the quantitative genetics of key traits related to growth and form and have provided fundamental information for breeding (Baltunis and Brawner, 2010). Genomic research on *P. radiata* has made progress in the last decade. A full reference genome sequence is not yet available in this species, but transcriptome sequence data provide a large set of genome-wide single nucleotide polymorphism (SNP) markers useful for research and breeding (Telfer *et al*., 2018).

Pseudotsuga menziesii (Mirb.) Franco (Douglas fir) is native to North America. Two varieties are known: *Pseudotsuga menziesii* var. *menziesii* (Mirb.) Franco (= var. *viridis* (Schwer.) Franco) (coastal Douglas fir), and *Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco (interior, Rocky Mountain or blue Douglas fir). These varieties differ in growth rate and size at maturity, with the variety *menziesii* having more rapid growth and a larger size than the variety *glauca*. Further, the variety *glauca* grows at higher altitudes than the coastal variety. *P. menziesii* has a broad geographic range in North America and exhibits great genetic and adaptive differentiation associated with environmental and geographic clines (Chakraborty *et al*., 2016). *In situ* studies, coupled with *ex situ* common garden trials, have shown geographic patterns of genetic and phenotypic variation in the native range. Populations markedly differ in adaptive traits such as bud phenology and seedling emergence.

P. menziesii evolutionary adaptation to western North America is mainly shaped by winter temperatures and frost dates (St. Clair *et al*., 2005). This species was introduced in Europe in 1827; it was planted in the United Kingdom of Great Britain and Northern Ireland it was planted initially for ornamental purposes and later for forestry. Thanks to its adaptive trait variability, *P. menziesii* has become an important planted species in temperate biomes of Europe, South America, South Africa, New Zealand and Australia. In Europe, it is one of the most successful introduced species, being well adapted to various climates and soils (Ducci *et al*., 2003; San-Miguel-Ayanz *et al*., 2016). The germplasm introduced in Europe mainly represents the coastal variety and originates from a wide range of provenances, whereas the interior variety has limited presence (van Loo *et al*., 2019).
More than 50 provenance trials have been established in Europe for the evaluation of hundreds of provenances. Replicated trials have shown that stem growth traits display a significant effect of provenance origin, whereas phenology is dependent on the climate conditions of the growing site (Gould, Harrington and St. Clair, 2012).
P. menziesii is one of the few conifers with recently developed genomic resources, including a reference genome sequence (Neale *et al*., 2017).

Management of fast-growing tree genetic resources

Genetic resource management serves to ensure conditions in which the genetic diversity of tree species can evolve in response to an ever-changing environment, maintaining vitality of forests and resilience to pests and diseases. The management of FGT genetic resources is also the foundation for breeding and selection programmes (Bradshaw and Strauss, 2001). Human activities, deforestation, habitat fragmentation and climate change are major threats to the integrity of genetic resources. Uncontrolled movement of forest reproductive material (FRM) and introduction of exotic species are additional causes of decline (Amaral, Thomson and Yanchuk, 2004). Static (short-term) and dynamic (long-term) approaches for conservation of genetic resources are complementary and can be used in combination (St. Clair and Hove, 2011). Dynamic gene conservation aims to maintain the evolutionary processes of tree populations to safeguard their adaptive potential. Restoration of degraded ecosystems is a strategy of dynamic conservation that enhances and accelerates natural processes of regeneration (Rotach, 2001; Vietto *et al*., 2008). Tree stands can be established outside the native range of the species (dynamic *ex situ* conservation), according to climate-change predictions and supported by the characterization of plant material in previous provenance trials. The planted *ex situ* germplasm should represent the genetic diversity of the original population, and the stands must be large enough to ensure a minimum viable population size (FAO, 1992). In response to climate change, tree species have to adapt *in situ* or migrate to more suitable environments (range shift) (Hamrick, 2004; Marchi and Ducci, 2018). Marginal populations may be crucial for adaptation to future environmental conditions.
Forest genetic resources dynamically change, and genetic monitoring has been recently introduced to quantify the temporal changes in genetic variation and in the structure of populations. This approach should focus on keystone tree species and on rare or endangered tree species (Aravanopoulos, 2016). Dynamic gene conservation strategies concentrate on gene conservation units, which refer to a stable tree population in specific environmental conditions, selected for its high potential for adaptive evolution (EUFGIS, n.d.). Static approaches of *ex situ* conservation have the objective of preserving the current genetic diversity of a species in germplasm collections. Clonal archives (e.g. poplars, willows [*Salix* L.], elms [*Ulmus* L.], eucalypts [*Eucalyptus* L'Hér], casuarinas [*Casuarina* L.], paulownias [*Paulownia* Siebold & Zucc.] and *Pinus radiata*), seed orchards (e.g. alders [*Alnus* Mill.], locusts [*Robinia* L.], *Pinus taeda* L. and *Pseudotsuga menziesii*) and seed banks in cold storage (e.g. poplars, locusts and eucalypts) are used in conservation programmes and support plant breeding. For most broadleaved trees, seed banks are considered a short-term conservation strategy, but other species, such as species of pines and locusts, have orthodox seeds that maintain a high germination rate over many years of storage. Some forest species with recalcitrant seeds require frequent regeneration or advanced techniques such as tissue culture and cryo-conservation (Willan, 1985; Engelmann, 2004; Pritchard *et al*., 2014).

Long-term conservation of ecosystems at the pan-European level, including native populations of FGTs, is ensured by Council Directive 92/43/CEE "Habitat" (Ministero della Transizione Ecologica, 2021). In this context, the "Natura 2000" ecological network has been established to ensure the preservation and long-term survival of threatened species and habitats. It is the largest coordinated network of protected areas worldwide and covers 27 European Union countries (European Commission, n.d.). To promote a European conservation strategy, a European Forest Genetic Resources Programme (EUFORGEN) was established in 1994, with considerable efforts to conserve forest genetic diversity (de Vries *et al*., 2015). Currently, the global conservation of genetic resources is addressed by the European Union programme GenRes Bridge, which aims "to strengthen conservation and sustainable use of genetic resources by accelerating collaborative efforts and widening capacities in plant, forest and animal domains" (GenRes Bridge, n.d.). Within EUFORGEN, priority is given to the dynamic *in situ* conservation of forest genetic resources. A pan-European network of selected genetic conservation units (Koskela *et al*., 2013), with the European Information System on Forest Genetic Resources (EUFGIS) (Kelleher *et al*., 2015), has been created to conserve the adaptive genetic diversity of various tree species and to promote links among national forest genetic resources conservation programmes. The EUFGIS database (available at http://portal.eufgis.org/) contains information on 3 210 conservation units and 107 tree species in 35 European countries. Several FGT species are listed in this information system, and technical guidelines for genetic conservation and use of some of them are available at https://www.euforgen.org/publications/technical-guidelines/.

Beside the conservation issue, several attempts have been made to share plant genetic resources and their benefits. In 2010, the Tenth Conference of the Parties to the Convention on Biological Diversity (CBD) adopted the Nagoya Protocol on Access and Benefit Sharing, an "international agreement which aims at sharing the benefits arising from the utilization of genetic resources in a fair and equitable way" (SCBD, 2011). The protocol requires that users of genetic resources and associated traditional knowledge from other countries (for research and development purposes) must receive permission and the terms and conditions of the exchange in advance. The protocol does not apply to the use of genetic resources for production purposes, such as obtaining seeds for growing and planting seedlings as part of normal forestry operations.

Selection and breeding of fast-growing trees

Forest tree breeding has been developed since the beginning of the last century. It mimics natural selection through recombination and selection pressure, but with two main differences: (1) artificial selection is directed, focusing on socioeconomic needs and adaptation requirements, and (2) the selection process is faster. Forest tree breeding is mainly concerned with species of economic importance, for which artificial regeneration through planting or direct sowing is a common practice. Several FGT species have breeding programmes geared towards the selection and approval of clones. Nevertheless, in central and northern Europe, clonal forestry is viewed critically because genetic diversity is considered a higher priority. The spectrum of breeding methods applied to FGT species ranges from traditional hybrid breeding to cultivar development supported by molecular genetic studies. The development and status of breeding activities in some of these species are summarized below.

Poplar breeding began in 1914 in the Royal Botanical Gardens, Kew, United Kingdom of Great Britain and Northern Ireland (Stanton, Serapiglia and Smart, 2014). In the 1990s, breeding programmes were restructured in two directions: long term and short term (Kang, Lascoux and Gullberg, 1996). Long-term breeding aims to preserve genetic diversity to ensure adaptability. Short-term breeding, on the other hand, aims at the rapid selection of clones as commercial varieties (Bisoffi and Gullberg, 1996). The success of poplar breeding is measured by how easily interspecific hybrids with high vigour (*P.* ×*canadensis* Moench; *P.* ×*generosa* A. Henry; *P.* ×*wettsteinii* Hämet-Ahti) and easy vegetative propagation can be obtained (Figure 3). The genetically superior quality of poplar clones allows immediate gains in productivity but can also result in serious losses, as in the case of the *Marssonina brunnea* (Ellis & Everh.) Magn. pathogen on poplar plantations in Europe (Zsuffa *et al*., 1993).

Currently, the main poplar breeding objectives are survival and growth, disease and insect resistance, adaptability, crown architecture and wood quality. In short-rotation forestry (SRF), there are additional breeding goals: rapid juvenile growth, sprouting capacity after coppice and density tolerance (Liesebach, Schneck and Wolf, 2012). Breeding objectives are distinct from traits evaluated as selection criteria. A frequent approach in long-term breeding includes first-generation interspecific hybridization, combined with reciprocal recurrent selection of the parental species (Box 1). Other breeding strategies (backcrossing, multiple species hybridization, polyploidy and somaclonal variation) are not frequently applied in long-term breeding but are used in short-term programmes (Stanton, Neale and Li, 2010). Poplar breeding can be accelerated by genomic resources (Tuskan *et al*., 2006), high-throughput genotyping (Levy and Myers 2016) and automated phenotyping (Ludovisi *et al*., 2017). The extensive knowledge on poplar genetics has been poorly applied by marker-assisted selection (MAS), but recent approaches of genomic selection allow the prediction of breeding value using genome-wide DNA polymorphisms and could greatly accelerate genetic gain in poplar breeding (Alves *et al*., 2020; Pégard *et al*., 2020). Genetic transformation has been applied to improve wood quality (Boerjan *et al*., 1997), to confer herbicide resistance (Meilan *et al*., 2002), and to enhance phytoremediation capacity (Doty, 2008). Validating gene function is a fundamental technique, but the commercial use of genetically modified poplars is still challenging due to governmental regulations and societal perceptions (Strauss *et al*., 2004). Genome editing by CRISPR-Cas technology is the new frontier of plant genetic improvement, but its application to forest trees has been limited because of the high heterozygosity (Zhu, Li and Gao, 2020). Recent research has demonstrated the efficiency of CRISPR-Cas to obtain modified phenotypes (i.e. altered cell wall composition) by inactivation of genes (Takata *et al*., 2019). Given the societal scepticism towards transgenic plants, genome editing is promising as it does not require the integration of transgenic DNA.

Willow (*Salix* L.) breeding began in Sweden with hybridization (Heribert-Nilsson, 1918) and cytological studies (Hakansson, 1938). Twelve species and hybrids are included in willow breeding for biomass and wood production (Stanton, Serapiglia and Smart, 2014). Most of the commercial willows come from the United Kingdom of Great Britain and Northern Ireland and Sweden, and the largest germplasm collection, with 1 500 accessions, is conserved at Rothamsted, United Kingdom (FAO, 1979b). In addition to increasing biomass production, the improvement of resistance to leaf rust, in connection with molecular genetics, is an important target of willow breeding (Hanley *et al*., 2011). In Sweden, willow breeding restarted in 1978 with the selection of vigorous individuals in natural stands and is mainly based on the species *Salix viminalis* L. and *S. dasyclados* Wimm. The Swedish breeding programme is closely linked to molecular genetics and ecophysiological research at Swedish Uppsala University (Weih *et al*., 2008), where a collection of 600 accessions has been established as the basis for recurrent selection breeding (Gullberg, 1993). This breeding programme is geared towards increasing yield, rust resistance, insect tolerance and frost hardiness, with the objective of regularly deploying new varieties (Gebhardt, 2012). Willow varieties adapted to warm and dry climate conditions have been recently selected (Salix Energy Europa AB, 2016). In Argentina, willow breeding began in 1950 (Ragonese and Rial Alberti, 1958). Currently, the breeding programme continues with the development of hybrids, mainly *S. matsudana* Koidz. × *S. alba* L; selection focuses on disease tolerance, adaptation, higher yield and quality of wood for the paper and sawmill industries (Cerrillo *et al.*, 2016). There is also a focus on the conservation of *S. humboldtiana* Willd., the only native species (Gallo *et al.*, 2020). The selection of five improved clones of *S. viminalis* L. for basketry was recently completed, to be applied in plantations in Delta del Paraná, Argentina (Cerrillo, 2021).

The most intensive breeding of ***Robinia pseudoacacia*** L. (black locust) outside its natural range has been carried out in Hungary, where selection began in 1930 (Fleischmann, 1933). From 1951, black locust improvement was further intensified (Keresztesi, 1983; Rédei, Osváth-Bujtás and Veperdi, 2008). The aim of the Hungarian breeding programme was to improve wood quality and growth performance. The best stands across the country were selected and approved as seed stands that produce most of the propagation material (Rédei, 2003). Furthermore, particularly vigorous trees were selected from these stands and the vegetatively propagated (root cuttings, tissue culture) clones or clone mixtures were tested in field trials. The best clones and clone mixtures were approved as varieties and propagated for cultivation (Keresztesi, 1983). In recent years, clones for biomass production in SRF have been selected and deployed (Rédei, 2003). Parallel efforts have been made to improve black locust in the United States of America. Clones of *R. pseudoacacia* were selected in 1938, and field trials were carried out on this material between 1948 and 1965 (Bongarten, 1992). This programme resulted in two seed orchards and the approval of three clones for commercial distribution. Other programmes were based on progeny tests of *R. pseudoacacia* plus trees (Liesebach and Schneck, 2018).

Eucalypts are now grown in over 100 countries for biomass and solid wood production, pulp and paper, charcoal for the steel industry and biochemicals. In Brazil, eucalypt breeding started in 1941 with species and provenance testing (de Oliveira Castro *et al*., 2016). Initially, planting was performed using seeds from non-selected stands, with low productivity and susceptibility to pathogens. To minimize these issues, different species were crossed to produce hybrids with the objective of improving productivity and wood properties for industry plantations. In the mid-1970s, research on quantitative genetics gained strength, and the breeding of eucalypts focused mainly on clonal selection to replicate superior genotypes. Genetic improvement involves three selection stages (Rezende, de Resende and de Assis, 2014): (1) selecting parents for hybrid recombination ability; (2) selecting candidate clones among the hybrid offspring based on field progeny tests; and (3) selecting operational clones based on clonal field trials. Currently, nearly 50 percent of eucalypt forests in Brazil are clonal (Rezende de Resende and de Assis, 2014). Nowadays, genomics tools are implemented in the breeding of eucalypts to efficiently improve productive traits such as diameter growth and wood quality (Resende *et al*., 2012; Müller *et al*., 2017).

Breeding of ***Pseudotsuga menziesii*** in western North America dates back to the 1950s and has been summarized by Howe *et al*. (2006), including the approach to breeding zones, breeding cycles and methods of deployment. Recently, Jayawickrama and Ye (2020) reported the status of the large and intensive second-cycle breeding and testing programme in the United States of America. In Europe, genetic improvement of *P. menziesii* began as soon as information on intraspecific variability was available. A second phase started in the 1960s and 1970s with the phenotypic selection of superior trees in the best stands. Currently, breeding of *P. menziesii* in Europe takes advantage of the knowledge provided by the existing network of provenance and progeny tests (Bastien *et al*., 2013). Genomic and phenotypic data can be combined to predict plant performance and could be further developed into genomic selection of *P. menziesii*, with better genetic gain for late-expressed and low-heritability traits (Ratcliffe *et al*., 2019, Thistlethwaite *et al*., 2019).

Breeding of ***Pinus radiata*** began in the 1950s in New Zealand and Australia, with the first seed orchards (Wu *et al*., 2007). Successful breeding of radiata pine is due to a combination of favourable conditions: early introduction of germplasm came from the better provenances (Año Nuevo and Monterey), and selection in local environments resulted in landraces adapted to the new habitat. The main objectives of breeding are fast growth, stem straightness, wood properties and resistance to diseases (Burdon, 2001). Mass selection was the first breeding strategy, with the phenotypic selection of superior trees; it was applied in New Zealand and Australia prior to the availability of seed orchards. In the early stages, seed orchards produced open-pollinated seeds with low genetic improvement (Burdon, Carson and Shelbourne, 2008). Later, seed orchards were established based on progeny tests, and improved, open-pollinated seed is currently used in most plantations (Mead, 2013). Control-pollinated orchards were set up in the 1990s and almost doubled the genetic gain (Carson, 1986; Burdon, Carson and Shelbourne, 2008). Recent developments of nursery cuttings, micropropagation and somatic embryogenesis have provided new ways for the deployment of clonal plant material (Carson and Carson, 2011). Newly selected clones have allowed high genetic gains in growth and wood traits (Mead, 2013). Selection and genomic prediction could be further applied in radiata pine to improve the efficiency of selection for traits with low heritability (Klápště *et al*., 2020).

Fast-growing tree reproductive material

The distribution of FRM is regulated to varying degrees (Stanton, Serapiglia and Smart, 2014). Some FRM is not traded, meaning that private forest companies can breed and produce reproductive material for their own forests. This also applies to cooperatives, as in the case of *Pseudotsuga menziesii* in the United States of America (Jayawickrama and Ye, 2020). At the international level, the Organisation for Economic Co-operation and

Development (OECD) Scheme for the Certification of Forest Reproductive Material Moving in International Trade (OECD, 2019) is open to OECD members (Table 5) and United Nations member states. The scheme was established in 1967 and is regularly revised. Under the OECD scheme, FRM may be produced and traded only with registered basic material. The OECD scheme includes four categories of FRM that derive from six types of approved basic material (Table 5 and Table 6). The scheme specifies minimum requirements, but each country can add further requisites in specific cases. There are no restrictions in international trade for the tree species included in the OECD scheme.

The legal framework for production and marketing of FRM in the European Union is Council Directive 1999/105/EC, which applies to all European Union member states and is harmonized with the OECD scheme. The requirements of this directive fall into four FRM categories (Tables 6 and Table 7). The directive sets rules for the approval of basic forest material and for the production and marketing of FRM. It also prescribes a system for registration, labelling and control to identify FRM from collection to the market (Konnert *et al*., 2015). The directive has been implemented into national law by all 27 European Union member states (Table 5), and its objectives are to:

- ensure free movement of FRM within the European Union;
- protect against the introduction and spread of organisms harmful to plants in the European Union;
- provide high-quality and genetically suited FRM for the various European Union site conditions; and
- conserve biodiversity, including forest genetic diversity.

The directive provides a common set of minimum requirements but allows European Union member states to enforce additional and more stringent requirements, except for marketing. According to the directive, forest seed and planting stocks produced in seven non-European Union countries (Canada, Switzerland, Norway, Serbia, Türkiye, the United Kingdom of Great Britain and Northern Ireland and the United States of America) and officially certified under the OECD scheme are considered equivalent to seed and planting stocks complying with Council Directive 1999/105/EC. Supplementary third countries, such as Serbia and the United Kingdom of Great Britain and Northern Ireland, have adopted similar rules. Türkiye has also adopted the Council directive, with all definitions of FRM categories. The directive's scope is limited to 47 species and to artificial hybrids important for forestry purposes. Some member states have not approved FRM for tree species without national economic importance, but the cultivation and distribution of FRM by national forest seed and plant companies are allowed.

Neither the European Union directive nor the OECD scheme include requirements on the end use of FRM, but states are free to determine requirements in their national or regional legislation (Liesebach, 2020). The European Union has established the online database FOREMATIS (Forest Reproductive Material Information System) on approved basic material, with a search tool for forest breeders, forest nurseries, experts and the general public (available at https://ec.europa.eu/forematis/). Willows do not fall under the European Union directive or national law and may be freely propagated and marketed, provided that there is no plant variety protection. An international register of poplar clones, with 358 entries, has been established by the IPC and is frequently updated (available at www.fao.org/forestry/ipc/69637/en/).

An important aspect of FRM trade is protection against the introduction of pathogens and pests, an increasing risk due to market globalization and climate change. It is therefore necessary to adopt measures against phytosanitary risks, subject to international agreements and international conventions such as the International Plant Protection Convention (the treaty was originally signed in 1951 and revised in 1997). For European Union member states, Regulation 2016/2031 recently came into force (European Union, 2016), replacing Directive 2000/29/EC. This regulation poses some limitations to the free trade of FRM.

Table 5. European Union member states and the Organisation for Economic Co-operation and Development Scheme for the Certification of Forest Reproductive Material Moving in International Trade

Continent	Country (ISO 3166)	OECD scheme	Council Directive 1999/105/EC
Africa	BF, KE, MG, RW, UG	X	
North America	CA, US	X	
Asia	TR	X	
Europe	AT, BE, BG, DK, DE, FI, FR, IE, IT, HR, HU, NL, PT, RO, SK, ES, SE, SI	X	X
	CH, NO, GB, RS	X	
	EE, GR, LV, LT, LU, MT, PL, CZ, CY		X

Notes: OECD = Organisation for Economic Co-operation and Development. A key to country names is available at https://www.iso.org/obp/ui/#search. Sources are given in Table 7.

Table 6. Categories of forest reproductive material and origin of breeding material

Origin of breeding material	Categories of forest reproductive material			
	Source-identified	Selected	Qualified	Tested
Seed source	X			
Stand	X	X		X
Seed orchard			X	X
Parents of family/ies			X	X
Clone			X	X
Clonal mixture			X	X

Note: Sources are given in Table 7.

Table 7. Definitions of the four categories of forest reproductive material

Category	OECD scheme[i]	Council Directive 1999/105/EC[ii]
Source-identified	This is the minimum standard permitted. The location and altitude of the place(s) from which reproductive material is collected must be recorded; little or no phenotypic selection has taken place	Reproductive material derived from basic material, which can be either a seed source or stand located within a single region of provenance and which meets the requirements of Annex II[ii]
Selected	The material must be phenotypically selected at the population level	Reproductive material derived from basic material, which shall be a stand located within a single region of provenance, which has been phenotypically selected at the population level and which meets the requirements of Annex III[ii]
Qualified	The components of the basic material have been selected at the individual level; evaluation may not have been undertaken or completed	Reproductive material derived from basic material which shall be seed orchards, parents of families, clones or clonal mixtures, the components of which have been phenotypically selected at the individual level, and which meets the requirements of Annex IV.[ii] Testing need not necessarily have been undertaken or completed
Tested	The superiority of the reproductive material must have been demonstrated by comparative testing or an estimate of its superiority calculated from the genetic evaluation of the components of the basic material	Reproductive material derived from basic material which shall consist of stands, seed orchards, parents of families, clones or clonal mixtures. The superiority of the reproductive material must have been demonstrated by comparative testing or an estimate of the superiority of the reproductive material calculated from the genetic evaluation of the components of the basic material. The material shall meet the requirements of Annex V[ii]

Notes: Sources of tables 5-6-7:
[i] **OECD (Organisation for Economic Co-operation and Development).** 2019. *OECD scheme for the certification of forest reproductive material moving in international trade*. OECD Forest Seed and Plant Scheme. Paris. www.oecd.org/agriculture/forest/documents/forest-scheme-rules-and-regulations.pdf
[ii] *Council Directive 1999/105/EC of 22 December 1999 on the marketing of forest reproductive material*. http://extwprlegs1.fao.org/docs/pdf/eur34525.pdf

What do we need?

Forest trees are poorly domesticated, but FGT species are an exception as methods from agriculture are used on a large scale. The present challenge is to increase FGT wood production without eroding long-term adaptive potential or impairing the production capacity. Natural populations of forest trees represent a reservoir of genetic resources for FGTs. *In situ* and *ex situ* studies of wild germplasm are fundamental for characterizing the genetic and adaptive diversity of FGTs. *Ex situ* collections and field trials should be better connected with breeding and conservation programmes. Long-term field trials in replicated environments provide vital information on plant adaptability and allow for the monitoring of the impacts of climate change, but such research infrastructures lack support for long-term management and monitoring.

Fast-growing tree species are widely planted worldwide, and activities to explore and characterize the natural genetic resources of FGTs need to be better connected in an international network. Climate change has an impact on the integrity of FGT genetic resources and represents a challenge for their future adaptability. Genetic resources are also exposed to various threats: deforestation and habitat fragmentation, uncontrolled movement of FRM, introduction of exotic pests and human activities. It is therefore necessary to sustain the conservation of genetic resources *in situ* and expand *ex situ* collections with new germplasm.

Forest genetic resources dynamically change in response to strong pressures, and it is necessary to implement genetic monitoring on gene conservation units for dynamic *in situ* conservation. The existing networks for conservation of forest tree genetic resources are managed at the local level and need to be more coordinated worldwide. To support the sustainable use of FGTs, the different governments need appropriate policies and regulation frameworks.

Fast-growing trees are the most domesticated of forest trees, and genetic improvement has been typically designed to increase yield, wood quality and pest resistance. Present breeding programmes should match the future changes in environmental conditions and market demand, and new breeding objectives should include environmental adaptability and tolerance to emerging pests. The clonality and narrow genetic diversity of highly selected FGTs represent a vulnerability factor, and continuous infusion of wild germplasm into breeding programmes is necessary to support the resilience of plantations.

Hybridization among species continues to be a major way of genetically improving some FGTs, such as poplars and eucalypts. Forest tree genomics and phenotype predicting models could considerably accelerate tree improvement, but implementation of genomic selection in operational breeding requires a complex and multidisciplinary approach. Genetic improvement of tree species is a long-term business, which needs continuity in breeding programmes.

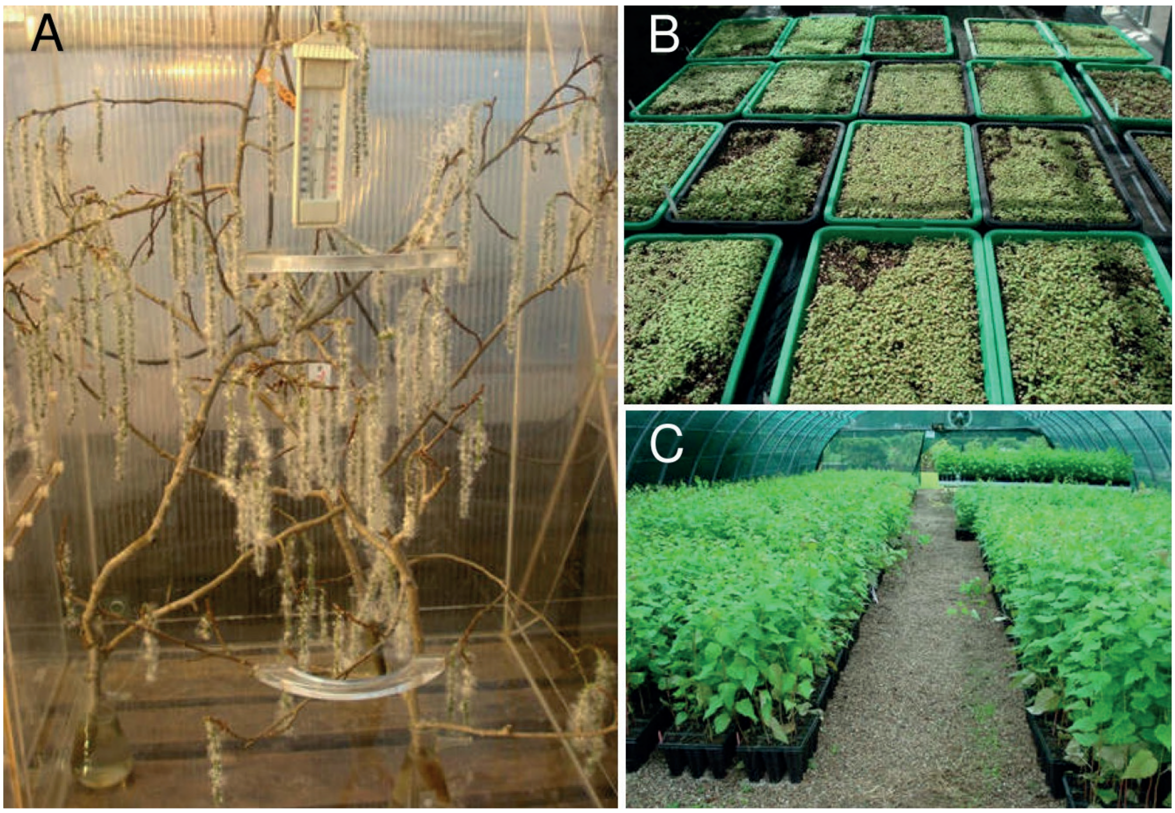
Currently, trading of FRM is largely unhindered, but some countries only allow local FRM for plantations. These restrictions need to be adjusted to use FGT plant material better adapted to climate change. The area of deployment should be recorded by authorities to allow for long-term monitoring of tree adaptive response. Reproductive material of FGT species should be marketed worldwide according to uniform rules.

Take-home messages

- Natural populations of FGTs represent a reservoir of genetic resources and are worthy of thorough *in situ* characterization and conservation.
- Germplasm collections and common gardens support conservation strategies and breeding but lack adequate investments for long-term maintenance and monitoring.
- Dynamic gene conservation of FGTs *in situ* requires the definition of gene conservation units, the implementation of genetic monitoring and better international coordination.
- Breeding programmes have selected highly productive FGTs for intensive cultivation, and new breeding objectives are required in response to climate change and emerging pests.
- Interspecific hybrids will continue to be the main road for the improvement of some FGTs, and genomics, phenomics and modelling will be implemented in future genetic improvement programmes.
- Trade and deployment of FRM at a global scale would benefit from a wider participation of countries in the OECD scheme.

Figure 2. Natural population of *Populus nigra* along the Paglia River, Acquapendente, Italy

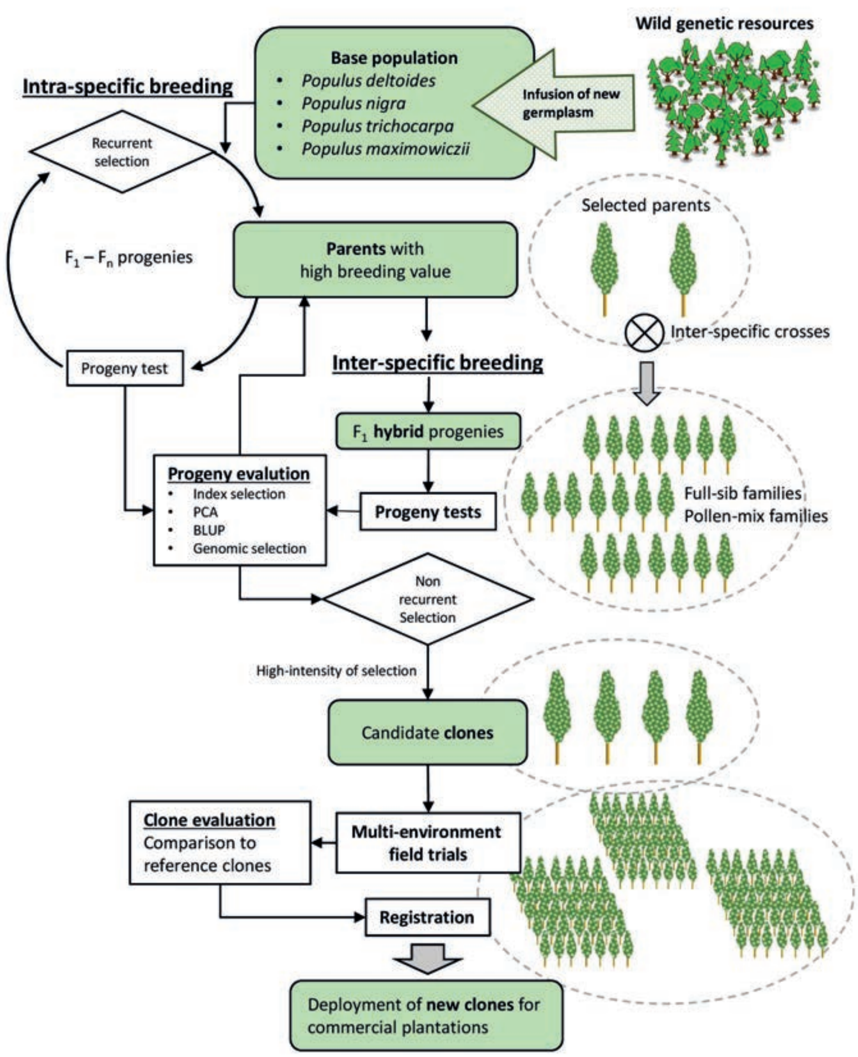
Figure 3. *Populus ×wettsteinii* interspecific breeding: A) release of seeds from female catkins after controlled crossing; B) full-sib progenies in germination trays; C) transplanted seedlings in the greenhouse



Box 1. OVERVIEW OF POPLAR BREEDING FOR HYBRID CLONES

Base plant material (seeds or cuttings) is sampled from wild populations considered to be representative of the genetic and environmental diversity of each species and is grown in *ex situ* collections. Germplasm collection over a latitudinal gradient is important to capture the variation of adaptive traits. The continuous infusion of new germplasm is necessary to avoid relatedness and loss of genetic variability. Recurrent intraspecific breeding of two or more parental species is then conducted, based on the performance of intraspecific progeny tests. Parents with high breeding value are selected and crossed to obtain F_1 interspecific hybrids, which are tested in replicated field trials. Linear models integrate data from several traits to achieve a multitrait evaluation of F_1 progenies using the selection index method, principal component analysis (PCA) and best linear unbiased prediction (BLUP). Genomic data, phenomics and phenotype prediction can be implemented in poplar breeding to accelerate selection steps (genomic selection). Progeny tests of hybrid families may influence the intraspecific recurrent selection to obtain parental clones with high interspecific combination ability. The hybrid clones are screened with high-intensity selection to identify a small set of candidate clones for multi-environmental field trials. This evaluation is performed on diverse sites over multiple years, with continuous comparison to local reference commercial clones. The superior clones must be accepted for registration (depending on country regulations) and are then deployed in operational plantations. Figure 3 presents a simplified breeding scheme for poplar hybrid clones.

Figure 4. Breeding scheme for poplar hybrids
Source: Authors' own elaboration.



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4 Ecological benefits of fast-growing trees and their contributions to environmental sustainability

4.1 Ecosystem services

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Summary

Fast-growing trees (FGTs) provide a multitude of ecosystem services that sustain people and the environment. Enhancing the ecosystem services provided by FGT biomass production systems can contribute to achieving many of the Sustainable Development Goals (SDGs). Fast-growing trees create economic, social and ecological opportunities for local communities that can be scaled up to benefit society at regional, national and global scales.

Keywords: Ecosystem services; Sustainable Development Goals; phytotechnologies

Introduction

Fast-growing trees can provide multiple ecosystem services that sustain people and the environment. The Millennium Ecosystem Assessment (2005) identifies four categories of ecosystem services. These are provisioning, regulating and cultural services, which provide direct benefits to people, and supporting services that are needed to maintain the other services. Section 4.1 introduces some the ecosystem services provided FGTs that are most relevant for community health and well-being.

Ecosystem services and fast-growing trees

According to the Millennium Ecosystem Assessment (2005), ecosystem services are (1) *provisioning services*, the products obtained from ecosystems, such as freshwater, timber or fibre; (2) *regulating services*, the benefits obtained from an ecosystem's control of natural processes, such as soil quality, flood regulation and reduced soil erosion, filtering of groundwater nutrients, contaminants in soil and other pollutants, and reduction of greenhouse gases; (3) *cultural services*, the non-material benefits obtained from ecosystems, such as those that provide aesthetic, spiritual or recreational values (e.g. conservation of the rural landscape and public use); and (4) *supporting services*, the natural processes that maintain the other services, such as the nitrogen cycle, photosynthesis and the creation of buffer zones between wooded and agricultural lands.

Forest plantations with FGTs, also known as short-rotation woody crops (SRWCs), are used in multiple applications ranging from biomass production for wood and energy to remediation of organic contaminants (Zalesny *et al*., 2016a, 2016b): they sequester carbon, produce clean water, regulate the water cycle, improve the connectivity of landscape mosaics, enhance biodiversity and alleviate desertification (Kanninen, 2010). Fast-growing trees provide feedstock for the growing bioenergy and bioproducts sectors (Rockwood *et al*., 2008; Stoof *et al*., 2015; Ferrarini *et al*., 2017; Gasparatos *et al*., 2018), as well as serve as living pumps to reduce environmental degradation and restore ecosystem services through phytotechnologies (Gopalakrishnan *et al*. 2009; Burges *et al*. 2018). Phytoremediation, the most common phytotechnology approach, utilizes inherent growth and physiological mechanisms to reclaim, remediate and restore polluted waters and soils (Cunningham and Ow, 1996; Arthur *et al*., 2005; Mirck *et al*., 2005). Therefore, sustainably managed FGTs that deliver balanced packages of ecosystem services can play a major role worldwide in helping achieve the SDGs (Zalesny *et al*., 2019b).

Short-rotation poplars (*Populus* L.), willows (*Salix* L.), eucalypts (*Eucalyptus* L'Hér) and pines (*Pinus* L.) are among the most commonly used FGTs for phytotechnologies and ecosystem services (Zalesny *et al*., 2011, 2016a, 2016b) due to their:

- phreatophytic traits (i.e. extensive root systems, fast growth and elevated hydraulic potential);
- well-established silvicultural prescriptions (Stanturf *et al*., 2001; Rockwood *et al*., 2004; Dickmann, 2006); and
- broad genetic variation that increases their resilience to climate extremes (Eckenwalder, 1984; Aravanopoulos, Kim and Zsuffa, 1999; Monclus *et al*., 2006; Chhin, 2010).

Phytorecurrent selection and other genotypic selection methods are of utmost importance for enhancing ecosystem services, given the need to identify and choose favourable genotypes with enhanced abilities to take up, degrade or immobilize particular pollutants (Zalesny *et al*., 2007, 2016a). Globally, the overarching objective of most phytoremediation applications is to reduce land degradation in urban and rural landscapes while maximizing biomass production (provisioning services) and carbon sequestration (regulating services) (El-Gendy *et al*., 2009; Zalesny *et al*., 2019a). Differences in aboveground biomass between rotation-age poplars grown for phytoremediation (on contaminated sites) and those grown for traditional bioenergy-related end uses in agricultural fields in the Midwestern United States of America have been reported to be negligible (Zalesny *et al*., 2019a). Similar results have been shown worldwide (Dipesh *et al*., 2015; Burges *et al*., 2018).

Economic valuation of ecosystem services supports their consideration as market services that can be exchanged and the provision of incentives for their continuous supply through payments for ecosystem services (PES). These PES compensate the service producer for an ecosystem service that benefits the community, contributing to increase its revenue (e.g. farmers' incomes from taking their annual crops out of production and establishing riparian buffers, including SRWCs to increase soil carbon sequestration).

Take-home messages

- There is a strong linkage between ecosystem services and the SDGs, with FGTs, also known as SRWCs, being particularly valuable for multiple end uses ranging from biomass production to remediation of contaminants.
- Forest plantations with SRWCs provide ecosystem services such as wood for timber production, biomass for energy, carbon sequestration, clean water production, regulation of the water cycle, improvement in the connectivity of landscape mosaics, biodiversity conservation and alleviation of desertification.

Case study 4

ECOSYSTEM SERVICES OF THE NORTH AMERICAN GREAT LAKES

Ronald S. Zalesny Jr., Elizabeth R. Rogers and Ryan A. Vinhal

The Laurentian Great Lakes Basin of eastern North America ("the Great Lakes") is the largest surface freshwater ecosystem in the world, containing 20 percent of global freshwater supply and 95 percent of the surface freshwater of the United States of America. The Great Lakes provide substantial provisioning, regulating, supporting and cultural ecosystem services throughout the United States of America and Canada. Since 2016, a regional phytotechnologies network consisting of 16 agroforestry phytoremediation buffer systems (i.e. phytobuffers) was established to protect terrestrial water cycles and reduce impacts to water quantity and quality within the basin. Over 20 000 poplar (*Populus* L.) and willow (*Salix* L.) trees were planted to reduce potential surface runoff and subsurface water flow at landfills in the Lake Superior and Lake Michigan watersheds. The phytobuffers also provide additional benefits, such as water-quality improvement, stream-bank stabilization, forest-cover enhancement and ecosystem restoration.

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4.2 Climate-change mitigation and resilience

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Summary

Climate change is increasing ecosystem vulnerability and biodiversity loss, leading to greater spread of invasive alien species, with the potential to alter ecosystems. Because of their carbon sink capacity, fast-growing trees (FGTs) contribute to climate-change mitigation. Fast-growing trees also contribute to climate-change adaptation by reducing soil erosion and providing benefits for agricultural production in a changing climate. Resilience to climate change is one of the criteria for selection of some FGT genotypes.

Keywords: Climate-change mitigation and adaptation

Ecosystems are drastically impacted by the effects of climate change, such as increased surface temperatures and altered weather patterns (Thornton *et al*., 2014), which are affecting their exposure, sensitivity and adaptability to extreme events and increasing their overall vulnerability (Hobday *et al*., 2006). Furthermore, climate change increases biodiversity loss, leading to greater biological spread of invasive alien species that could alter ecosystems (Bellard *et al*., 2013). However, ecosystems continuously adapt to climate change, though adaptations are not always beneficial to human activities. For example, rising carbon dioxide (CO_2) levels can increase the growth and reproduction of C3 plants (approximately 95 percent of plant species), including invasive weeds of significance to agriculture (Ziska *et al*., 2018). Changes in the global climate also exacerbate the spread of plant pathogens.

Fast-growing trees such as poplars (*Populus* L.) and willows (*Salix* L.), can contribute to climate-change mitigation. As tree growth rate is related to carbon sink capacity, FGT plantations lead to higher forest carbon stocks (Keenan *et al*., 2016). Furthermore, biomass from FGTs is a renewable energy source that can be used by the pyrolysis process (avoiding CO_2 production), an example of a "circular economy" system (Corona *et al*., 2019).

Fast-growing trees can also contribute to climate-change adaptation. Breeding programmes of poplar genotypes have selected clones resistant to the main pests and diseases. New genotypes in Italy show reduced CO_2 emitted from cultivation phases compared to widespread clones such as 'I-214' (a *Populus ×canadensis* Moench. genotype) (Chiarabaglio *et al*., 2020). Fast-growing tree plantations, especially poplar, can reduce soil erosion and gravel deposition during more frequent extreme flood events by acting as buffer strips (Chiarabaglio *et al*., 2014). Fast-growing tree species can also be used as biological windbreaks, reducing wind speed and improving the microclimate of protected areas. These species offer direct benefits to agricultural production in a changing climate while also increasing ecosystem biodiversity (Tsarev *et al*., 2020).

Resilience in the face of climate change is one of the criteria used in poplar selection, such as adaptation to drought, water stress and high temperatures as well as salinity, wind and soil conditions. Examples of selection projects include:

- the B4EST project funded by Horizon 2020, a research and innovation funding programme of the European Union, which aims to select *Populus nigra* L. genotypes resistant to water stress; and
- the Carter project launched in Veneto, Italy, by the European Agricultural Fund for Rural Development (EAFRD), which is studying water stress in a group of poplar clones to select and promote the cultivation of resilient clones.

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4.3 Biodiversity

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Summary

Agriculture and forestry depend on high ecosystem biodiversity, which contributes to healthy soils, nutrient cycling and global carbon turnover and improves ecosystem resilience. Biodiversity loss driven by human activities is correlated with biological invasions, which threaten ecosystems. Poplar stands have been shown to have higher biological soil quality than agricultural soils. Fast-growing trees (FGTs) can be implemented on agricultural land, disturbed ecosystems and urban landscapes to mitigate biodiversity loss.

Keywords: Biodiversity loss; ecosystem resilience; biological soil quality index; new-generation plantations

According to Carnus *et al*. (2006), the biodiversity of forest ecosystems is the sum of four components of diversity: genetic, species, structural and functional. Important sectors like agriculture and forestry directly depend on high ecosystem biodiversity; the diversity of genes and species and ecological multifunctionality contribute to healthy soils, nutrient cycling and global carbon turnover (Daily, 1997). More generally, biodiversity enhances ecosystem resilience, stability and productivity (Oehri *et al*., 2017).

Biodiversity loss is largely driven by human activities that modify ecosystems and induce "genetic erosion" (Bijlsma and Loeschcke, 2012). Often, biodiversity loss is correlated with biological invasions that negatively impact ecosystems. In 2015, the European Union released its Invasive Alien Species of Union Concern list, which includes all invasive species that have a high to medium impact on biodiversity, human health or the economy.

The monitoring of biodiversity loss can be conducted via micro- and macroinvertebrate assays. For example, the biological soil quality index (BSQ index) analyses the diversity of arthropods in the first 10 cm of soil (Parisi *et al*., 2005; Çakır, 2019). Investigations on soil biodiversity in Italy showed that poplar (*Populus* L.) stands could have a BSQ index of 120–160, while the index was higher than 180 for natural woodlands and less then 90 for agricultural lands (Chiarabaglio *et al*., 2009). Ground beetles are one of the most common and species-rich families used as bioindicators of biodiversity loss. Chiarabaglio, Allegro and Giorcelli (2014) showed that the biodiversity of ground beetles was higher in poplar stands compared to annual crops.

One way to increase biodiversity is through the implementation of FGT plantations on agricultural land. For example, FGTs produce high amounts of dead wood used by a wide range of organisms (Jastrzebska, 2020). Fast-growing trees provide tree microhabitats in a shorter time than slower-growing species. However, since in Douglas fir (*Pseudotsuga Menziesii*) forests the observed microhabitat variability has been shown to be lowest in recently managed stands compared to stands with low treatment history and natural stands, active management for microhabitats in silviculturally treated stands of even-aged FGTs is important to create structural complexity for a variety of organisms and ecosystem functions (Michel and Winter, 2009). Crown shape can also affect species richness. *Populus trichocarpa* Hook. and *Larix ×eurolepis* Henry. have low leaf area index values, which can positively influence the presence of organisms, such as birds and insects (Jastrzebska, 2020). In addition, FGTs can increase the biodiversity of epiphytic lichens and mosses, which has been demonstrated in hybrid aspen plantations (*Populus tremula* L. × *Populus tremuloides* Michx.) (Randlane *et al*., 2017). Despite the invasive nature of *Robinia pseudacacia* L., FGT plantations of the species, if well-managed, can mitigate biodiversity loss in disturbed ecosystems and become ecological niches in artificial urban landscapes (Vítková *et al*., 2020).

Take-home messages

- Biodiversity loss is a critical issue caused by human activities.
- Agriculture and forestry rely on the ecosystem services provided by healthy ecosystems with high biodiversity.
- Fast-growing tree plantations can help address biodiversity loss in degraded ecosystems, and in agricultural and urban landscapes.

Case study 5

PERMANENT POLYCYCLIC PLANTATIONS

Paolo Mori

Many of the environmental benefits provided by FGT plantations are lost at the end of the management cycle when trees are felled. Permanent polycyclic plantations are generally mixed and have two or more production cycles on the same land plot. This tree plantation strategy provides potential productivity outcomes similar to traditional tree farming and benefits similar to those of forests. In the municipality of Villa Bartolomea in Veneto, Italy, a polycyclic plantation was established within an area currently used for intensive agriculture. The overarching objective was wood production, but other objectives were to reduce management costs and environmental impacts. Three production cycles of different lengths were planned on the same parcel, allowing for the production of woodfuel from *Platanus* L. (first cycle of 6–7 years, followed by 4–5-year cycles); wood veneer for the production of plywood from poplar (*Populus* L.) every 9–11 years; and veneer and sawntimber for the production of furniture and wooden objects from walnut (*Juglans regia* L.) and lime tree (*Tilia platyphyllos* Scop.) every 25–30 years. Ancillary tree and shrub species were also planted to help tree farmers reduce production costs and environmental impacts. This kind of polycyclic plantation could potentially be "permanent", meaning that it is possible to manage the plantation without ever completely harvesting it. This approach leads to increased biodiversity due to the range of tree and shrub species used and the other plant and animal species linked to them. The fact that the plantation is never fully used also improves carbon storage in the soil and reduces the landscape impact of harvesting.

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4.4 Water

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Summary

Broad genetic variation in fast-growing trees (FGTs) grown as short-rotation woody crops (SRWCs) provides resilience to climate extremes that cause both water excess and water shortages. There is great potential in breeding and selecting FGTs with high productivity potential when grown on sites with limited or abundant water. Selecting SRWCs with improved drought tolerance and water-use efficiency (WUE) has been studied to match genotypes to sites based on water availability. Poplar clones with high WUE have been shown to be less susceptible to water stress, suggesting that productivity zones could be extended from alluvial plains to uplands with greater water shortages. In tree-based water remediation systems, proper species selection for the remediation objective is also important.

Keywords: Water-use efficiency; optimal genotype × environment interactions; short-rotation woody crops; water-consumer versus water-saver genotypes

Water use and conservation are important for woody biomass production systems of short-rotation woody crops (SRWCs) using poplars (*Populus* L.), willows (*Salix* L.), eucalypts (*Eucalyptus* L'Hér) and pines (*Pinus* L.) (Cacho *et al*., 2018). These systems are grown across the rural to urban continuum to enhance environmental sustainability as well as socioeconomic sustainability (see Chapter 5) (Zalesny *et al*., 2016a, 2016b). Regardless of end use, the broad genetic variation in all four genera provides resilience to climate extremes that cause water excess as well as water shortages (Zalesny *et al*., 2019). For example, Mirck and Volk (2009) reported within-season differences in transpiration among shrub willow varieties grown as an evapotranspiration cover in Solvay, New York, United States of America. Clone *Salix sachalinensis* F. Schmidt × *Salix miyabeana* Seemen ('9870-23'or 'Marcy') had greater transpiration during the spring and early summer, while *Salix purpurea* L. ('9882-34' or 'Fish Creek') favoured site conditions during late summer and autumn. The mean crop coefficient (Kc) across all willow genotypes tested was 1.20 ± 0.05 across the growing season, resulting in 20 percent greater transpiration for willow than well-watered grass (*Poa* L.), for the northeastern United States of America (Mirck and Volk, 2009).

Unlike most slower-growing tree genera, there is tremendous potential in breeding and selecting these fast-growing species with high productivity potential when deployed across sites exhibiting limited or abundant water (Dimitriou, Mola-Yudego and Aronsson, 2012; Dvorak, 2012; Zalesny *et al*., 2019). The practical importance of selecting SRWC genotypes with improved drought tolerance and water-use efficiency (WUE) (i.e. the proportion of water utilized in tree metabolism relative to water lost via transpiration) has been studied to match SRWC genotypes to sites based on site water availability (Leffler and Evans 1999; Dillen *et al*., 2008). Yin *et al*. (2005) reported that poplars with high WUE were less susceptible to water stress than clones with low WUE. This was corroborated by Monclus *et al*. (2005), who reported a significant positive correlation between WUE and biomass productivity for certain poplar clones on water-limited sites. For poplars, productivity zones may be extended from alluvial plains and bottomlands to uplands with less available soil moisture and more prolonged periods of water shortage (Monclus *et al*., 2006).

Understanding ecophysiological parameters such as sapflow and WUE are important for the design, implementation and monitoring of purpose-grown tree plantations. These can be used in selection indices to inform optimal genotype ×environment interactions (Zalesny *et al*., 2006; Mirck and Volk, 2009). In addition to traditional bioenergy feedstock systems, an opportunity for water management innovations exists with the integration of proper clonal selection and subsequent deployment on polluted sites such as landfills, surface mines, military installations and brownfields (Pilipović *et al*., 2012; Zalesny *et al*., 2020). In particular, SRWCs are a widely used and proven tree component of phytoremediation and associated phytotechnologies (Zalesny *et al*., 2016b; Pilipović *et al*., 2019).

Poplars and willows have been used worldwide to remediate soils and waters polluted with both inorganic and organic contaminants (Zumpf *et al*., 2017; Pilipović *et al*., 2020), including but not limited to wastewater irrigation and re-use applications (e.g. irrigating trees with landfill leachate) (Aronsson, Dahlin and Dimitriou, 2010; Dimitriou and Aronsson, 2010; Shifflett *et al*., 2014) as well as remediation efforts targeted at point and non-point source pollution (e.g. planting trees atop contaminated groundwater plumes) (Quinn *et al*., 2001; Ferro *et al*., 2013).

Regardless of the application, given that uptake and remediation potential are highly correlated with tree size (i.e. via transpiration–cohesion processes), understanding water use of the trees enhances remediation success (Zalesny *et al*., 2019). For example, reported values for poplar transpiration, a direct proxy for water use, range widely, from less than 1 mm per day (0.63 mm/day, *Populus deltoides* Bartr. *ex* Marsh ['178'] [Guevara-Escobar *et al*., 2000]; 0.74 mm/day, *Populus euphratica* Olivier [Voigt, Khamzina and Diekkrüger, 2018]) to over 10 mm/day (11.8 mm/day, *Populus fremontii* S. Watson [Nagler *et al*., 2007]; 11.33 mm/day, *Populus nigra* L. × *Populus maximowiczii* A. Henry ['NM6'] [Zalesny *et al*., 2006]). In a remediation context, species with greater water use are desirable, whether for reducing the volume of contaminated water (Vose *et al*., 2000; Clinton *et al*., 2004), attaining hydrological control of a contaminant plume (Ferro *et al*., 2013) or mitigating pollution in riparian (or other water-saturated) environments (Schultz *et al*., 2004). Therefore, proper species selection can greatly enhance the efficiency of tree-based water remediation systems. Similarly, WUE of poplars varies greatly, resulting in the identification and selection of water-consuming and water-conserving (i.e. drought-tolerant) clones (Zalesny *et al*., 2019). In the midwestern United States of America, for example, carbon isotope discrimination of poplars is used in the evaluation of poplar clones suitable for growth at localities with different soil water properties (Pilipović *et al*., 2022). At these sites, varying responses of productive clones define them as "water savers" or "water consumers", regardless of site conditions. Another example of the implementation of carbon isotope discrimination in the midwestern United States of America is the evaluation of poplar clone landfill phytoremediation potential by defining the effect of contaminated soils on their WUE.

Overall, water-soil-tree relations govern genotype × environment interactions of SRWCs. Therefore, selection of genotypes with requisite levels of WUE is a key focus of SRWC deployment for maximizing productivity potential while avoiding drought stress and growth impacts to the trees (Zalesny *et al*., 2019). On sites with limited water, clonal selection for water-saver genotypes can maximize biomass production without negative impacts to water supply or quality. In contrast, on sites with abundant water (e.g. wastewater phytotechnology applications), clonal selection for water-consumer genotypes increases biomass production and reduces runoff from polluted sites while helping achieve environmental sustainability objectives.

Take-home messages

- Unlike most slow-growing tree genera, there is tremendous potential for breeding and selecting FGTs, also known as SRWCs, with high productivity potential when deployed across sites exhibiting limited or abundant water.
- The practical importance of selecting SRWC genotypes with improved drought tolerance and WUE has been studied to match SRWC genotypes to the sites of deployment, based on varying levels of water availability.
- Understanding these genotype × environment interactions increases the potential of expanding productivity zones from alluvial plains and bottomlands to uplands with less available soil moisture and more prolonged periods of water shortage, thus contributing to improved livelihoods for communities across the rural to urban continuum.

Case study 6

CROP WATER CONSUMPTION OF WHOLE-TREE WINDBREAK SYSTEMS

Niels Thevs

Central Asia is one of the world's largest dryland regions. The countries of that region, Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan, are forest-poor countries that import most of the wood resources required by their domestic markets. At the same time, agriculture largely depends on irrigation, which has resulted in the overexploitation of water resources; the desiccation of the Aral Sea is the most vivid outcome of water extraction for irrigation. Due to climate change, water resources available for irrigation are expected to decrease while the occurrence of heatwaves is expected to increase.

Tree windbreaks composed of poplars (*Populus* L.) have long been implemented across Central Asia and are one option for reducing water consumption in irrigated agriculture and building resilience against climate change. Tree windbreaks also provide wood resources, which make the Central Asian countries less dependent on costly wood imports.

This case study showed that poplar windbreak systems attained a higher overall water productivity than crops without tree windbreaks. Specifically, the water consumption of cotton (*Gossypium* L.), combined with that of single tree lines from poplar windbreak systems (200 m between tree lines), was 777 mm, while cotton without tree windbreaks consumed 904 mm. This study also assessed the growth rates of 30 poplar cultivars unknown to the region with a view to increasing the wood yields obtained from tree windbreaks. Most of the new cultivars tested, particularly *Populus deltoides* Bartr. ex Marsh. × Populus nigra L. hybrids, grew 2–3 times faster than the locally used *P. nigra* cultivars. Further, their water consumption was similar to that of the locally used cultivars.

Newly developed poplar cultivars have the potential to increase the yield of wood resources to be harvested from tree windbreaks while simultaneously helping to reduce water consumption of irrigated agriculture.

Case study 7

PAULOWNIA WATER USE

Niels Thevs

The five countries of Central Asia, Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan, have forest covers well below 10 percent of their total land area. This low forest cover is linked to the arid and semi-arid climates of the region, as well as forest degradation through uncontrolled woodfuel removal, timber harvesting and overgrazing. Consequently, these countries import most of their wood resources. Fast-growing trees planted in agroforestry systems or woodlots, particularly poplar (*Populus* L.) and paulownia (*Paulownia* Sieb. & Zucc.), have been gaining the attention of governments and businesses as a domestic wood resource. Water scarcity and water overuse for irrigated agriculture are widespread across Central Asia and are expected to become even more prevalent due to climate change. Therefore, it is crucial to assess the water consumption of such FGTs to avoid additional strain on already-scarce water resources. This study took place on the first large-scale paulownia plantation in Central Asia and is the first to investigate the genus's water consumption in this region. Water consumption of 4-year-old trees (third year after coppicing) ranged from 253 to 557 litres per tree over the growing season. The biomass increment ranged from 4.3 to 5.2 kg per tree. Poplar trees studied at the same time as paulownia, 3 years after planting, had consumed 1.5 times more water than paulownia at similar biomass increments. Therefore, paulownia will not add disproportionally high pressure on the strained water resources of Central Asia when compared with other trees (e.g. poplar) and crops. Paulownia clearly offers potential for plantations and agroforestry systems, though only if enough water can be supplied through drip irrigation. This requirement makes it difficult for many farmers to integrate paulownia into their ongoing land use. Poplars, on the other hand, can easily be integrated into the ongoing land use and irrigation.

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4.5 Soil

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Summary

Planting trees on agricultural and bare soils is an efficient, low-cost and nature-based method to improve soil quality. However, the overall effect of fast-growing trees (FGTs) on soil fertility is strongly influenced by soil preparation, rotation age, choice of tree species, and harvesting and management practices. In the tropics and subtropics, fertilizer trees (FTs) intercropped in agroforestry systems have been shown to improve soil fertility and crop yields; in temperate areas, the use of tree alley cropping and linear tree plantings along field margins has been shown to increase soil fertility and soil carbon content. However, short-rotation coppice (SRC) systems for energy can negatively impact soil fertility. This effect can be minimized by harvesting leafless plants, debarking, or longer rotations.

Keywords: Soil fertility; fertilizer trees; minimizing soil impacts of short-rotation coppice systems

Planting trees on agricultural and bare soils is generally considered an efficient, low-cost, nature-based method for improving soil quality. Even though soil fertility in plantations remains lower than in natural forests, planted trees are typically used to increase soil fertility, protect against water and wind erosion, and increase soil organic matter and carbon sequestration (Liao *et al.*, 2012). Additionally, trees are extensively studied for the phytoremediation of contaminated soils. Using FGT species – often planted to provide products such as timber, bioenergy, fodder and green manure in a relatively short space of time – may accelerate the desired soil improvement, be it soil fertility enhancement or soil decontamination. However, the overall effect of FGTs on soil fertility depends on factors such as initial site conditions, soil preparation and rotation age, with strong influences of tree species and management.

Soil preparation for seedling establishment is crucial for creating favourable conditions for root development. During soil preparation, conditions such as soil aeration and the moisture regime are improved and weed competition and potential damage from insects and small mammals are reduced (Mayer *et al.*, 2020). Different mechanical operations can be applied, depending on factors such as soil depth and texture, drainage regime and soil layers resistant to root penetration. In general, it is important to maintain the original soil stratification and take care not to bring soil layers with unfavourable chemical or physical characteristics to the surface. Ploughing to a depth of 30–50 cm is recommended as a general rule, combined with scarification down to 70–120 cm when the soil profile allows it. In agroforestry systems, which require fewer tree plantings and in which soils are continuously disturbed via ploughing, localized soil preparation is possible by digging a hole using a spade and shovel or a mechanical auger. Digging a square hole (or auguring out a round hole and squaring it up with a spade) will encourage roots to venture out into the surrounding soil once hitting a corner (Morhart *et al.*, 2019). Once trees are planted, tree uses and rotation are key elements. Short-rotation coppice plantations and FTs show opposite effects on overall soil fertility.

In tropical and subtropical areas, FGTs (especially nitrogen-fixing species) are planted on agricultural land to fertilize the soil. Fertilizer trees (Akinnifesi *et al.*, 2010) can be managed in improved tree fallows and woodlots and intercropped in agroforestry systems, whether in temporal rotations with trees or in spatial arrangements with crops. A review of FTs summarized impressive positive benefits on soil fertility and farming systems. Fertilizer trees annually add more than 60 kg/ha of nitrogen through biological nitrogen fixation, reducing the requirement for mineral nitrogen fertilizer by 75 percent, thus leading to large savings on mineral fertilizers (Akinnifesi *et al*., 2010). Further, FTs can substantially increase crop yield; for example, they have been demonstrated to double maize yields. In southern Africa in particular, there is substantial, widespread adoption and scaling up of FTs in farming systems (Akinnifesi *et al*., 2010).

Similarly, in temperate areas, agroforestry systems can reduce soil erosion and improve soil fertility through nutrient cycling between trees and associated crops (Feliciano *et al*., 2018). Model simulations showed impressive results of tree alley cropping with fast-growing poplars (*Populus* L.) for reducing soil erosion on test sites in Europe (Palma *et al*., 2007). In many areas of the world, poplars are frequently used in linear plantings along field margins for shelterbelts or additional wood production, or both. Recent findings have demonstrated that those trees can positively affect soil fertility and carbon content up to several metres away (Pardon *et al*., 2017). Thus, such linear systems can have positive benefits on soil fertility, also contributing to the resilience of farming systems in temperate areas with intensive industrial agriculture. Scaling up trees interplanted with agricultural crops in European agricultural areas can produce significant improvements in soil quality and fertility at the continental level (Kay *et al*., 2019).

Harvesting is the final operation in tree plantations that can strongly affect soil fertility in terms of soil compaction, organic matter and carbon content, and nutrients (Mayer *et al*., 2020). Soils can be excessively compacted by heavy harvesting equipment. The soil moisture regime can exacerbate this negative effect; thus, it is essential to operate harvesting equipment during relatively dry periods in the tree-dormant season. During the dormant season, plant nutrients and carbon are stored in the wood and root tissues. As such, removal of harvest residues (e.g. leaves or needles, branches, twigs, low-quality or small-diameter stems, bark, dead wood and roots) should be minimized as much as possible, depending on the production objectives of the plantation. Harvest residues on the plantation floor can also reduce soil compaction by heavy machinery. Finally, the harvest practice with the greatest impact on soil fertility is stump removal. During stump removal, an important component of belowground organic matter is removed, and soils are greatly disturbed. Therefore, stump removal should be carefully evaluated on a case-by-case basis, considering its cost, the subsequent use of harvested land and possible effects in terms of root disease, as in the case of plantations of *Hevea brasiliensis* (Jussieu) Müller (Vrignon-Brenas *et al*., 2019).

Short-rotation coppice plantations are widely studied and are sometimes implemented at a commercial scale in temperate areas for woodchip production for energy conversion. Planting densities are high and rotation cycles are very short, from 2 to 5 years, with multiple rotations during the lifespan of a commercial plantation. Harvesting is generally fully mechanized and takes place in winter on leafless aboveground woody biomass composed of small stems. Fast-growing tree species most frequently used in SRC plantations are improved clones of hybrid poplars, willows (*Salix* L.) and eucalypts (*Eucalyptus* L'Hér), along with alders (*Alnus* Mill.) and robinia (*Robinia* L.). Short-rotation coppice systems can negatively impact soil fertility because many nutrients are exported from the soil with the harvested biomass. To minimize this effect, harvesting should always be performed on leafless plants. Additionally, with longer rotations (e.g. 5 years), nutrient uptake in the harvested biomass decreases as the ratio of nutrient-rich bark to wood decreases (Paris *et al*., 2015). Debarking harvested biomass is widely practised in eucalypt plantations in Brazil.

In the case of phytoremediation, FGTs have been recognized as a promising approach for the decontamination of polluted soils because of their rapid growth, extensive root system and, above all, high water uptake. Many experiments have been conducted on different types of contaminants, such as heavy metals (Pilipović *et al*., 2019), polycyclic aromatic hydrocarbons (Košnář, Mercl and Tlustoš, 2020), hydrocarbons (Ossai *et al*., 2020) and nitrogen (Wu, Xiong and Sha, 2020; Zalesny *et al*., 2020). However, care must be taken when using the harvested biomass because it could contain harmful concentrations of contaminants that were taken up and stored in the wood.

Take-home messages

- Planting FGTs on agricultural and bare soils is considered an efficient, low-cost and nature-based solution for improving soil quality (e.g. soil fertility enhancement or decontamination). In tropical and subtropical areas, FTs on agricultural land improve soil fertility and crop yield; in temperate areas, FGTs in linear plantings increase soil fertility and carbon content.
- However, effects can vary depending on initial site conditions, tree species and management, along with the final use of the tree products and services.
- Proper soil care should be taken from the initial stages of soil preparation to the final wood harvesting stage.

Case study 8

NUTRITIONALLY SUSTAINABLE EUCALYPTS: PRACTICES FOR SMART SOIL MANAGEMENT AFTER BIOMASS HARVESTING

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In the short-rotation forest cycles of eucalypt (*Eucalyptus* L'Hér) plantations grown in midwestern and southeastern Brazil, soils may take time to incorporate the nutrients of forest residues left on the ground after biomass harvesting, which can increase fertilizer use and costs for producers. Experimental trials were conducted in clay and sandy soils to test whether (1) the use of smart soil practices, (2) the coppice system implemented, and (3) the selection of clones with higher nutrient-use efficiency could support the sustainable management of forestry sites. The above- and belowground biomass and the stock nutrients of eucalypt commercial clones managed in coppice rotations were measured. Different growth strategies and biomass allocation patterns were observed across soils for the eucalypts. The greatest nutrient exports were assigned to the stem wood fraction for calcium (Ca) and potassium (K) and to the leaves fraction for nitrogen (N). Experimental practices showed that FGT plantations managed in clay soils retained high productivity, even with one-quarter of the conventional level of fertilization for the same stand density, leading to reduced silvicultural costs. On the other hand, eucalypt trees planted in the sandy soils required more attention, as well as a low-impact harvesting system that kept the forestry residues on the ground. In these sandy soils, nutrients of the superficial soil layers – phosphorus (P), K, magnesium (Mg) and Ca – were depleted less than 2 years after planting when considering the full-tree harvesting system at the end of rotation. To minimize nutrient export, the bole bark and tree crown must be left on the ground after harvesting. Therefore, when selecting *Eucalyptus* trees, biomass production for each fraction (foliage, branches, stem, stump and rootstock), as well as overall nutritional efficiency, must be taken into account to ensure the sustainability and productivity of this genera in South America.

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4.6 Phytotechnologies

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Summary

Fast-growing trees (FGTs) are increasingly used to restore degraded land and soils and water contaminated by inorganic and organic pollutants. Examples of deployment include urban greening programmes, planting as forest buffers in agricultural landscapes to reduce ecological impacts, and use as land-use alternates on former surface mining sites. Phytoremediation with FGTs is an innovative, cost-effective approach for immobilizing, extracting, degrading and transforming contaminants, thereby protecting human health. Fast-growing trees can be grown in landscapes for integrated biomass production and phytoremediation, thereby providing ecological, social and economic benefits to communities. Plant–microbe partnerships are being investigated for improved remediation of organic pollutants.

Keywords: Phytoremediation; short-rotation woody crops; integrated phytoremediation and biomass production; plant–microbe partnerships

Human activities worldwide have caused widespread land degradation, resulting in detrimental impacts on public health and ecosystem services (Donohoe, 2003; Rodríguez-Eugenio, McLaughlin and Pennock, 2018). Across the urban to rural continuum, activities related to agriculture, industry and urbanization (e.g. herbicide and pesticide use, mining and petroleum extraction) have greatly contributed to water and soil pollution at local, regional and national scales (Bai *et al*., 1999; Lin *et al*., 2011; Borišev *et al*., 2018). Both inorganic and organic contaminants threaten biological diversity and ecosystem health in aquatic and terrestrial environments (Dodds, Perkin and Gerken, 2013), with one-third of the Earth's soils at risk of degradation and more than 22 million hectares already impacted (Rodríguez-Eugenio, McLaughlin and Pennock, 2018). Municipal waste has also contributed to substantial land degradation (Perkins *et al*., 2014). In the United States of America, over half of the nearly 258 million tonnes of municipal waste generated was landfilled in 2014 (United States Environmental Protection Agency, 2016), creating heightened potential for waters and soils to be polluted.

Fast-growing trees (FGTs) have been used for centuries to restore degraded lands. Given the intensification of land degradation in recent times, their deployment has increased worldwide in the first two decades of the twenty-first century (Caterino *et al*., 2017; Burges *et al*., 2018). Examples of innovations in FGT deployment include:

- incorporating poplars (*Populus* L.) and willows (*Salix* L.) into anthropogenic succession strategies to increase urban afforestation and optimize ecosystem services provided by forests in cities;
- developing riparian forest buffer systems containing FGTs to reduce agrichemical transport from agroecosystems; and
- selecting woody species as potential post-mining, land-use alternates at surface mining sites (Zalesny *et al*., 2021).

Some of the world's largest cities have established "million tree" planting programmes to increase green spaces within urban areas, thereby recognizing the socioeconomic values that trees provide (Berman, Jonides and

Kaplan 2008; Nowak and Greenfield, 2018). Similarly, increased planting of FGTs in agricultural landscapes enhances forest succession and reduces ecological impacts from crops, livestock and other production activities. In the midwestern United States of America, one of the most degraded agricultural areas in the world, tree-based innovations are being deployed to reduce impacts. For example, vegetative forest buffers have been reported to reduce contaminant loads and enhance degradation of herbicides and veterinary antibiotics (Lin *et al*., 2010, 2011). Furthermore, FGTs serve a vital role in reducing environmental and human health risks from surface mining, which can cause 2 to 11 times more land degradation than belowground mining (Bai *et al*., 1999). Bradshaw and Johnson (1992) reported that revegetation is a favourable approach relative to alternatives such as traditional physicochemical treatments (Ortega-Larrocea *et al*., 2010).
Common to all these innovative technologies is the need for remediation of degraded lands before stand- or landscape-level restoration can occur. Conventional practices of remediation, while often rapid, can be expensive, rendering them impractical to treat widespread pollution (Tsao, 2003). Further, these practices often involve transferring or covering up pollutants rather than eliminating them. Excavation, one of the most common forms of remediation, involves moving contaminated soil to another site for long-term storage. Capping a site, another common conventional remediation method, does not prevent eventual flow of the contaminants into aquifers. Incineration of polluted soils can lead to air pollution. Bioremediation, a biological approach involving injection of pollutant-degrading microorganisms into contaminated sites, relies on adequate dispersal of the microbe, carbon sources and buffers, as well as continued health of the microbial strain for effective treatment. For contaminated aquifers, pumping the liquid to the surface and filtering or chemically treating the pollutants is a common yet expensive treatment method. Hundreds of thousands of contaminated sites are abandoned due to the high cost of these clean-up methods. Left untreated, polluted sites continue to pose human and environmental health risks.

Such costs have stressed the need for innovative, cost-effective mitigation measures, such as phytotechnologies, to remediate and reclaim aquatic and terrestrial ecosystems (Nixon *et al*., 2001; Lima *et al*., 2016; Lerch *et al*., 2017; Pilipović *et al*., 2019). Phytoremediation – the use of plants to clean soil and water – is a proven approach for restoration of degraded lands that utilizes the natural ability of plants to take up water and chemicals, functioning as solar-driven, pump-and-treat systems. Not only is phytoremediation a less expensive alternative to conventional remediation strategies (McCutcheon and Schnoor, 2003), its application also results in the provision of essential ecosystem services through the immobilization, extraction, degradation or transformation of contaminants (Mirck *et al*., 2005; Pilipović *et al*., 2012). In addition to these ecological benefits, phytoremediation reduces the risk of pollutant exposure and therefore protects the quality of human life (Donohoe, 2003). Monitoring a phytoremediation site is relatively easy compared to having numerous, expensive monitoring wells. Trees can be assessed visually and through leaf sampling for the presence of pollutants and their degradation products (Gopalakrishnan *et al*., 2007; Limmer *et al*. 2011).

Tree selection is essential for phytoremediation success (Kuzovkina and Volk, 2009; Zalesny *et al*. 2016, 2019a; Pilipović *et al*., 2020). Poplars, willows, eucalypts (*Eucalyptus* L'Hér) and other short-rotation woody crops have a long history of global feedstock production for traditional uses such as biomass, bioenergy and bioproducts (Dickmann, 2006; Zalesny *et al*., 2011) and have become the most widely used and proven trees for environmental remediation (Pulford and Watson, 2003; Rockwood *et al*., 2004). Given land-use change and food-versus-fuel concerns associated with these applications, the use of FGTs for phytoremediation enables the integration of ecological restoration with biomass production (Caterino *et al*., 2017), thereby enhancing overall ecosystem services (Ferrarini *et al*., 2017; Zalesny *et al*., 2019a, 2019b). For example, in the midwestern United States of America, non-fertilized and non-irrigated willows grown for bioenergy have been used as riparian buffers to filter excess nutrients from agricultural operations (Ssegane *et al*., 2015). Likewise, in Serbia, poplar and willow clones have been tested for phytoremediation of soils contaminated with crude oil generated by a petroleum refinery (Pilipović *et al*., 2012) and dredged river sediments (Pilipović *et al*., 2019). Incorporating phytoremediation in integrated landscape approaches for the reduction of broad-scale, non-point source pollution has the potential to bring economic benefits to communities across the globe (Licht and Isebrands, 2005).

One cutting-edge example highlighting the broad-scale potential of FGTs on degraded lands involves plant–microbe partnerships for improved phytoremediation of organic pollutants. While phytoremediation of organic pollutants has been successfully used (Burken and Schnoor, 1998; Lin *et al*., 2010), there can be some challenges. For example, the concentration of the pollutant can be too high, causing phytotoxic effects (e.g. stunted growth, reduced ecophysiological processes or decreased biomass productivity). Contaminated areas often have more than one class of pollutant such that the optimal plant for one chemical may be killed by another chemical. These problems, however, can be overcome by using appropriate plant–microbe partnerships.

The plant microbiome can profoundly impact the health of a host plant, providing increased access to nutrients, tolerance to drought and defence against pathogens. Endophytes, the microorganisms within plants, can have stable, close associations with the host plant, providing an especially useful tool for augmenting plant health and growth. Plants suitable for phytoremediation can be inoculated with endophytic bacterial strains that degrade pollutants, relieving phytotoxic effects. For example, a trichloroethylene (TCE)-degrading bacterial endophyte of poplar was isolated (Kang, Khan and Doty, 2012). Used as a degreaser and solvent, TCE is one of the most common organic pollutants. Inoculation of poplar with the TCE-degrading bacterial strain enhanced tree growth on a TCE-contaminated field test site, improving degradation and overall effectiveness of phytoremediation (Doty *et al*., 2017). Though poplar is able to degrade TCE (Shang *et al*., 2001) and effectively remediate TCE-contaminated water (Newman *et al*., 1999), higher TCE concentrations can cause phytotoxic effects, which limit poplar effectiveness. Another common class of organic pollutants that can be phytotoxic is polycyclic aromatic hydrocarbons (PAHs). A PAH-degrading endophyte was isolated from poplar; when added to willow and grasses, it relieved phytotoxicity and improved uptake of the pollutant (Khan *et al*., 2014). Application of this bacterial strain for phytoremediation at a field site also increased plant growth, health and effectiveness (Landmeyer *et al*., 2020).

Take-home messages

- Fast-growing trees have been used for centuries to restore degraded lands, and their deployment has increased worldwide in the first two decades of the twenty-first century.
- In addition to traditional phytoremediation applications, current examples of novel phytotechnologies using FGTs include (1) incorporating poplars (*Populus* L.), willows (*Salix* L.) and their hybrids into anthropogenic succession strategies to increase urban afforestation and optimize ecosystem services from forests in cities; (2) developing riparian forest buffer systems containing FGTs to reduce agrichemical transport from agroecosystems; and (3) selecting woody species as potential post-mining, land-use alternates at surface mining sites.
- An additional cutting-edge example highlighting the broad-scale potential of using FGTs on degraded lands involves plant–microbe partnerships for improved phytoremediation of organic pollutants, whereby the plant microbiome can profoundly impact the health of a host plant, providing increased access to nutrients, tolerance to drought and defence against pathogens.

Case study 9

PHYTOTECHNOLOGY APPLICATIONS OF FAST-GROWING TREES IN THE UNITED STATES OF AMERICA

Ronald S. Zalesny Jr., Elizabeth R. Rogers and Ryan A. Vinhal

Landfill phytoremediation in the United States of America. Poplars (*Populus* L. species and their hybrids) are ideal for phytoremediation. Poplars have been shown to accumulate heavy metals and other inorganic pollutants, as well as metabolize organic contaminants and excessive nutrients. A long-term poplar phytoremediation system in northern Wisconsin, United States of America, was tested throughout its 17-year rotation for differences among poplar clones for biomass productivity, carbon storage potential, carbon isotope discrimination, phytoaccumulation and phytoextraction of inorganic pollutants, wood properties and biofuel recalcitrance. Combining waste management with biomass production creates economic, social and ecological opportunities for local communities, which can be scaled up to benefit society at regional, national and global scales.

Salt-tolerant agroforestry poplar genotypes. Agroforestry practices provide some of the most common phytotechnologies with FGTs and are being used to reduce winds, manage snow distribution and reduce energy demands for snow removal, as well as for livestock feed and the heating of buildings. Salt-affected soils such as those in the northern Great Plains of North Dakota, United States of America, can prevent or reduce long-term survival and growth of trees in agroforestry systems. Russian olive (*Elaeagnus angustifolia* L.) has been shown to grow on highly sodic soils (Zalesny, Stange and Birr, 2019), and specialized poplar (*Populus* L. species and their hybrids) genotypes tolerating soil salinities as high as 9 decisiemens per metre have been identified and may provide tree options. An agroforestry demonstration site was established in Burleigh County, North Dakota, to compare survival, height growth and phytoextraction potential of these salt-tolerant poplar genotypes versus Russian olive. This information is important for researchers, land managers and landowners when making decisions about species selection for agroforestry systems.

Case study 10

PHYTOTECHNOLOGY APPLICATIONS OF FAST-GROWING TREES IN SCANDINAVIA

Mauritz Ramstedt

Landfill phytoremediation in Sweden and Norway. Willows (*Salix* L. species and their hybrids) are widely used for short-rotation coppice, producing wood chips for burning to generate heat. Certain willow clones with rapid growth traits are selected, as well as genotypes that have the potential to use large amounts of water, thereby taking up water-soluble pollutants and nutrients from the soil. Many of these clones are also known to be able to accumulate and tolerate high amounts of heavy metals, stimulate microorganisms in the rhizosphere and contribute to metabolization of organic contaminants. Current projects in central Sweden and Oslo, Norway, have successfully used willows for remediation of contaminated landfill soils and wastewaters. In an ongoing European Union LIFE-financed project that began in 2016, a closed system was developed to mitigate leakage of wastewaters from landfills. This application was shown to be able to address both heavy metals and compounds with perfluoroalkyl and polyfluoroalkyl substances. The system includes recirculating landfill leachate from storage ponds to irrigate willow plantations designed to utilize the wastewater, resulting in limited off-site transport of the wastewater and its contaminants and reduced potential for impacts to nearby soils and waters.

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5 Socioeconomic benefits of fast-growing trees and their contributions to livelihoods and production for the bioeconomy

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5.1 Introduction

This section focuses on the major contributions of fast-growing trees (FGTs) to human communities in terms of enhanced livelihoods, social equity and non-wood products (NWPs), such as food, medicines and cosmetics.

Fast-growing tree plantations are generally understood to be highly efficient tree crops produced on an industrial scale using industrial methods. Fast-growing trees are extensively used worldwide to supply large quantities of high-quality wood products. Fast-growing trees are an important source of fibre and wood for domestic markets of products such as wood pulp and wood panels for construction (e.g. plywood) and furniture. These markets bring substantial economic benefits to large tree plantation companies and smallholder farming communities alike. Furthermore, sustainable FGT plantations generate by-products that can support smallholders and their families in securing alternative incomes and developing and sustaining their livelihoods. New demands from society are also expanding the role of FGT plantations. Challenges linked to global changes in climate systems, energy and water resources, agriculture, rapidly evolving processing technologies and global markets, and the privatization of the timber production sector are all promoting a more diversified use of species. Smallholder plantations are increasingly included in industrial forestry and farming systems, including conservation agriculture. Non-wood products from trees, including foods, have the potential to improve livelihoods. This section highlights some examples and ways in which concrete, innovative opportunities for non-wood products from FGTs are created and re-created, such as with *Moringa oleifera* Lam. plantations in Africa and Southern Asia.

To boost the livelihood component of FGT-oriented farming systems, specific governance arrangements are needed. Increasing the role of FGTs in improving livelihoods and mainstreaming this role in public and development policies requires sectoral governance platforms based on public–private partnerships as well as capacity-building opportunities involving public institutions, private-sector organizations, and educational bodies such as national universities, extension services and farmer field schools.

Implementing public–private partnerships as a core aspect of improving the governance of the forest sector, including forest plantations, agroforestry and FGTs, is the subject of discussion and capacity-building processes in many Asian countries (AFoCO Secretariat, 2022). One problem noted in many country profiles is the weakness of a consolidated culture of corporate governance that could contribute, together with technological and capacity development, to supporting livelihoods on multiple scales.

During a monitoring campaign of poplar (*Populus* L.) plantations in 2018 by the Forest and Rangeland Research Institute of the Iran (Islamic Republic of), a high productive capacity was identified for *Populus nigra* L., *Populus deltoides* Bartr. ex Marsh. and hybrid *Populus euramericana* (Dode) Guin. clones planted around farmlands for environmental protection and wood production. An integrated farming agroforestry system was evaluated as an optimal approach for developing wood farming and improving the economic efficiency and livelihoods of farmers. There was particular interest in the intercropping of wheat (*Triticum* L.), alfalfa (*Medicago sativa* L.) and peanuts (*Arachis hypogaea* L.) in the poplar plantations.

Several investments have been made in overcoming rooting problems and modernizing the production of smallholder eucalypt (*Eucalyptus* L'Hér) coppices. Technical innovations have been developed to deliver high-quality propagation material.

Sustainable livelihoods are not just a matter of income. Improving sustainable livelihoods beyond the income opportunities offered by nature-based solutions, such as those of FGTs, means developing and consolidating a series of environmental tools that effectively promote empowerment and welfare.

Case study 11

INTEGRATED COMPANY GOVERNANCE SUPPORTING SMALLHOLDER LIVELIHOODS AND BEYOND: RUBBER FOR PEOPLE IN GHANA

Adapted from: Steel and van Lindert, 2017

In the Ahanta West district in the Western Region of Ghana, rubber is the main cash crop, as it has been for almost a century. Until recently, rubber was primarily produced by a large-scale plantation company controlled by a foreign company (Ghana Rubber Estates Limited or GREL). In the mid-1990s, the company started a programme for smallholders and outgrowers. Those selected for participation in the scheme were able to borrow money and buy extension services and seedlings of high-yielding varieties from the company. Rubber trees mature after 4–5 years, and the outgrowers were able to start tapping the latex after that and transport it to the company's processing facility.

Due to comparatively high purchase prices, more and more city dwellers in the Ahanta West district are starting to produce rubber as smallholders. They come from various towns and cities in the coastal districts of Ghana, particularly Takoradi, from where they commute to the rubber plantations. This is aided by the country's good road infrastructure and cash-crop economy, with both national and international links. These conditions have combined to make rubber production attractive to urban-based farmers, many of whom are involved in the outgrower scheme as self-financing farmers.

Case study 12

THE BENEFITS OF POLLARDING POPLARS AND WILLOWS TO PROVIDE STOCK FODDER

Ian McIvor

Poplars (*Populus* L.) and willows (*Salix* L.) are planted extensively in the pastoral hills of New Zealand for soil stabilization but serve other important functions that make them multipurpose trees. Among other roles, they are a valuable and underused source of fodder for pastoral farmers.

Tree fodder utilization usually occurs during the summer and into autumn, when pasture quality is the lowest and trees are in full leaf. Stock animals readily eat the leaves, small stems and bark of both genera. Trees aged 5–10 years yield up to 22 kg of dry matter of edible forage per tree. Willows grow 4–5 times the number of new shoots and carry more edible fodder than poplars. Condensed tannins and higher levels of zinc and magnesium than pasture are added stock health benefits of willow fodder. Willows are also easier than poplars to manage for harvesting fodder. Willows are harvested for fodder every 3–4 years, with the trees reduced to a pollarded form.

Extension activities emphasize the multiple uses of these trees, promote their use and provide information on management for fodder and safe harvesting practices. The intentional planting of poplars and willows for multiple purposes is increasing, with farmers seeking information on fit-for-purpose clones, planting a wider variety of clones and attending to their management.

5.2 Fast-growing trees and the forest industry

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Summary

Fast-growing trees (FGTs) like poplar (*Populus* L.) are grown for a wide range of end uses, including to produce wood. Some wood products from FGTs are obtained by primary processing, while others derive from innovative transformation and modification processes.

Keywords: Wood products; material use; bioeconomy

Introduction

As a renewable and recyclable raw material, wood is assuming a central role in the transition to a bioeconomy in societies that will have to address the effects of climate change and the environmental impacts of human activity. In this context, the demand for timber is following a trend of continuous growth, and the different models of FGT plantations are expected to be a strategic resource, with positive implications in terms of productivity, cost-effectiveness and socio ecological benefits.

The use of species/cultivars that are resistant to pathogens, are suitable for different site conditions and have enhanced wood properties, combined with the optimization of plantation management, contributes to reducing costs and accelerating the production of trees with larger diameters, larger volumes and higher quality, thereby creating opportunities for applications in non-traditional markets.

Moreover, technological innovations in the wood-processing industry are allowing wood from FGT plantations to be increasingly used in the manufacturing of structural products for the building industry. Many of these products have a longer service life than other building materials, as well as enhanced carbon sequestration potential. Further, these products can help improve energy efficiency, provide thermo-acoustic insulation and, by appropriate design, minimize seismic risk.

The wider dissemination of sustainable management and traceability certifications in accordance with various standards will help meet requirements in terms of domestic and international legality and green public-procurement policies.

Wood products

The production of wood and fibre, and biomass for energy use, is often the primary management objective for FGT plantations. A range of cultivation models are used to provide raw materials for the primary and secondary wood processing industries, as well as the pulp and paper and bioenergy sectors (Balatinecz *et al*., 2014). Additionally, plantations intended to produce non-wood products, such as rubber, also provide wood products.

In the wood industry, the use of recycled materials is long established, as shown by recycled paper production, the manufacture of particle board and fibre-based panels from wood packaging and building materials at the end of their life cycle, and the use of woodfuels (in the form of wood chips, briquettes and pellets) obtained from wood industry waste. This approach, which represents an increasing trend, is already in line with the modern requirements for sustainability and recent indications for the cascading use of available wood resources and contributes to the circular economy. In the current global context of increasing demand for wood, FGT plantations can play an important role as a source of raw materials for the bioeconomy (McEwan *et al*., 2020). They can alleviate pressure on natural forests, where there can be significant constraints on timber harvesting due to potential detrimental impacts on ecosystem functions. Moreover, plantations can potentially increase the availability of raw materials with homogeneous properties, which can be obtained with shorter cycles (to optimize the allometric potential of certain species).

It is true that, within the same species, the mechanical properties of wood obtained in the context of intensive production, as is the case in many arboricultural models, are not comparable with those of wood from natural forests, where the crop cycle is much longer (Van den Bulcke *et al*., 2011). Faster tissue formation induces changes at the anatomical level (adjusted cellular dimensions and arrangement) that can significantly impact the physical and mechanical properties of the wood produced and often results in a material that is different in both appearance and mechanical aspects (De Boever *et al*., 2011; Defoirdt *et al*., 2017).

However, the development and enhancement of many modern wood-based products allow significant improvements in raw material performance. A reduction process to units of various sizes and shapes (sawntimber, sheets, particles and fibres) and controlled reconstitution make it possible to manufacture semi-finished products, including structural products (Vansteenkiste, Stevens and Van Acker, 1997; Baldassino, Zanon and Zanuttini, 1998). The products created in this manner show high reliability and create new opportunities for non-traditional, innovative end uses (Gu *et al*., 2015; Negro *et al*., 2016; Marsich *et al*., 2018). A critical aspect of the timber intended for value-adding transformation (by slicing, peeling or sawing) is undoubtedly the diameter of the assortments that can be obtained. The greater the diameter for a given rotation period, the higher the potential processing yields will be.

Hence, the wood industry should combine selection and breeding of new varieties with plantation planning. Tree improvement practices can be implemented to speed up growth rates, increase pathogen resistance and enhance suitability for processing.

Fast-growing tree plantations are frequently based on various acacia (*Acacia* Mill.), pine (*Pinus* L.), poplar (*Populus* L.) and eucalypt (*Eucalyptus* L'Hér) species. The potential and opportunities for using raw materials from plantations for value-added products are discussed below.

A first example is provided by poplar (*Populus* L.) cultivation in Europe (Castro and Zanuttini, 2008; Spinelli *et al*., 2011). At the end of the rotation (10–25 years), the tree can be divided into commercial assortments of various types that allow the integral use of the biomass produced (Figure 4). In this sense, the lower portion of the stem, up to a height of 5–8 m, which is of better quality (mainly linked to characteristics like diameter, taper and shape) is intended for peeling and the production of plywood, laminated veneer lumber (LVL) (Rahayu *et al*., 2015) or multilaminar wood (Castro and Zanuttini, 2004). When this portion contains defects not permissible for these products, it can still be used in the production of boxes for fruit and vegetable packaging (mainly from rotary cut veneer) and for sawing, pulp and the production of oriented strand board (OSB) (Zanuttini *et al*., 2020). Finally, the top part of the trunk and the crown are used to provide chips for particle or fibre board production or are transformed into woodfuel for power plants to produce thermal energy or for cogeneration.

In Europe, conifer plantations of species such as *Pseudotsuga menziesii* (Mirb.) Franco or *Pinus pinaster* Aiton provide timber used primarily to produce sawnwood and structural components of solid wood that are turned into glued laminated timber (glulam) (both as linear or curved components), characterized by a long service life.

Recently, also in the European context, there have been noteworthy trials of newly selected paulownia (*Paulownia* Siebold & Zucc.) clones, which have yielded promising results in terms of growth rate and wood production and which could be used in the development of lightweight products and composites.

Some plantations established in climatically favourable environments also aim to produce timber of valuable species in a relatively short space of time. Though naturally occurring in limited geographical areas, this material is often rare, subject to various levels of protection and difficult to obtain in a forestry context. Sourced from plantations, these species are traded and transformed, sometimes only for niche, high-value markets. An example is teak (*Tectona* L. f.) plantations in some African and Central American countries, the management of which may be certified as well-managed in accordance with a recognized independent certification scheme.

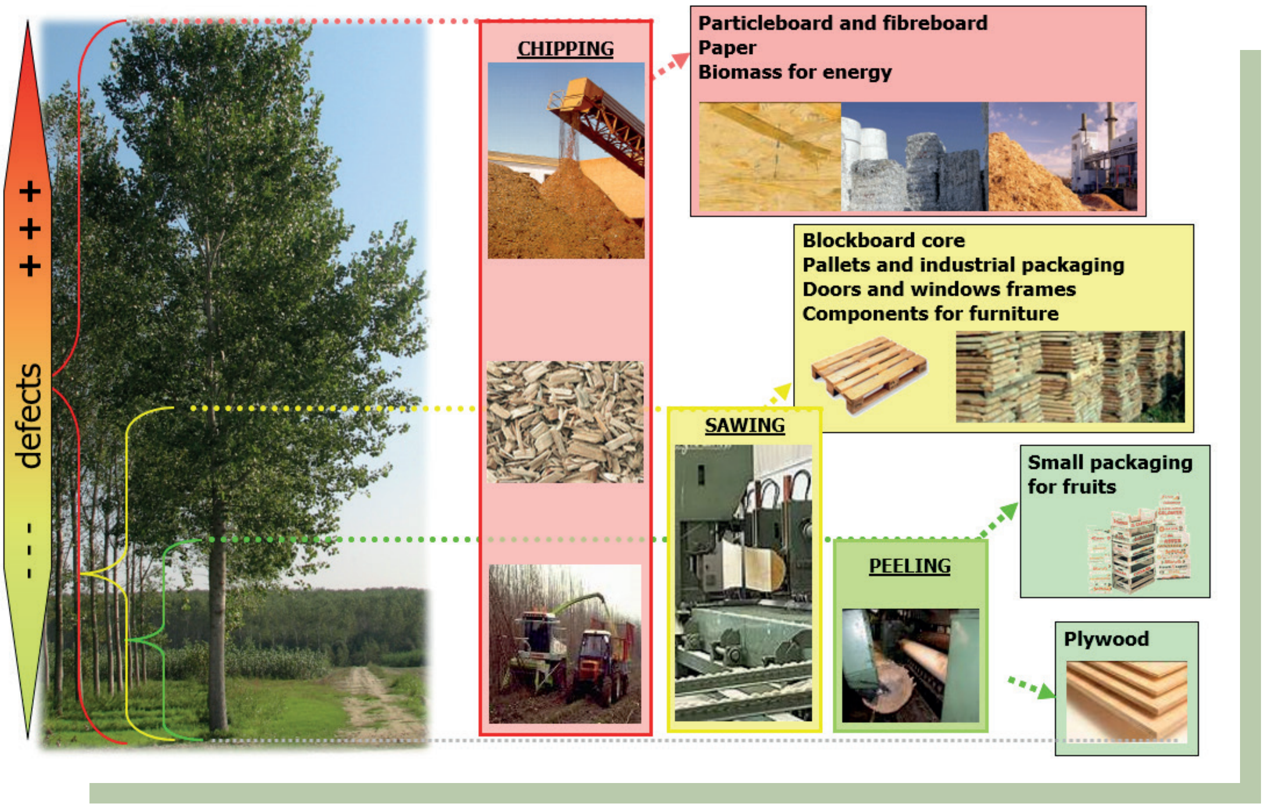
Such schemes can also serve to guarantee the legal origin of the raw materials; a certified chain of custody can increase the value or marketability of the final products.

The production of timber assortments requires particular attention to plantation management to meet specific dimensional, shape and quality requirements. Such requirements often involve the need for adequate practices during cultivation, like early pruning. In contrast, when the wood is intended to be shredded, the main objective is to produce as much biomass as possible by optimizing the interactions between the species used, the treatments carried out and site characteristics.

Take-home messages

- Plantations with FGT species produce many raw materials, such as wood, fibre and biomass, demand for which is expected to grow further.
- The production of timber assortments from FGTs requires particular attention to plantation management to meet specific dimensional, shape and quality requirements, which depend on the end use.

Figure 5. Diagram of the common uses for different poplar tree portions, with reference to the integrated structure of the forestry wood industry chain



Source: Adapted from **Castro, G. & Zanuttini, R.** 2008. Poplar cultivation in Italy: history, state of the art, perspectives. *Proceedings of the IPC Working Party on Harvesting and Utilisation of Poplar and Willow Wood Conference: "Engineered Wood Products Based on Poplar/Willow Wood"*. 21–24 October 2008, Nanjing, China.

Case study 13

INDUSTRIAL WOOD PRODUCTION

Marton Nemeth

Hungary has a wide range of low-quality, sandy sites with limited agricultural uses. Establishing cultivated *Robinia pseudoacacia* L. forests to utilize these areas is very common. However, commonly used *R. pseudoacacia* systems must evolve into plantation-based systems to address current factors, including accelerated social and economic development, increasing awareness of environmental issues and low rates of industrial wood production. Efforts to address these issues, including through research and development, began decades ago. The introduction of fast- and straight-growing varieties of *R. pseudoacacia*, such as 'Turbo Obelisk', already in production by Silvanus Forestry, can help solve complex issues in terms of cost-effective production, rural development and environmental protection. It can increase the production of industrial wood, especially sawlogs. The short and intense cultivation period of *R. pseudoacacia* is also favourable for carbon sequestration. Further, *R. pseudoacacia* varieties can enrich the range of plantations options in temperate and subtropical zones due to their high tolerance for low-quality, marginal soils and low precipitation. Another important aspect of *Robinia pseudoacacia* is the nitrogen-fixing bacteria on its roots, which produce more nitrogen than used by the tree itself, hence increasing soil quality and creating an opportunity for use of the tree for intercropping, and eventually making the sites suitable for agricultural production again in the future.

Case study 14

"UNDER-THE-RADAR" TIMBER PRODUCED BY SMALLHOLDERS IN THE ECUADOREAN AMAZON

Adapted from: Erazo *et al*., 2013

In rural Amazonia, local people produce and market many types of timber for a variety of uses. This wood is in high demand globally, with much of it coming from slow-growing trees in natural forests. However, this is increasingly out of the reach of local residents, and local demand has led to a growing market for faster-growing, lower-quality timbers, known as "under-the-radar" timbers. The demand for these products allows the rural poor to generate income from these niches, often in ways that are well adapted to their customary livelihoods. This is the case with production and marketing of pigüe (*Piptocoma discolor* [Kunth] Pruski), a fast-growing softwood species native to Amazonia and Central America used extensively in the Ecuadorian Amazon to make pallets and small crates for the transport of fruit. Pigüe is produced by farming communities of ethnic Kichwa through management of fallows, where it regenerates naturally. Logs are harvested and sold roadside to small local, low-tech pallet mills, depending on household needs (e.g. health emergencies or special events requiring cash). In the month of the harvest, a typical producer family can earn an extra two-thirds of their monthly income from pigüe. The activity falls under a special provision of the national forest management system, whereby no forest management plan is required (since pigüe is produced on agricultural fallows on collective farming land rather than in a managed forest), but there is a permit system for harvesting and transport, which requires registering, georeferencing and zoning of the production area, and a legal land title. This aspect is a serious challenge for the formal implementation of pigüe conservation as most farmers operate informally because of the high costs of compliance. A less onerous regulation of the trade would be beneficial. Because the processing of pigüe is part of the subsistence system of economically vulnerable people, the related taxes and licensing should be reviewed and potentially eliminated as part of a poverty alleviation agenda. Furthermore, the pigüe value chain could be supported through a rural assistance programme providing subsidies or microcredit to producers, allowing more families to use their own labour to harvest and transport logs to the nearest road accessed by buyers.

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Industry, technology and transformation

The wood industry has long shown a great interest in fast-growing tree (FGT) plantations and is closely monitoring their expansion worldwide as an important source of raw materials for primary processing. The technologies currently available in the wood industry for sawing, peeling, slicing, chipping and defibration allow the manufacture of a wide range of semi-finished and finished products in solid wood, or reconstituted from smaller wood components (from sheets to particles) or fibres through drying, gluing and pressing, or extrusion.

The development of new adhesives and glue-lamination technology have made it possible to overcome the dimensional and behavioural limitations inherent to solid wood, paving the way for new structural applications and allowing modern wood materials to acquire a level of reliability in design and use comparable to materials traditionally used in the building and construction sector.

Engineered wood products (EWPs) such as glued laminated timber (glulam) (De Boever and Van Acker, 2008), cross-laminated timber (CLT), veneer-based panels like plywood and laminated veneer lumber (LVL) (Baldassino *et al.*, 1996), and oriented strand board (OSB) (Cetera *et al.*, 2018) are available for large-scale use in structural and functional applications in full compliance with current standards and rules (Negro *et al.*, 2017). Cross-laminated timber is one of the most referred-to innovations in the last decade because it enables the construction of high-rise, multistorey timber frame buildings while meeting fire-safety and energy-efficiency requirements.

Wood and wood-based products are valued not only because they are able to meet technological performance requirements but also for their environmental merits. Modern EWPs suitable for wood construction are key for developing sustainable green building strategies over the coming decades. In this context, raw materials can also come from plantations based on fast-growing hardwood species (Van Acker, Defoirdt and Van den Bulcke, 2016).

Fast-growing tree plantations can also provide the resources needed for biorefineries, as well as innovations such as nanocellulose and translucent wood. Technological innovations such as the development of wood modification processes (physical and chemical) broaden the range of wood-based products that meet specific requirements, such as vacuum thermal treatment of poplar veneers to produce plywood panels with reduced hygroscopicity and improved durability and dimensional stability (Sandak *et al.*, 2016; Zanuttini *et al.*, 2019).

Engineered wood products for high-value building applications, both for new construction and renovation, can promote a new generation of zero-waste, low-carbon building systems based on products specifically designed to optimize mechanical performance, fire safety, thermal insulation, service life and seismic behaviour (Goli *et al.*, 2015; Li *et al.*, 2016). Engineered wood products can thus help meet the demand for new and sustainable construction products that address the performance and sustainability challenges of modern society (Castro and Paganini, 2003; Van Acker *et al.*, 2003). The raw materials from FGT plantations could provide products complementary to traditional softwood-based products, with the added benefit of being locally produced and transported over shorter distances (De Boever *et al.*, 2008; De Windt *et al.*, 2018).

Wood is a renewable resource provided that the forests from which it is sourced are managed sustainably. Plantation-based EWPs increase the availability of materials for construction in a strategic interaction with the agriculture sector and therefore offer strong potential as a flexible and sustainable resource.

By providing a range of products for the building and bioenergy industries, a sustainable and zero-waste wood industry chain allows the use of high-quality trees or logs for high-value applications such as in construction, as well as the optimized use of various grades of wood for different purposes, including residual and end-of-life products for pulping and bioenergy.

In the past, most of the timber produced in FGT plantations was considered low quality and suitable only for pulp or bioenergy. However, established, specialized industries using poplar (*Populus* L.) in North America and Europe show that EWPs made with these species have good mechanical features and exhibit suitable performance. Figure 5 illustrates the potential to progress from current poplar-based products to a range of complementary EWPs suitable for biobased green building.

From today's reliance principally on softwood production, there is a clear need to involve hardwoods in the value chain for building with timber. Given the increasing demand for wood raw materials in the emerging bioeconomy, fast-growing hardwood plantations have strong potential to further increase and complement regional productions from forests.

Increasing the use of wood from FGT plantations in the building sector will underpin sustainability and environmental objectives related to greenhouse-gas emissions. Fast-growing tree plantations can also improve the vertical integration between cultivation and the wood industry as part of the transition to a bioeconomy. This is particularly relevant for rural communities in countries with low wood production. In this context, the sustainable and positive environmental impacts of wood from plantations are achievable through various cultivation schemes.

Sustainably managed FGT plantations contribute to the economy, society and the environment. This potential is maximized through the manufacture of high-value, high-performing EWPs for the construction sector. Combining traditional products from FGTs with innovation in several sectors linked to biorefineries and EWPs will create many opportunities for the future.

Take-home messages

- Through adequate processing technologies, high-value, performance-engineered products can be manufactured with wood from FGT plantations.
- The raw materials from FGT plantations could provide products complementary to traditional softwood-based products, with the added benefit of being locally produced and transported over shorter distances.

Figure 6. Potential for producing engineered wood products from poplar to complement current poplar-based products in biobased green buildings

Note: OSB: oriented strand board; CLT: cross laminated timber; LVL: laminated veneer lumber.

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5.3 Bioenergy

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Summary

In recent decades, fast-growing tree (FGT) plantations have frequently been established as energy crops to decrease fossil-fuel use in developed countries or to slow deforestation processes in tropical and subtropical areas while maintaining the livelihoods of local communities. In Europe, the most widely used cultivation system to produce lignocellulosic biomass is the short-rotation coppice (SRC) system, while, in Latin America, plantations established for energy purposes are short-rotation woody crops (SRWCs). Commonly cultivated tree species are poplars (*Populus* L.), willows (*Salix* L.) and black locust (*Robinia pseudoacacia* L.) in temperate regions and eucalypts (*Eucalyptus* L'Hér), acacias (*Acacia* Mill.), casuarinas (*Casuarina* L.) and gamhar (*Gmelina arborea* Roxb.) in the tropics and subtropics. To reduce competition between bioenergy plantations and food production systems, bioenergy plantations can be intercropped with traditional agricultural crops on fertile soils, or they can be established on marginal lands with low nutrient content. Therefore, recent research has focused on the associations between energy woody crops and cereals or other agricultural crops, the inclusion of nitrogen-fixing tree species in energy plantations; and the identification of microbial communities capable of improving plant resistance to abiotic stresses such as limited nutrients and drought. These studies may enhance the sustainability of bioenergy plantations.

Keywords: Bioenergy plantations; short-rotation coppice; short-rotation woody crops; woody biomass; plant microbiome; marginal lands

Introduction

Bioenergy and biomass plantations with FGT species have gained importance during the last four decades. In developed countries, this growing interest is in the context of mitigating climate change: specifically, using alternative energies (such as biomass and bioenergy from FGT plantations) to reduce greenhouse-gas emissions. In developing countries, bioenergy plantations are viewed from the perspective of producing woodfuel to halt deforestation and improve local people's livelihoods. Wood (including charcoal) from natural forests is commonly used for heating and cooking by significant parts of the population in developing countries. The use of woodfuel in developed countries can be common in rural areas, and most woody biomass is harvested according to sustainable criteria. The main issues presented in this section concern bioenergy plantations with FGTs, their applications and limits in temperate, tropical and subtropical areas, along with the recent research results on the plant microbiome, FGT nutrition and FGT adaptation to abiotic stress.

Overview of bioenergy plantations

Today, FGT plantations are frequently dedicated to the production of woody biomass to be used as a raw material for the development of thermal and electrical energy or the production of biofuels using highly efficient, industrial processes (Szostak and Bidzińska, 2013). Bioenergy is thus considered the only renewable energy source that could potentially replace fossil fuels in all energy markets for the production of heat, electricity, and fuels for transport (Bauent *et al*., 2009), thus making a significant contribution to reducing the impacts from climate change.

The species used in bioenergy plantations differ in relation to bioclimatic areas. For example, poplars (*Populus* spp.), willows (*Salix* spp.) and black locust (*Robinia pseudoacacia* L.) are commonly used in temperate regions, while casuarinas (*Casuarina* spp.), acacias (*Acacia* spp.) and eucalypts (*Eucalyptus* spp.) are suitable for tropical and subtropical areas. Establishment and maintenance techniques also differ in relation to site conditions and species. In Europe, the most widely used cultivation system for producing lignocellulosic biomass is short-rotation coppice (SRC) (Rödl, 2017). These are plantations of poplars, willows, black locust or other FGTs with high re-sprouting ability that are established at high planting densities and harvested every 2–7 years. Harvests can be repeated for three to four rotations before renewing the plantation. In this context, two cultivation methods are used (Rödl, 2017): (1) very high-density plantations ranging from 5 000 to 15 000 trees per ha with 2- to 3-year cutting cycles; and (2) high-density plantations ranging from 1 500 to 2 000 trees/ha with 5- to 7-year cutting cycles. The very-high-density plantations supply wood chips for energy conversion, while the high-density plantations supply wood chips and other feedstocks for the packaging industry at the end of the first rotation (Facciotto *et al*., 2020). Therefore, the latter system can be more advantageous than the former, allowing for the obtainment of a wider range of wood products. In Europe, SRC plantations cover a total estimated area of 50 000–70 000 ha (Weitz, 2014).

Breeding programmes for SRC genotypes have selected numerous cultivars of hybrid poplars and willows, along with some clones of black locust in several European countries, including Czechia, Germany, Hungary, Italy, Spain and Sweden (Rödl, 2017). Therefore, many genotypes are available for specific site conditions. Biomass yields are extremely variable, between 1 million and 24 million grams (Mg) of dry matter (DM)/ha annually, with an average annual production of 9.5 Mg DM/ha (Njakou Djomo *et al*., 2015). Productivity is sensitive to species, clones and their responses to specific site conditions, as well as to silvicultural prescriptions and cultural inputs. Therefore, yields in commercial plantations are much lower than expected, with potential negative consequences for the financial profitability of these woody crops (Hauk, Knoke and Wittkopf, 2014). Irrigation is a limiting factor for SRC productivity in many areas of southern Europe (Paris *et al*., 2018). Additionally, frequent harvests often impact soil fertility, with high amounts of soil nutrients taken up and removed with the harvested woody biomass, which is composed of small-diameter stems that are relatively rich in nutrients (Paris *et al*., 2015). Biomass quality for combustion in modern combustion systems can also be negatively affected by excessive bark percentages (Hytönen, Beuker and Viherä-Aarnio, 2018). Therefore, innovations in SRC in Europe mainly focus on cultivation systems with lower planting densities and longer rotation cycles. In addition, this approach has positive consequences for the full environmental impact of SRC, with low requirements for cultivation and chemical inputs for fertilization and pest control (Gonzalez *et al*., 2012; Facciotto *et al.*, 2020).

Species such as black locust that fix nitrogen (N) are another innovation of SRC. Unfortunately, in many European contexts, this species is almost neglected as an alien and invasive species (Nicolescu *et al*., 2020). Additional N-fixing species are alders (*Alnus* Mill.), which have mostly been studied in northern Europe (Aosaar, Varik and Uri, 2012). For southern Europe, Italian alder (*Alnus cordata* Loisel.), the endemic species of southern Italy and Corsica, might have interesting applications for bioenergy plantations and requires further investigation. In order to reduce the potential impact of SRC on food security, research has also addressed intercropping strips or rows of coppiced trees with crops in the alleys between the trees. This system has been named coppice alley cropping (Kanzler *et al*., 2019). Another integrative system is the intercropping of timber trees with SRC, combining timber and bioenergy production (Morhart *et al*., 2014). Mixed bioenergy and timber plantations are being studied in Canada and Italy (Coaloa *et al*., 2020; Paquette and Messier, 2010).

In tropical climates, bioenergy plantations already constitute significant shares of global energy use but may become an even more important source of renewable energy in the near future. The current status of bioenergy plantations in Latin America and the Caribbean (LAC), Asia and Africa is assessed in this section.

Globally, annual woodfuel consumption is 1.87 billion cubic metres (m^3). Of this amount, 13 percent is consumed in the tropical and subtropical regions of America and the Caribbean, 30 percent in Africa, and 30 percent in Asia and the Pacific region (FAO, 2011; Seifert *et al*., 2014). While woodfuel production in developing countries is still heavily dominated by natural or semi-natural forests (FAO, 2001), initial afforestation programmes for that purpose began in the middle of the last century and mainly took place in tropical and subtropical countries (Evans, 1997). In recent decades, these kinds of plantations have become more popular in temperate regions, resulting in a greater current proportion in these regions. In the tropical regions, there is growing recognition that bioenergy plantations with woody species can be an important means of providing energy. However, enthusiasm for establishing such plantations has decreased as potential competition for land with agriculture has challenged the security of sustainable food supplies for growing populations in many tropical countries, along with questions concerning environmental and social sustainability (Maltsoglu, Koizumi and Felix, 2013; Ham and Kleynhans, 2014). There is mounting evidence that an expanding bioenergy sector would interact with other land uses, such as food production and also impact biodiversity, soil and nature conservation and community well-being (Berndes, Hoogwijk and van den Broek, 2003). This has led to great potential for using FGTs and grasses (e.g. acacias, eucalypts, poplars, willows and *Miscanthus* Andersson and *Panicum* L.) as energy crops because these do not directly compete with food production systems (Beringer, Lucht and Schaphoff, 2011).

In LAC countries, tree plantations cover an area of more than 21 million ha (FAO, 2020), and the proportion of introduced species varies greatly among countries. In South America, 97 percent of plantation forests consist of introduced species, whereas in the Caribbean and Central America, this share is much lower (32 percent and 18 percent, respectively) (FAO, 2020). The greatest share of tree plantations was established for fibre rather than energy, but precise statistics are not readily available. In 1965, Brazil started a massive reforestation effort including SRWC plantations (Betters, Wright and Couto, 1991) that were often used as feedstocks for charcoal production for industrial purposes. In the state of Minas Gerais, it was reported that several private companies have 150 000–200 000 ha of eucalypt plantations each, also being grown for charcoal production (Turnbull, 1999). On a broader scale, the Brazilian example has been an exception; only 50 percent of the LAC countries have established plantations based on SRWCs (Moya, Tenorio and Oporto, 2019). While a wide range of around 50 species are used in Latin America for SRWCs, the most important are poplars, willows, eucalypts, acacias and *Gmelina* (*Gmelina arborea* Roxb.), which, due to the tropical climate, can achieve high annual yields of 10–20 Mg DM/ha (Moya, Tenorio and Oporto, 2019; Tonini *et al*., 2018).

Asia has approximately 80 million ha of plantation forest, with 32 percent of this total consisting of introduced species (FAO, 2020). The annual rate of gain in the area of plantation forests has declined from 1.26 million ha/year (1990 to 2000) to 735 000 ha/year (2010 to 2020) (FAO 2020). From 1990 to 2020, the average annual woody biomass production in Southeast Asian forests was estimated to be about 563.4 million tonnes/year, decreasing at a rate of about 1.5 percent/year over the same period (Sasaki *et al*., 2009). While the use and trade of solid biomass for modern bioenergy has grown rapidly in Asia (Junginger, Koppejan and Goh, 2020), the share of bioenergy plantations is still low. This is partially due to the region's agriculture-based economy and the fact that most Southeast Asian countries have an abundance of biomass sources for the energy sector (Tun *et al*., 2019). An increasing share of liquid-biofuel plantations has been observed during the past decades with *Jatropha* plantations. According to Brittaine and Lutaladio (2010), Asian countries harboured more than 85 percent of the global 900 000 ha of *Jatropha* plantings, with a focus on Myanmar, India, China and Indonesia.

Africa has close to 637 million ha of forests, but the continent also currently faces the highest rate of forest degradation and loss globally (FAO, 2020). In many African countries, there is a direct correlation between forest loss and population growth (Seifert *et al*., 2014). Biomass is Africa's primary energy source, with more than two-thirds of all Africans relying on woodfuel for their primary supply (Maishanu, Sambo and Garba, 2019). Charcoal and solid fuelwood are typically sourced from natural forests, savannahs and woodlands (Chirwa, Syampungani and Geldenhuys, 2014). Bioenergy constitutes a substantial source of income and is a significant contributor to local economies (Ham and Kleynhans, 2014). Commercial forest plantations, often established by international investors, typically consist of exotic genera such as *Pinus* L., *Eucalyptus* and Australian *Acacia* in the subtropical regions, along with *Hevea* Aubl., *Tectona* L. f., *Terminalia* L. and *Gmelina* L. in the humid tropical regions. These commercial plantations have been established in several African countries, covering more than 13 million ha (FAO, 2006; Jacovelli, 2014). However, such plantations are typically managed intensively for timber, pole and fibre production and provide energy only as a by-product (du Toit, 2014). Nevertheless, they contribute significantly to the local woodfuel supply (Mensah *et al*., 2017). Dedicated bioenergy plantations are found in lower-rainfall countries such as Ethiopia and South Africa, where drought-resistant *Eucalyptus*, *Acacia* and *Casuarina* have been used, typically in smaller woodlots at the farm level to provide a local energy source (du Toit *et al*., 2017). Some of those species show remarkable biomass production considering the limited water resources available (Phiri *et al*., 2015; du Toit *et al*., 2017). Further, plantations for liquid biofuels such as *Jatropha* are playing an increasing role. Africa has about 120 000 ha of *Jatropha*, which is 12 percent of the global plantation area (Brittaine and Lutaladio, 2010). Another considerable source of bioenergy is provided by bush encroachment and invasive tree species that were originally introduced for dune stabilization in countries such as Ethiopia, Namibia and South Africa (Stafford *et al*., 2017). At the same time, land degradation of ecosystems originally dominated by trees is prevalent. Generally, bioenergy plantations would be most suitable on degraded land as a means for converting these areas back to productive land, rather than competing for fertile land with agriculture or commercial timber and fibre production.

Harnessing the power of the plant microbiome to increase environmental sustainability of bioenergy crop production

Bioenergy production will increasingly rely on marginal lands with limited available nutrients to minimize impacts on agricultural systems (Farrar, Bryant and Cope-Selby, 2014; Quinn *et al.*, 2015; Taylor *et al.*, 2019). Nitrogen is often the most limiting macronutrient, leading to a dependence on N fertilization to maximize yields, which both adds cost and is environmentally unsustainable. The widespread use of chemical fertilizers, primarily in agriculture, has had negative impacts on the environment, including eutrophication of waterways and increased levels of atmospheric ammonia and nitrous oxide (Aneja *et al.*, 2008; Olivares, Bedmar and Sanjuán, 2013; Seitzinger and Phillips, 2017). Because the production of N fertilizer requires fossil fuels, life-cycle assessments (LCAs) of biomass production are negatively impacted when chemical fertilizers are required. The use of freshwater in biomass production is another challenge in the effort to make biomass production more sustainable (Sevigne *et al.*, 2011; Vásquez, Milota and Sinha, 2017; Teter *et al.*, 2018). A promising strategy for improving plant production and tolerance to stress is to take advantage of the natural plant–microbe partnerships that develop in challenging environments. The plant microbiome, including microbial endophytes and epiphytes – the microorganisms living within and on the surface of plants, respectively – has a profound influence on the productivity and resilience of the host plant. Current research aims to guide construction of microbial communities that can improve the abilities of plants to endure abiotic stresses, including limited nutrients and drought stress, enhancing the environmental sustainability of bioenergy crops.

Leguminous plants are known to have highly efficient symbioses with N-fixing (diazotrophic) rhizobia, but some non-nodulating plant species are also able to colonize low-nutrient sites through close association with a variety of diazotrophic bacteria. Associative N fixation by endophytes and by other closely associated bacteria can provide significant amounts of N to non-leguminous plant species (reviewed in Carvalho *et al.*, 2014; Doty, 2017). In sugar cane (*Saccharum officinarum* L.), for example, the total N harvested from aboveground biomass exceeds the N fertilizer inputs without depletion of soil N (Boddey *et al.*, 2003). Using the ^{15}N dilution technique or natural ^{15}N abundance, studies showed that 50–80 percent of the N in Brazilian sugar cane could be attributed to biological N fixation (BNF) (Lima, Boddey and Döbereiner, 1987; Boddey *et al.*, 1991, 1995; Urquiga, Cruz and Boddey, 1992; Boddey, 1995). N fixation was also demonstrated in *Miscanthus* (Davis *et al.*, 2010; Keymer and Kent, 2014), poplar (Doty *et al.*, 2016) and switchgrass (*Panicum virgatum* L.) (Davis *et al.*, 2010; Roley *et al.*, 2018, 2019), often at highly variable levels. Some of the diazotrophic bacteria could be cultured and added to other plants, providing significant levels of BNF in non-leguminous plants (Boddey, 1995; Reinhold-Hurek and Hurek, 1998; Boddey *et al.*, 2001; Döbereiner, 1997; de Morais *et al.*, 2012; Urquiaga *et al.*, 2012). Studies using stable isotopes, nitrogenase mutants, total N accumulation and growth promotion in nutrient-limited conditions all demonstrated strong evidence for N fixation of specific diazotrophic strains in sugar cane (Boddey *et al.*, 1995; Sevilla *et al.*, 2001), kallar grass (*Leptochloa fusca* L.) (Hurek *et al.*, 2002), wheat (*Triticum aestivum* L.) (Iniguez, Dong and Triplett, 2004), rice (*Oryza sativa* L.) (Elbeltagy *et al.*, 2001), *Setaria* P.Beauv. (Pankievicz *et al.*, 2015) and corn (*Zea mays* L.) (Van Deynze *et al.*, 2018). Poplar and willow of the *Salicaceae* family are both feedstocks for bioenergy production (Hinchee *et al.*, 2009; Porth and El-

Kassaby, 2015). In these and other bioenergy crops, addition of diazotrophic endophytes increased growth promotion with reduced fertilizer needs (thus improving N-use efficiency) in switchgrass (Lowman *et at.*, 2016) and poplar (Knoth *et al.*, 2014). While the contributions of BNF are clear, there are also cases where there was no apparent contribution through BNF and no response to inoculation with diazotrophs (Dobbelaere, Vanderleyden and Okon, 2003; Pankievicz *et al.*, 2015; do Amaral *et al.*, 2016). The underlying mechanisms for effective mutualisms for BNF are yet to be elucidated and are the subject of current research.

The plant microbiome has been found to adapt rapidly to alleviate host stresses (Timm *et al.*, 2018; Xu *et al.*, 2018; Cheng, Zhang and He, 2019; Hartman and Tringe, 2019; Jones *et al.*, 2019; Xu and Coleman-Derr, 2019; Gao *et al.*, 2020). Meta-analyses of hundreds of experiments have indicated that microbes can significantly ameliorate the impacts of plant stress (Rho *et al.*, 2018a; Porter *et al.*, 2020). Utilizing symbiosis with microorganisms could thus potentially allow plants to overcome the challenges faced on suboptimal sites (Rodriguez and Redman, 2008; Ryan *et al.*, 2008; Yang, Kloepper and Ryu, 2009; Mei and Flinn, 2010; Berendsen, Pieterse and Bakker, 2012; Lau and Lennon, 2012; Coleman-Derr and Tringe, 2014; Farrar, Bryant and Cope-Selby, 2014; Busby *et al.*, 2017; Meena *et al.*, 2017). The microbial strains most effective as bio-inoculants under these conditions can be found by tapping into what nature has already achieved through natural selection in wild plants thriving in challenging environments (Rodriguez *et al.*, 2008; Pérez-Jaramillo *et al.*, 2018).

Poplar and willow species occupy a challenging ecological niche by colonizing new land following riparian flooding that deposits cobble, sand and sediment (Stettler *et al.*, 1996; Stettler, 2015). For example, in the pristine riparian settings in the Cascade Mountain Range of Washington State, United States of America, the rivers are fed by high alpine snow melt, and the coarse river beds can be extremely N-poor, with no soil and limited organic matter. In these native habitats, poplar and willow have a diverse microbiome that provides services such as fixation of dinitrogen gas (Doty *et al.*, 2016), phosphate solubilization (Varga *et al.*, 2020), and promotion of overall plant growth and health, especially under nutrient-limited conditions (Xin *et al.*, 2009; Khan *et al.*, 2012; Knoth *et al.*, 2014). There is great potential for improving the sustainability of biomass production with reduced inputs of fertilizers for enhanced N use efficiency by utilizing N-fixing endophytes.

Drought stress, in particular, has a strong influence on plant microbiome assembly (Naylor *et al.*, 2017; Santos-Medellín *et al.*, 2017; Fitzpatrick *et al.*, 2018; Naylor and Coleman-Derr, 2018; Timm *et al.*, 2018; Xu *et al.*, 2018; Hartman and Tringe, 2019). The composition of the root exudate changes in response to drought conditions (de Vries *et al.*, 2019), impacting the microbiome. In some plant species, carbon exudation is equal to or even increased above normal levels under drought (Henry *et al.*, 2007; Preece *et al.*, 2018), despite reduced photosynthesis due to stomatal closure (Karst *et al.*, 2016; Karlowsky *et al.*, 2018; Timm *et al.*, 2018). It has therefore been argued that root exudates have a central involvement in plant response to drought (Williams and de Vries, 2020). Only a small number of beneficial plant microbial interactions are well characterized and exploited in agriculture; therefore, these microorganisms are a relatively untapped resource (Farrar, Bryant and Cope-Selby, 2014; Seshadri, 2020). In challenging environments, the microorganisms associated with wild plants have already been shaped over time by natural selection, and therefore the microbial strains most effective as bio-inoculants are best found by tapping into existing wild plant microbiomes (Rodriguez *et al.*, 2008; Pérez-Jaramillo *et al.*, 2018). Endophytes of wild poplar and willow promoted drought tolerance in greenhouse experiments with poplar (Khan *et al.*, 2016) and conifers (Aghai *et al.*, 2019). Studies with rice have demonstrated that the endophytes have profound effects on host-plant water relations in that they improve water-use efficiency (WUE) through stomatal conductance and number and alleviate the impact of water stress through physiological adjustments such as leaf abscisic acid (ABA) levels (Rho *et al.*, 2018b). Addition of the endophytes to rice appeared to eliminate the down-regulation of photosynthesis under high carbon dioxide (CO_2) concentrations (Rho, Doty and Kim, 2020). Stomatal conductance of rice plants was modulated to increase intrinsic WUE in response to inoculation by diazotrophic bacteria both in ambient and elevated CO_2 conditions (Rho *et al.*, 2018b).

As the power of the microbiome to impact host-plant productivity and development is becoming clearer, there is a shift in our understanding, recognizing that plants exist not as individuals but rather in communities with microorganisms, forming holosymbionts that together can survive environmental challenges (Coleman-Derr and Tringe, 2014). The emerging view of the plant as a "holobiont" recognizes the interdependence of the plant and its microbiome, including bacteria, fungi and viruses (recently reviewed in Sánchez-Cañizares *et al.*, 2017). By tapping into this natural resource, the plant microbiome can be utilized in bioenergy plantations to reduce fertilizer and water requirements, thereby improving the environmental sustainability of bioenergy production.

Conclusion

Fast-growing trees represent a resource for the establishment of bioenergy plantations in temperate, tropical and subtropical regions. Further, FGTs can provide woodfuel for industrial purposes and for meeting the needs of local communities in a relatively short space of time. The major obstacle for energy plantations is their competition with agricultural food systems on fertile lands. This challenge can be overcome by the association of energy plantations with agricultural crops in agroforestry systems or by growing energy crops on less fertile marginal lands. The latter choice requires cultivation strategies that aim to make FGT species more resistant to nutrient and drought stresses. Recently, researchers have demonstrated the role of the plant microbiome in alleviating host stresses, thus enhancing the prospect of interesting applications for FGT cultivation in less-fertile soils.

Take-home messages

- Fast-growing trees can provide considerable amounts of woodfuel in relatively short times when cultivated in bioenergy crop systems.
- Appropriate strategies are being perfected to avoid competition between FGT energy plantations and agricultural food systems.

Case study 15

MULTICLONAL FIELD TRIALS AND NURSERY SCREENING TO IDENTIFY FAVOURABLE GENOTYPES OF BIOENERGY TREES

Nataliia Kutsokon

In many countries, there is great interest in short-rotation forestry (SRF) based on fast-growing bioenergy trees, such as poplars (*Populus* L.) and willows (*Salix* L.), but it is still poorly implemented in Ukraine. During the 1950s–1970s, many prospective poplar and willow cultivars were obtained by Ukrainian breeders to meet the needs of conventional forestry for the timber and paper pulp industries. To identify the most promising clones for bioenergy production, two plantings of FGTs were established as part of a collaboration of research institutions, including the Institute of Cell Biology and Genetic Engineering NAS of Ukraine. The first plot, containing clonal field trials with ten poplar and three willow clones, was established at the Kharkiv Forestry Research Station of the Ukrainian Research Institute of Forestry and Forest Melioration. This research plantation also serves as a demonstration site for local farmers and foresters. The second planting, containing an FGT nursery of 19 poplar and ten willow clones, was established on the plot for bioenergy plants at the National Botanical Garden NAS of Ukraine in Kyiv. As it is located in an urban botanical garden, the nursery serves to demonstrate a bioenergy tree plantation for visitors, in addition to serving as an experimental plot and providing stock for collection. In both the field trials and the nursery screening, clones were characterized by their growth and biofuel performance. Based on the measurements performed, several poplar and willow clones were found to have promising performance while others are not recommended for biomass production in short-rotation plantations. This is the first time that such multiclonal screening of bioenergy trees for planting in short rotations was described in Ukraine. The results obtained may be useful to farmers and foresters by providing recommendations on planting methods, management and clonal assortment. Growing trees are also serving as living stock for cultivar propagation and preservation.

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5.4 The circular economy and opportunities for small and medium-sized enterprises

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Summary

The world's current economic system has contributed to growth in economic output, wealth creation and improved human welfare. However, it has also exacerbated social inequalities and loss of natural resources to the point that resource limitation is today the biggest constraint on economic development. With an increasing need for circularity and improving the carbon storage capacity of all materials, business opportunities for small and medium-sized enterprises (SMEs) involved in making this a reality are flourishing. In developed countries, small businesses are focusing on value-added products and are usually formalized as legal entities, which entails a series of benefits for the entrepreneurs. On the other hand, this is not the case in less-developed countries. This section presents several success stories that demonstrate the possibilities for diversifying and re-purposing main and sidestream products from fast-growing trees (FGTs) to increase SME incomes.

Keywords: Circularity; bioeconomy; smallholders; small and medium-sized enterprises

Introduction

The world's current economic system has contributed to growth in economic output and wealth creation and improved human welfare. However, it has also exacerbated social inequalities and the loss of natural resources to the point that resource limitation is the biggest constraint on economic development. Limited resource availability intensifies inequalities among, and more critically, within countries, and among regions, and this is worsened by the effects of climate change (Islam and Winkel, 2017). The adoption of fair, inclusive, rapid and resilient solutions to these challenges, and the facilitation of progress and collective cooperation on these global challenges, are of paramount importance.

In recent years, one of the most popular solutions for addressing climate change and contributing to sustainable economic development has been to increase the total number of existing trees, even though planting trees will never be a substitute for reducing fossil-fuel emissions (Marland and Marland, 1992; Brown *et al*., 1996; Krause, Knoke and Rammig, 2020). Though reforestation has become one of the most popular climate-mitigation tools, many factors need to be considered to make the most of this option. In this regard, FGT species have been gaining significant recognition for their role in combating climate change as they provide timber relatively quickly with few inputs, integrate well with agricultural crops and fix carbon dioxide (CO_2) within their biomass. However, their popularity has not come without raising controversies in public opinion, especially regarding the potential negative effects of excessive and poorly thought-out planting of trees on delicate ecosystems in terms of biodiversity and land-use change (Cossalter and Pye-Smith, 2003).

Fast-growing trees represent a versatile source of raw materials suitable for diverse industries (Lee, Lee and Lee, 2021). They can be used to produce posts and fence panels – depending on the species and the age at which they are harvested – rubber, building insulation and fillers for securing transport of fragile goods. They are also able to provide good-quality biomass for energy conversion, with a typical calorific value of around 4.5 kilocalories per gram (kcal/g) within 2–5 years. With the increasing need for circularity and improving carbon storage capacity for all materials, business opportunities are flourishing for SMEs involved in making this a reality.

In developed countries, small businesses in the FGT sector are focusing on products with higher added value, such as packaging, textiles, composite materials, cosmetics and pharmaceuticals; generally, they are formalized as legal entities, which provides a series of benefits for the entrepreneurs. However, in less-developed countries, the situation is quite different. For instance, in several countries of the Association of South East Asian Nations (ASEAN), SMEs struggle to become formalized due to problems in understanding and meeting regulations, lack of incentives, and limited understanding of the benefits that can be gained by operating as a legal entity (World Bank, 2019). This lack of formalization is limiting opportunities for innovation and, as a consequence, the development of the whole sector (Kirk *et al*., 1997; Díaz *et al*., 2018; Milanesi, Guercini and Tunisini, 2020). The benefits of formalization for local SMEs can be seen in the rubber sector, where improved recognition and networking capacity and cooperation with local research facilities have led to the upgrading of what were low-value products and the replacing of mass exports by large foreign-owned companies (Box 2).

In terms of products, many FGT species are commonly utilized to produce wood-composite materials. Poplar (*Populus* L.), for instance, is a major input for this industry, both for producing wood-composite panels (particle board, fibre board, waferboard, oriented strand board [OSB] and plywood) and structural composite lumber (laminated veneer lumber or LVL, parallel-strand lumber, laminated strand lumber, and composite wood I-beams), leading to a strong industrial sector that contributes to a higher added-value economy.

Fast-growing tree species are also highly suitable for the pulp and paper industry. Most of them have a higher proportion of fibres than other trees and are suitable for producing different fibre-based products depending on fibre length and size. For example, poplar fibres are short with small cells and thus provide suitable raw material for paper production. In past decades, because of the decline of the paper industry, an excess of lower-grade wood has been left unharvested, contributing to the decline of lower-value markets Now, through innovative approaches and re-purposing, the same raw material has become a valuable and more circular alternative for producing packaging fillers (Box 3).

The wide range of secondary products that FGTs provide can broaden the ecosystem of stakeholders that can directly benefit from their innovative potential. Innovation is possible at product as well as process level. Pulp processing, for instance, consists of cooking wood chips under pressure with the addition of several chemicals. This process eliminates lignin from the wood and loosens the wood's cellulose fibres. These fibres are then washed, separated, bleached and dried and can be used as raw material in several industries, thus playing an accelerator role for niche start-ups (Box 4). In addition to the fibres, the lignin itself can be converted into new products, bioenergy, renewable diesel or biochemicals.

Besides their economic value, primary production of FGTs can mitigate and prevent unsustainable resource use and conflicts over resources. For example, FGTs can provide a source of energy (e.g. fuelwood for cooking and heating) in refugee camps to serve the large number of displaced people (Box 5).

Take-home messages

- The business opportunities for SMEs linked to the FGT sector are flourishing as a response to the need for increased circularity and carbon storage capacity of materials.
- Small and medium-sized enterprises involved in the FGT sector development can benefit from formalization and innovation, but challenges exist in less-developed countries, where formalization is limited.

Box 2. SMALL AND MEDIUM-SIZED ENTERPRISES, NATURAL RUBBER AND INFLUENCING FACTORS

Most rubber is produced by smallholders. In some countries, such as China and Thailand, smallholder rubber production has been shown to be a viable, effective way of lifting households and communities out of poverty (Fox and Castella, 2013). In order for smallholders to produce enough rubber, they require support through targeted policies; coordination of their efforts, organization and recognition; and incentives to adopt innovative techniques and technologies to boost yields and production levels. Small-scale rubber farmers can initially feed the high-value niche markets suited to small-scale production, but with targeted support they can gradually transition to targeting the much larger commodity markets, increasing their income by up to ten times per capita (Fu *et al*., 2009). To secure this transition, it is necessary to boost scientific, technological and experience-based knowledge (Joseph, Thapa and Wicken, 2018). The successful development of small-scale rubber farmers into large-scale producers was recently demonstrated in Thailand during the coronavirus outbreak. The pandemic fuelled a global need for rubber gloves. Suppliers increased their production in a sustainable way, securing the raw material before investing in infrastructure and focusing on quality through cooperation with local research institutions.

Greater demand for gloves undoubtedly helped producers cope with the aftermath of the fall of rubber prices in 2015 (ILO ACT/EMP, 2016). Hypo-allergenic alternatives to latex have also been taking a larger share of the market in the past few years, but through transdisciplinary and cross-cutting cooperation, the sector has been able to innovate and diversify its product offering, such as with rubber road barriers and cosmetics, allowing the industry to remain relevant.

Box 3. NATURAL PACKAGING VOID FILLERS

Void fillers protect goods during transport by taking up empty space inside the shipping container. From the 1960s onwards, most of the packaging fillers available were made of polyethylene. In recent years, sustainable materials have been enjoying renewed interest to fulfil this role. Brands are more and more interested in promoting the use of sustainable packaging fillers as part of their sustainability marketing. This trend not only increases sustainability but also creates jobs and helps build local economies and community livelihoods by adding value to existing and unused natural resources. With the decline of the paper industry, FGT species have decreased in value. One option for boosting the profitability of SMEs in this sector would be to promote re-purposing of this raw material by producing wood wool or curls as packaging fillers, thereby increasing circularity.

Box 4. TEXTILES FROM WOOD PULP

In recent decades, the demand for fibre has been growing while cotton availability has decreased. By 2030, about one-third of textile fibres used will have to be cellulosic. Turning wood into soft fibres that can be woven to make fabric is a chemically intensive process. Starting from wood chips, chemicals are used to process the raw material into cellulose pulp, which is further chemically processed, pressed, dried and shredded to produce a dry cellulose compound. This dry cellulose is dissolved to make a solution, transformed into strands, then stretched to produce long, straight fibres. After washing, these fibres are ready to be made into clothes and textiles. Regenerated cellulose fibres are thus not entirely "environmentally friendly". To overcome this issue, a "closed-loop" manufacturing process can be implemented by collecting, recycling and reusing many of the chemicals involved, thus reducing the environmental impact of regenerated cellulose fibres. A recent development in this sector involves the Finnish company Spinnova, which turns microfibrillated cellulose into a fluffy but strong, wool-like material that can be used for textile production. The only by-product is the water vapour released, which is fed back into the process.

Box 5. FAST-GROWING TREES AND DISPLACEMENT SITUATIONS

Refugee camps and displacement settlements are usually in need of substantial amounts of building materials, especially during their establishment but also throughout their use for the maintenance of fencing and buildings. Poles, posts and sawntimber represent the supplies most needed, and they are usually gathered from surrounding areas.

This practice is leading to high levels of environmental degradation and conflict between displaced and local communities. In addition to building materials, a continuous supply of woodfuel is needed for cooking and heating, and this is placing additional pressure on the environment.

Plantations of FGT species established within and around refugee camps can play a pivotal role by providing the needed resources and mitigating conflicts among the displaced communities as well as between these and local ones

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6 Sustainable management of fast-growing trees

6.1 Nursery practices and propagation techniques

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Summary

Nursery technology has evolved as the demand for a wider range of higher-quality, genetically improved plant species has increased. Seed propagation has improved through such practices as seed coating, seed priming and innovations in seed orchard management. Vegetative propagation has advanced with the use of micropropagation to produce large numbers of uniform plants. In addition, changes in the nursery environment influence phenological and morphological targets, condition plants for environmental stresses at the outplanting site, and improve energy, water and other resource efficiencies.

Keywords: Seed coating; seed priming; organogenesis; somatic embryogenesis; culturing practices

Introduction

Although standard nursery propagation techniques are available for most fast-growing tree (FGT) species, these techniques are constantly being refined. Additionally, new techniques are being developed to overcome seed germination and clonal production challenges, produce specific genotypes, and maximize growth and survival after outplanting. This section gives an overview of recent innovations in seed and vegetative propagation techniques as well as advances in nursery culturing practices.

Seed propagation

Seed propagation is not generally considered "innovative", but it continues to be the primary means for plant production around the world. To enhance seedling characteristics, tree breeding programmes and seed orchards are commonly used to produce seeds from preferred genotypes. While seed orchard programmes are not new, greater efficiencies have resulted from high-density or hedged orchards (Kolpak *et al*., 2015) and containerized orchards (Box 6). Not only are orchard trees used for seed production, they also provide cuttings for vegetative propagation and scion for grafting.

Seed coating technology is a relatively new approach for tree seeds that can facilitate sowing, enhance germination and improve seedling establishment of some species (Afzal *et al.*, 2020). Seed coatings often consist of inert matter that serves to pelletize small or irregularly shaped seeds, to make them uniform in size, easier to singulate and flow better through sowing equipment, thereby increasing seed-use efficiency and substantially reducing costs (Shea, 2014). These coatings may also be supplemented with nutrients, pesticides or biostimulants to protect and support growth and survival of germinants. This is an effective technology for some tree species (Shea, 2014) but can lower germination for others (Khadduri, 2007).

Another tool to increase germination percentages is hydro- or thermo-seed-priming, whereby metabolic and biochemical processes are stimulated during hydration–dehydration or temperature cycles (Doody and O'Reilly, 2005; De Atrip, O'Reilly and Bannon, 2007; Becerra-Vázquez *et al.*, 2020). In a study with five spruce (*Picea* A. Dietr.) seed lots, combined effects of moist chilling and thermo-priming significantly increased germination capacity, speed, lag and dormancy index (Liu, Kermode and El-Kassaby, 2013). Applying gibberellic acid to seeds can also be used to help overcome dormancy. Other techniques such as extended stratification, delayed dryback and mid-stratification high-grading are also helpful to increase germination uniformity, speed and percentage (Khadduri, 2021).

Synthetic seeds, while technically a vegetative propagation method, are another promising technique (Reddy, Murthy and Pullaiah, 2012). In a study with *Paulownia elongata* S.Y. Hu, Ipekci and Gozukirmizi (2003) successfully encapsulated somatic embryos from leaf and internodal explants to create synthetic seeds for rapid clonal propagation. Similarly, Khan *et al.* (2018) created "synseeds" from nodal segments containing axillary buds of a vulnerable willow (*Salix* L.) species.

Vegetative propagation

Clonal propagation techniques have been increasingly used to produce mass numbers of relatively uniform plants with desirable genetic traits such as growth rate, architectural form, wood properties and disease resistance. Such techniques need to consider the balance between genetic gain and genetic diversity when selecting the breeding population for clonal replication (Shelbourne, 2019).

Vegetative propagation from softwood or hardwood stem cuttings is an established technique for many FGT species with established protocols (Luna and Haase, 2014), and there is much ongoing research to refine and improve this technique (e.g. Husen and Pal, 2007; OuYang, Wang and Li, 2015). More recently, *in vitro* micropropagation techniques have been developed that offer higher cost efficiency and rooting performance (Muñoz-Concha, 2017). For example, eucalypts (*Eucalyptus* L'Hér) and other hardwoods have been propagated successfully on a commercial scale using microcuttings from plantlet apices and mini-cuttings from axillary shoots of rooted stem cuttings with a high degree of juvenility (de Assis, Fett-Neto and Alfenas, 2004). Minicuttings have also been used to successfully propagate pines (*Pinus* L.) (Majada *et al.*, 2011) and willows (Nissim and Labrecque, 2016).

Organogenesis, in which new plants are grown from axillary or adventitious buds, is another micropropagation technique used to clonally propagate many species, including teaks (*Tectona* L. f.) (Shirin, Rana and Mandal, 2005; Mendoza de Gyves, Royani and Rugini, 2007), willows (Palomo-Ríos *et al.*, 2015), eucalypts (Nakhooda and Jain, 2016) and paulownias (*Paulownia* Siebold & Zucc.) (Chunchukov and Yancheva, 2015). Production facilities often use ministumps, minihedges and minigardens to obtain the necessary propagative plant materials (de Assis, Fett-Neto and Alfenas, 2004; Stuepp *et al.*, 2015; Kuppusammy *et al.*, 2019).

Somatic embryogenesis is an additional tool used for mass propagation of elite individuals. This artificial process uses somatic cells to derive embryos for new plants and has been used successfully with eucalypts (de Assis, Fett-Neto and Alfenas, 2004), poplars (*Populus* L.) (Gaur *et al.*, 2016) and several conifer species (Sutton *et al.*, 2004; Salaj, Matusova and Salaj, 2015; Gautier *et al.*, 2018). Somatic embryogenesis is also a promising technique for producing transgenic plants (de Assis, Fett-Neto and Alfenas, 2004; Kutsokon *et al.*, 2013; Gaur *et al.*, 2016), though large-scale production can be problematic (Sedjo, 2006).

Culturing

Management of light, photoperiod, temperature, nutrition, water status and other aspects of the nursery environment can profoundly influence nursery productivity by reducing or increasing plants' internal carbohydrate and chemical concentrations, thus affecting rooting, growth, bud development, hardiness and nutrient uptake (de Assis, Fett-Neto and Alfenas, 2004; Batista *et al.*, 2015; Grossnickle, Kiiskila and Haase, 2020). For example, manipulating light spectra resulted in shoot and root morphological responses of spruce, pine and oak (*Quercus* L.) seedlings (Montagnoli *et al.*, 2018). Similarly, modifying nitrogen (N) fertilization on eucalypts can influence root growth potential and nutrient storage reserves and improve physiological performance on harsh sites (Acevedo *et al.*, 2021). Pine seedlings fertilized with organic N had minimized needle senescence, retained more nutrients in the oldest needles, and hastened development of water-use efficiency mechanisms compared with those fertilized with inorganic N sources (Sigala *et al.*, 2020). Thus, culturing can be used to not only achieve phenological and morphological targets but can also condition plants for anticipated environmental stresses. For example, tissue-culture medium supplemented with iron (III) oxide (Fe_2O_3) nanoparticles (Youssef, Abdel Aziz and Ali, 2019) and proline (Youssef, Hashish and Taha, 2020) improved salinity tolerance of poplar and paulownia trees, respectively. In another study, drought conditioning of poplar seedlings during nursery production increased growth, photosynthetic rates and xylem activity (Sloan, Burney and Pinto, 2020).

Nursery stocktypes have evolved significantly over the past few decades (Grossnickle and El-Kassaby, 2016) (Box 7). For bareroot nurseries, a variety of transplanted stocktypes are now used, sowing density has been reduced, and root culturing has been improved (Riley and Steinfeld, 2005). For container nurseries, a wide array of container types, sizes and shapes have been developed (Landis, Luna and Dumroese, 2014). These container choices can be tailored to root architecture (de la Fuente *et al.*, 2018), edaphic conditions (Pinto *et al.*, 2011), economic considerations (Puértolas *et al.*, 2012) and other factors.

Other objectives for modified culturing techniques are to reduce energy, increase water-use efficiency, and increase use of sustainable products. Apostol *et al.* (2015) showed increases in seedling growth and concomitant decreases in energy consumption for seedlings grown with light-emitting diode (LED) technology compared with traditional lighting. Further, van Iersel and Gianino (2017) found significant reductions in electricity use by implementing an automated duty cycle to control LED lights such that they provided just enough supplemental light to reach a pre-set threshold of photosynthetic photon flux. Water-saving strategies include using subirrigation systems (Schmal *et al.*, 2011), reducing misting frequency (Pinto, Dumroese and Cobos, 2009) and modifying irrigation regimes. Dumroese, Page-Dumroese and Brown (2011) found that the irrigation target for pine seedlings during the entire growing season could be reduced by 15 percent without significantly changing seedling size and water-use efficiency. Improved irrigation management also helps minimize nursery pests (Dumroese and Haase, 2018). Lastly, alternative growing substrates are increasingly used in nurseries to lessen impacts on soil and peat resources. Seedlings have been successfully produced using dredged sediments (Ugolini *et al.*, 2018), coconut husks (Krishnapillai *et al.*, 2020), bark (Aung *et al.*, 2019), biochar (Fornes and Belda, 2019; Dumroese, Page-Dumroese and Pinto, 2020), composts (López *et al.*, 2008), rice husks (Aung *et al.*, 2019) and other materials.

Plant growth regulators and stimulants have increasingly been used, and have been tested extensively, to determine optimum concentrations and timing by species and propagation technique (Nakhooda and Jain 2016; González *et al.*, 2018). For example, plant-growth-promoting rhizobacteria can significantly improve eucalypt rooting (de Assis, Fett-Neto and Alfenas, 2004), and combinations of abscisic acid (ABA) and water potential can promote development of somatic embryos in several conifer species (Sutton *et al.*, 2004).

Discussion

Innovations in tree propagation have evolved continuously for decades. Intensive, high-tech practices can produce specific genotypes and offer predictability to nurseries and land managers. For some species in some parts of the world, clonal techniques have radically changed plant production, from seeds grown in soil to tissues grown in laboratories. These micropropagation approaches continue to be researched for development of improved protocols (e.g. Grendysz, Wróbel and Kulpa, 2017; Pożoga, Olewnicki and Jabłońska, 2019; Di-Gaudio *et al.*, 2020), better understanding of explant choice (e.g. Bonga, 2017; Sarmast, 2018; Zeng, Han and Kang, 2019), and more efficient deployment. New developments in both seed and clonal propagation will continue to be necessary as more diverse species are cultured in nurseries.

Despite major advances in plant propagation technology, however, practitioners and researchers are necessarily constrained by the biological and phenological limits of each plant species. The ultimate success of any propagation technique or culturing strategy is dictated by the plant's subsequent ability to meet each project's land management objectives. To that end, all plants produced must have specific morphological and physiological quality characteristics (Haase, 2008). Further, appropriate species and genetic sourcing should be targeted to match the environmental conditions of the outplanting site such that they are able to survive and thrive after outplanting. This tenet, referred to as the "target plant concept" guides nursery propagation practices to produce plants with maximum potential for long-term success (Dumroese *et al.*, 2016).

In some parts of the world, especially in areas where tree planting is most needed (Strassburg *et al.*, 2020), simply upgrading nurseries from low-tech production to modern practices can be viewed as "innovative" and can dramatically improve seedling quality, quantity and outplanting success (Haase and Davis, 2017; Bannister *et al.*, 2018). Without adequate resources and local expertise, planting programmes often fail (DeGrande *et al.*, 2006; Gregorio *et al.*, 2017; Höhl *et al.*, 2020). For example, polybags are widely used for plant production. These containers, however, often result in poor-quality plants with deformed roots (Cedamon *et al.*, 2005; Takoutsing *et al.*, 2014). Training, funding, supplies and innovation with local resources, such as discarded plastic beverage bottles modified for nursery containers (Khurram *et al.*, 2017) and composted coconut husks turned into quality growing medium (Krishnapillai *et al.*, 2020), can profoundly transform nursery operations and plant quality to meet land-management objectives (Haase and Davis, 2017).

Conclusion

Innovative nursery techniques can help meet the demand for high-quality seedlings necessary for achieving worldwide forest restoration goals to mitigate climate change, protect watersheds, improve livelihoods, re-establish habitats, stabilize soils and generate wood products. These techniques may include high-tech advances such as synthetic seeds, organogenesis and high-efficiency supplemental lighting and can also include basic upgrades to low-tech nurseries to increase survival, growth and resiliency after outplanting.

Take-home messages

- Nursery propagation techniques and nursery culturing strategies have evolved significantly in the past two decades and continue to be refined and improved for many species.
- Propagation techniques are still constrained by biological limits of a given species. The target plant concept must be integrated into nursery and planting programmes to ensure the use of genetically appropriate, locally adapted, high-quality plant material to optimize outplanting performance.
- Education of nursery workers and simple upgrades to supplies and infrastructure can be deemed innovative in many places in the world and can have a dramatic impact on plant quality and programme success.

Box 6. CONTAINERIZED SEED ORCHARDS

Seed orchards have long been a useful and productive tool to provide genetically improved seed from many species worldwide. These orchards have traditionally been ground-based, requiring large areas of land to be cleared and maintained for seed production. One innovation in this technology is a containerized seed orchard in which plants of the target species are cultured in large containers and maintained in greenhouses or cold frames. The advantages of this type of orchard include reduced space requirements, better climate control, more efficient pollinations, and easier monitoring and control of insects and diseases. In addition, as new families with desirable genetic characteristics are discovered, older trees can easily be replaced by newer material.

Box 7. MODERN NURSERY STOCK TYPES

Information provided by Manuel Acevedo (INFOR) and Daniela Ruiz and Pablo Ramirez de Arellano (Arauco SA)

Forest companies have developed a combination of propagation and stock type to improve seedling quality. For example, the Compañía Manufacturera de Papeles y Cartones corporation in Chile produced 38 million seedlings in 2019 using varying techniques. *Pinus radiata* D. Don are propagated by seed (5 million), cuttings (8.9 million) and field cuttings (5.2 million) grown in both container and bareroot nurseries. For eucalypt production, *Eucalyptus nitens* Maiden is propagated from seed (16 million) and the *Eucalyptus globulus* Labill. × *nitens* hybrid from cuttings – all grown in containers.

Q-plugs

Small container plugs filled with stabilized medium have proven to be an effective method for propagating a variety of species to be transplanted into larger containers or bareroot nursery beds. Seeds can be directly sown into the plugs, receive any required stratification and be moved to a greenhouse or growing facility for germination. This method is often used for small-seeded species, seedlots with unknown or low germination, and to produce a large number of seedlings for transplanting later in the growing season. The advantages of this method include: easier handling of small seeds that can be sown when dry; less risk of wasted greenhouse space for species with low germination; rapid turnover of greenhouse crops; and the ability to transplant seedlings efficiently and quickly following germination with little risk of damage to the root systems.

Paper pots

In Chile, Forestal Arauco manages more than 1.1 million hectares of forestland. The production capacity of their three main nurseries is 82 million seedlings per year (*Pinus radiata*, *E. globulus*, and *E. nitens*). To help meet its sustainability goals and the development of circular-economy processes, the company has incorporated paper pots for seedling production. Paper pots are plantable containers that consist of growing medium wrapped inside single-cell systems with decomposable paper, thereby facilitating air circulation, drainage and root development. This stock type permits outplanting the seedling without removing it from the container. Forestal Arauco currently grows one-third of its seedlings and cuttings in paper pots (Ellepot® and Fibercell®). Paper pot brands differ mainly in the paper characteristics, porosity and decomposition process.

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6.2 Planted forests and permanent polycyclic plantations

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Summary

Many of the environmental benefits provided by fast-growing tree (FGT) plantations are lost at the end of a management cycle when the trees are felled. Permanent polycyclic plantations are generally mixed and have two or more production cycles on the same land plot. This strategy for tree plantation design and care produces results close to traditional tree farming and provides benefits to those near the forest.

Keywords: Tree farming; permanent polycyclic plantation; poplar clones; oak; *Quercus robur*; plane tree; *Platanus hispanica*

Introduction

Permanent polycyclic plantations can be designed using many different strategies, but all combine the advantages of tree plantations with some of those of the forest (Buresti Lattes and Mori, 2009). Many living organisms, including animals, insects and plants, are associated with an individual tree. Thus, the biodiversity of an area is enhanced as the number of trees and tree species increases, and the vertical or horizontal structure of the forest becomes more complex. This aspect is important not only in forested landscapes, but also in intensively cultivated agricultural lands and peri-urban areas, where the presence of trees and shrubs can increase biological diversity.

Trees also influence microclimate, regulate water flows and reduce the effect of some pollutants. Moreover, trees sequester carbon dioxide (CO_2) from the atmosphere. On permanently forested sites, carbon steadily accumulates in the soil; eventually, the amount of carbon sequestered in the soil may exceed the amount stored in the plant biomass (Petrella and Piazzi, 2006). Thus, trees are important not only for productive purposes but also because of their ecological and landscape impacts. Therefore, tree farming, especially in the context of polycyclic plantations, has an important environmental role.

Polycyclic tree farming covers a wide range of planning and management approaches, from Italian classical poplar (*Populus* L.) cultivation with large farmer inputs and strong impact on the environment (AA.VV., 1987), to silvicultural approaches with low farmer inputs and a more positive environmental impact. However, all tree plantations generally have the same fate: when the main trees reach the end of their economic life, all trees in the plantation are felled and the ecological and landscape benefits of the plantation are lost.

Recently (from 2001), Compagnia delle Foreste and researchers have started testing new permanent polycyclic plantations to extend the ecological benefits derived from plantations while maintaining financial benefits for the farmer.

What are permanent polycyclic plantations?

Polycyclic plantations are defined as plantations that are generally mixed and contain several groups of main trees with different objectives and production cycle lengths (Box 8 presents some useful terms for polycyclic plantation management). For example, a classical cloned poplar plantation is monocyclic, while a mixed plantation of poplar clones, oak (*Quercus* L. [e.g. Quercus robur L.]) or walnut (*Juglans* L. [e.g. *Juglans regia* L.]), and planes (*Platanus* L. [e.g. *Platanus hispanica* Mill.]) is a polycyclic plantation. During the first 20 years of experimentation, it was considered necessary to distinguish between two different kinds of polycyclics: the “full-term plantation” and the “permanent plantation” (Buresti Lattes and Mori, 2006, 2007a).

In full-term polycyclic plantations, the species with the longest production cycle are planted at a density that allows them to develop a closed canopy cover at the end of their production cycle. Trees are generally all cut once they reach maturity. This type of polycyclic plantation has two or three different wood production cycles from tree species that have different rates of growth. First, wood products are obtained from the fastest-growing species to occupy one part of the production surface (5–7 years). Then, wood products are obtained from fast-growing tree (FGT) species (9–12 years). Finally, the high-value wood products of medium-growing tree species (20–30 years) are obtained. The different species are planted simultaneously, but their ability to occupy the production area varies over time due to their different growth rates. In this manner, a variety of wood assortments can be obtained for one production area. In practice, the fastest-growing species are cut first, followed by the next fastest, and so on.

Permanent polycyclic plantations differ from full-term plantations in tree spacing and management strategy. Distances between main trees are greater in permanent compared to full-term polycyclic plantations to avoid development of a closed canopy (Buresti Lattes and Mori, 2007b). In practice, each main tree has its own space for its canopy, and FGTs are planted among the main trees, occupying part of the land surface not needed by the main trees. This allows trees on different production cycles to be planted between main trees (same or different species), and therefore the land remains continuously under tree cover.

An example of the different types of polycyclic plantation concerns a mixed polycyclic plantation with poplar clones, native species of *Populus alba* L. or *Populus nigra* L., and walnut. In polycyclic plantations (e.g. Ravagni and Buresti, 2003; Buresti Lattes and Mori, 2007b, 2009; Buresti Lattes *et al.*, 2008a, 2008b), when poplar is felled, walnut occupies all of the freed space, and the farmer must wait for walnut to complete its production cycle before establishing a new cycle with poplar or other (native) species. However, with permanent polycyclic plantations, walnut trees are spaced such that, at the end of the production cycle, their canopies do not occupy all the available space but instead leave space for subsequent tree populations (Box 8). As walnut grows, the farmer may thus be able to produce two or more cycles with other species in the available space. When the walnut trees are finally cut, trees of other species remain in the plantation to buffer the temporary and partial lack of large trees. A new productive cycle can then be started, replacing the harvested trees with walnut or other native species (i.e. *Quercus robur* L.), according to the farmer's production aims.

Discussion

Advantages of permanent polycyclic plantations

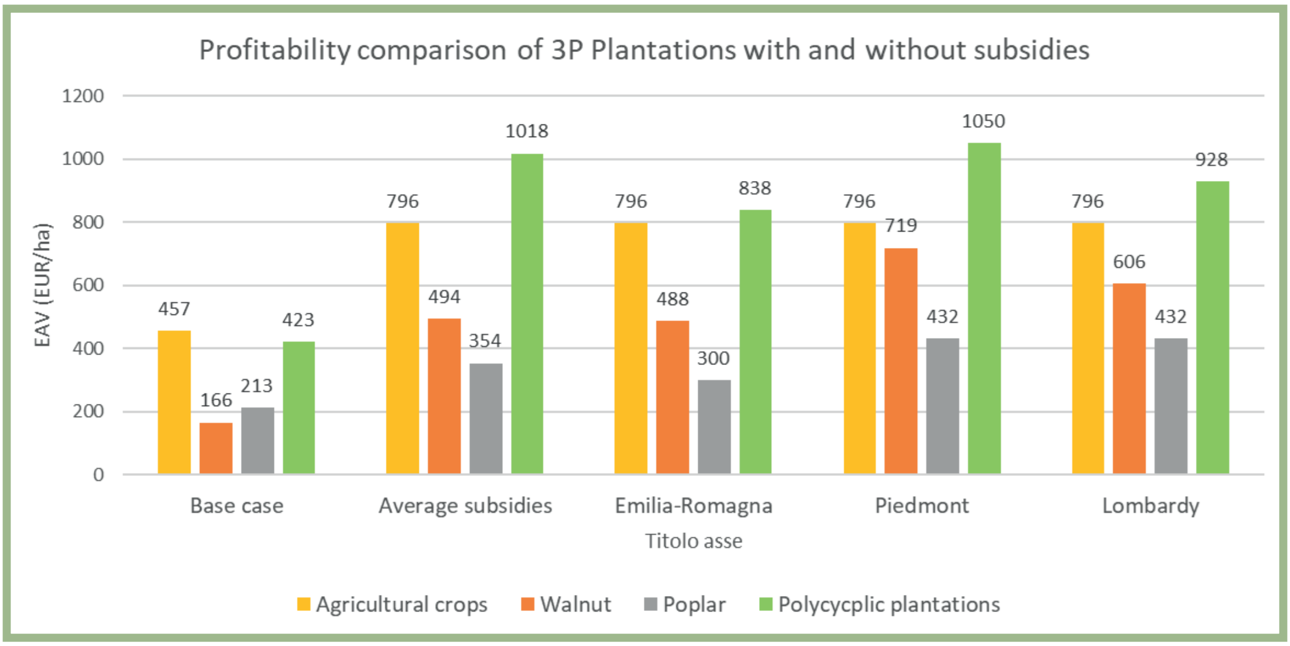
Permanent polycyclic plantations require careful planning and management that is adapted to the needs of the species and their different production cycles. The planner must choose the spacing between trees of the same and different production cycles to allow for the optimal performance of all trees. The larger the number of production cycles to be combined in the plantation, the greater the complexity of the design. The grower has to understand the growth dynamics of the different trees and the timing of each production cycle in order to conduct management interventions at appropriate times (e.g. pruning, felling or introduction of a new production cycle). Technical advice is very important during all these operations.

Planning and managing a mixed, multiobjective permanent polycyclic (3P) plantation is certainly more difficult than, for example, planning and managing a classic mixed plantation. However, 3P plantations can provide more benefits to both farmers and communities (Buresti Lattes, Mori and Ravagni, 2001; Buresti Lattes and Ravagni, 2003; Becquey and Vidal, 2008a, 2008b; Buresti Lattes and Mori, 2010; AA.VV., 2017; Pra *et al.*, 2019). Moreover, technological innovations are increasing helping with planning and management (Box 10).

Economic benefits for farmers

- With the right spacing, older trees will influence the shape and diameter of younger trees, making pruning simpler.
- With overlapping production cycles, income is received more frequently, and economic returns can be greater than from a less complex plantation (Figure 6).
- The plantation can be partially redesigned after a portion of the trees have been felled in each production cycle. Changes can be made to species, spacing and production objectives, and exploitation of the available space improved.

Figure 7. Results of sensitivity analyses on subsidies applying the entity–attribute–value model with a 3.5 percent discount rate



Source: Adapted from: **Pra, A., Brotto, L., Mori, P., Buresti Lattes, E., Masiero, M., Andrighetto, N., Pettenella, D.** 2019. Profitability of timber plantations on agricultural land in the Po valley (northern Italy): a comparison between walnut, hybrid poplar and polycyclic plantations in the light of the European Union Rural Development Policy orientation. *European Journal of Forest Research*, 138:473–494. https://doi.org/10.1007/s10342-019-01184-4

Notes: Base case is without subsidies. Emilia-Romagna, Piedmont and Lombardy are three different regions of Italy. The entity–attribute–value (EAV) model is a data model to encode, in a space-efficient manner, entities where the number of attributes (properties, parameters) that can be used to describe them is potentially vast but the number that will apply to a given entity is relatively modest.

Environmental and landscape benefits for people and the planet

Permanent polycyclic plantations provide ecological and other benefits for society that cannot be achieved with traditional plantations and full-term polycyclic plantations. These include:

- fewer changes in the landscape over time;
- continuous carbon storage;
- less habitat change for fauna that depend on trees for refuge and food; and
- increased biodiversity when 3P plantations are implemented in areas with intensive agricultural management.

For example, the effects of 3P plantations on biodiversity and the environment were evaluated through monitoring actions in the LIFE+ InBioWood project (EU LIFE Programme). Project duration (5 years) was relatively short compared to that required for long-term plantations. However, interesting trends were found. Specifically, 3P plantations were shown to improve biodiversity and environmental conditions in the medium to long term, not only compared to when there are no trees but also compared to traditional monospecific plantations. Below, the main results of the monitoring activities are summarized.

Entomofauna monitoring (Department of Land and Agroforestry Systems, Padua University)
The entomofauna monitoring results can be summarized as follows:

- Arthropoda is the most numerous phylum, and a comparison of "before" and "after" 3P plantations showed that arthropod presence increased.
- More mollusc species were observed in 3P plantations compared to in monoclonal poplar plantations.
- The distribution of annelids and chordates was quite homogeneous in all the investigated areas.
- Ectomycorrhizal ascomycetes and basidiomycetes were absent everywhere at the time of monitoring.

Bird watching (DREAm Italia s.c.a.r.l.)
According to the analysis results, polycyclic plantations were found to have a positive effect on the biodiversity of ornithic communities compared to traditional cultivation forms (Londi *et al.*, 2016). There was an increase in ornithic activity with the transition from traditional cultivation to polycyclic plantations and from traditional poplar plantations to polycyclic plantations.

Soil organic matter monitoring (PAN SRL)
Soil organic matter content tended to increase, both in the 0–30 cm (centimetre) layer and in the 31–60 cm layer with 3P plantations. This is a consequence of the accumulation of decomposing plant materials, which promotes CO_2 storage.

Economic evaluation of ecosystem services (Etifor)
Three ecological services were evaluated: climate regulation, water phytodepuration and habitat regulation for biodiversity.
According to the results, 3P plantations representing 25 ha of open field and 45 kilometres (km) of rows) had a quantitatively and economically significant impact in InBioWood areas, providing:

- 6 percent of the carbon sequestration service of the entire study area;
- 22 percent of the water purification service; and
- 69 percent of the biodiversity habitat regulation service.

The study estimated that the ecosystem services generated or conserved by 1 ha of 3P plantation had an annual economic value ranging from almost 4 000 EUR/ha to 7 150 EUR/ha. These estimates are a useful reference for public investments aimed at sustainable development of areas with intensive agricultural management, and for private investors interested in supporting these initiatives.

Conclusion

Permanent polycyclic plantations represent an innovative strategy for producing wood with positive financial returns and, at the same time, environmental and landscape benefits. In all polycyclic plantations, whether full-term or permanent, fast-growing species play a key role. The combinations of different species, types and proportions of wood products, environmental conditions (plains, hills or mountains) and geographical areas (boreal, temperate, subtropical or tropical) available provide numerous opportunities for experimenting with this kind of innovative plantation.

In Italy, extensive testing and experimentation for 20 years on permanent polycyclic plantations have produced promising results. It will be important to experiment further with this innovative plantation design and management system in other environmental, social and economic contexts in the coming years.

Take-home messages

- It is possible to combine financial returns and environmental benefits from wood production through the dynamic design and management of permanent polycyclic plantations.
- An infinite number of schemes for permanent polycyclic plantation can be implemented based on each mix of tree and shrub species, geographic area, and market and farmer needs.

Box 8. USEFUL TERMS FOR POLYCYCLIC MANAGEMENT PLANTATIONS

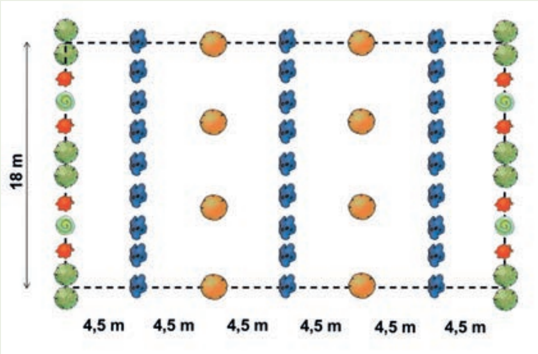
A *main tree* provides at least one of the main products for which the plantation was designed.

An *accessory tree or shrub* facilitates the management of the plantation by a farmer but can be substituted by cultural care.

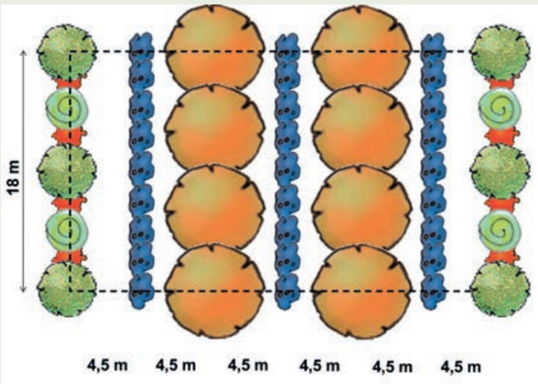
Multifunctional tree farming refers to tree cultivation designed to satisfy multiple functions, such as timber production and reducing pollutants in waterways, or in the case of common walnut, timber and fruit.

Multiobjective tree farming refers to tree cultivation designed to obtain more than one type of wood product, such as timber and biomass.

Box 9. Example of the first 35 years of management of a permanent polycyclic plantation producing woodfuel (hornbeam, *Carpinus* L.), veneer (poplar) and high-value wood (European oak, *Quercus robur*)

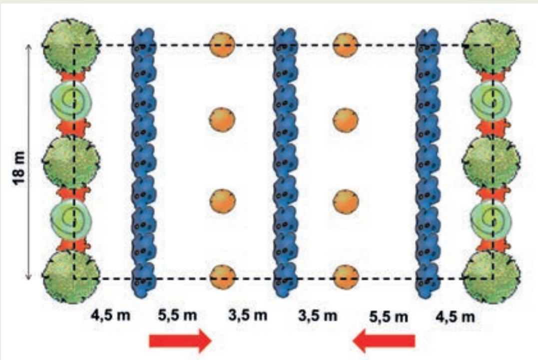


Year 0: First plantation scheme of all species



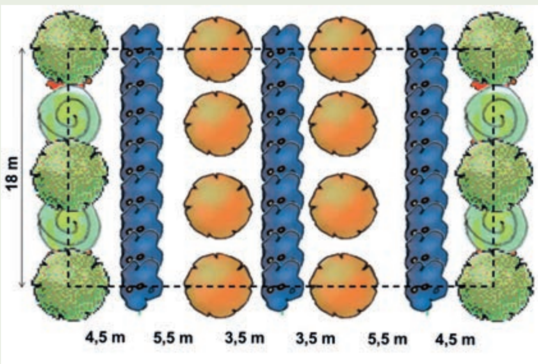
Year 10

The poplars, which should have reached the production target of a 40 cm trunk diameter, are felled.



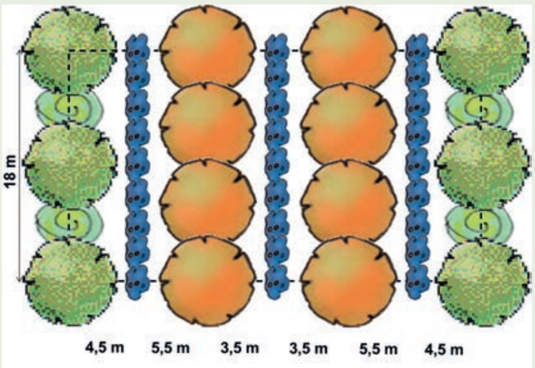
Year 10

Two new poplar rows are planted after felling of the poplar trees, spaced 7 m (metres) apart and each row 10 m away from the oaks. The hornbeam trees should not be cut at the same time as the poplars to avoid excessive and sudden isolation of the oaks, which could cause stress.



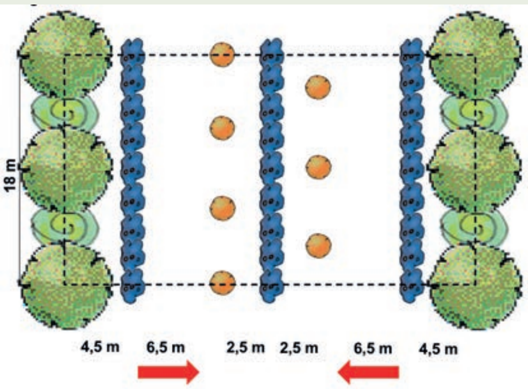
Year 15

The hornbeam is felled and replanted. The first cycle of hornbeam is relatively long compared with that of other native species suitable for producing woody biomass. The time it takes is due to the relatively slow initial growth of the hornbeam and the need to extend the oak protection for more years.



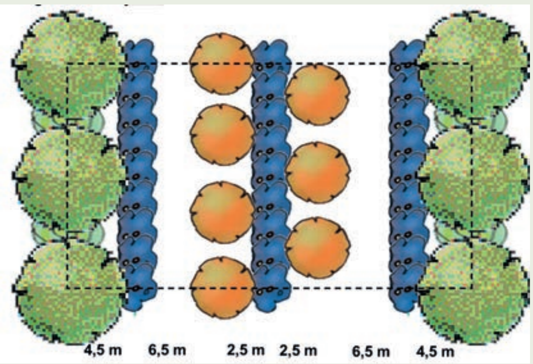
Year 20

Poplars should have reached the production target of a 40 cm in diameter and are felled.



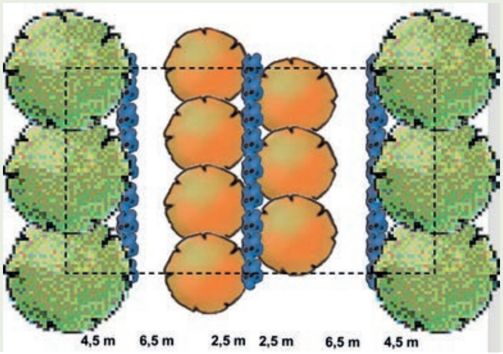
Year 20

Two new rows of poplar are planted. This time the rows are staggered to increase the spacing (trees will be 5 m × 5.6 m from each other). The minimum distance from the oaks (which are 20 years old and have well-developed crowns) is 11 m. This distance should be enough to allow the poplars to grow without competition from the oaks. The two, 5-year-old hornbeam rows that are 4.5 m from the oaks, should have a positive effect, protecting the oaks from isolation stress.



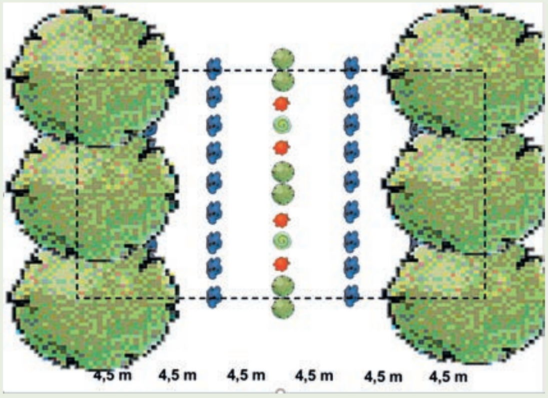
Year 25

The hornbeam suckers, which grow faster than seedlings, should be ready for felling.



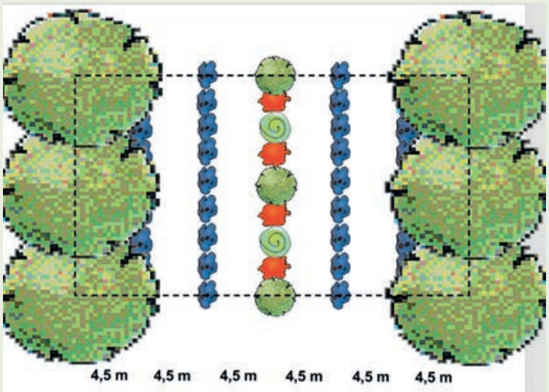
Year 30

The third cycle of poplar should now be felled and the hornbeam between the two poplar rows removed.



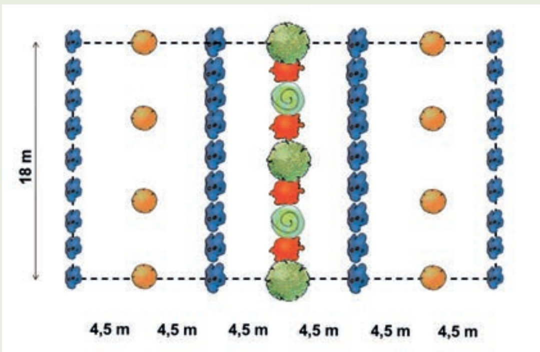
Year 30

A new row of oaks and accessory trees is planted together with two new rows of hornbeam 4.5 m from the oaks. The two new hornbeam rows are 13.5 m from the 30-year-old oaks.



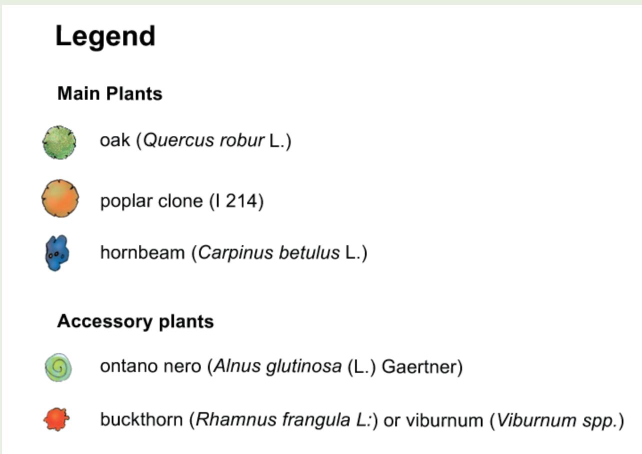
Year 35

The oaks should have reached their target size and should be felled. The hornbeam closest to the oak trees should also be felled, but yield will be low. At this point, thanks to the positive competition with the older oaks and the microclimate provided by them, the 5-year-old hornbeam plants should have sufficiently developed.



Year 35

New rows of poplar and hornbeam are planted. Trees for timber production are now planted where trees for biomass production were before, and vice versa.



Source: Author's own elaboration.

Box 10. PERMANENT POLYCYCLIC PLANTATION APP AND WEB APP FOR TECHNICIANS

The idea

A simple and operational tool is needed to promote take-up of these innovative permanent polycyclic plantations (3Ps) and dissemination of the findings of the LIFE+ InBioWood project. Additionally, this information must be conveyed effectively to assist technicians in designing 3Ps. To fill this need, a web application was developed that automatically generates project models according to specific requests from technical designers and landowners.

The tool

The name of the tool is "Legno & Ambiente" (Wood & Environment). It is a free web application that can be used on a laptop or desktop computer by visiting the website www.inbiowood.eu/webapp, or on Apple and Android smartphones and tablets by downloading Legno & Ambiente from the App Store or PlayStore, respectively. The app is made up of three main sections and a series of useful links. Here we briefly describe the first section, "Create a new plantation". Using Legno & Ambiente, a tree farm project is automatically generated by answering five simple questions. The questions first elicit information from the user on the type of desired plantation to be established (in an open field or in rows), as well as the types of main trees that will be planted (trees with medium long-, short- or very short-rotation cycles), and in what percentages. Then, the user must define the desired diameter for the main trees with a longer rotation cycle and whether to add dual-role trees or only accessory trees. Based on this information, the tool extracts a pre-compiled project from a database of as many as 116 possible solutions. The choice of the species to be planted remains the only aspect deliberately left in the hands of designers.

Customization and useful links

The second section of Legno & Ambiente, named "My projects", contains all the projects generated and saved by the user, exported in PDF format and named accordingly. In addition to the layout, each project is supported by a tree management plan, which contains a description of the necessary implementation and management techniques, as well as an indicative financial evaluation of costs and revenues. This financial evaluation can help owners decide whether to establish a 3P. Basic economic data involved in the evaluation are pre-set by the developers based on average values and specific experiences. However, the resulting estimate, though valid in general terms, may not be so in individual cases as it depends on factors that are not always common to all areas, such as the value of wood assortments or land-use costs. Therefore, the third section of Legno & Ambiente, "Set costs and revenues", is fundamental: designers and owners can set and save the typical parameters of their area, thus arriving at a financial assessment that is closer to reality.

For more information on the functionality of Legno & Ambiente, see a tutorial video available at: https://www.youtube.com/watch?v=gZhhdEC6Hkc

The Legno & Ambiente app is currently only available in Italian.

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6.3 Plantation monitoring and assessment

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Summary

Reliable information is essential for the planning and sustainable management of fast-growing trees (FGTs). Monitoring is a process of periodically collecting and using data to inform management decisions. This section provides general guidelines on data-collection methodology and procedures for FGT monitoring and assessment.

Keywords: Information; remote sensing; sampling; statistical data; survey; survey design

Introduction

There is increasing interest in information on FGT resources and their uses and on changes to support policy development and sustainable management at the local, national and international levels (Freer-Smith *et al*., 2019). Management of FGTs within agricultural farms is characterized by relatively short rotations and high dynamism compared to agricultural cultivation. Frequently updated, accurate and spatially detailed statistical data about tree species composition, stand structure and wood supply attributes is required. Such information is used to plan, design and implement FGT management at strategic, tactical and operational levels.

The survey strategy must allow information to be updated in short time frames, and the survey must be quick and simple to carry out so that it is suitable for trees that change rapidly on agricultural lands. Such a requirement may exceed the scope of conventional forest monitoring and assessment, making room for ad hoc information sources. Adequate approaches can usually be implemented by low-intensity survey strategies covering a range of biophysical and economic variables.

Plantation surveys

Monitoring reports should include substantive content with robust data to measure and assess outcomes. It is therefore advisable for the survey designer to carefully identify the information needs, highlighting what data are needed and what the tolerable errors are in the estimates. For example, to estimate the wood from an FGT plantation, information on the type of mass (e.g. total biomass, stem biomass, total wood volume or wood assortments) and how the mass should be quantified (e.g. as a total value, or broken down by species or age classes) is required. The necessary precision and level of statistical certainty of such information must also be defined.

In planning a survey of FGTs in a given territory or estate, it is essential to establish whether statistical information for the whole area or spatial distribution data within that area are needed, or whether a balance between these two types of data is desired. It should be considered that, for the purposes of FGT management, the availability of a permanent flow of information becomes effective only if accompanied by spatially localized data. Accurate and updated maps depicting the spatial pattern of FGTs throughout the area of interest are crucial for decision-making, planning and management. Remotely sensed information can be used as ancillary data to improve estimation of FGT attributes without increasing sampling effort and costs. Such data can be acquired through different platforms (spacecraft and aircraft) and sensors at different resolutions and can be exploited by a vast array of tools and methods (e.g. Schnell, Kleinn and Ståhl, 2015). In recent years, airborne laser scanning has become one of the main sources of data on the structural attributes (including timber) of FGT plantations (e.g. Vauhkonen, Rombouts and Maltamo, 2014).

Census surveys used in the past have made forestry operators reluctant to use probabilistic sampling techniques. This trend has almost completely disappeared today. The census may still be practicable for FGT plantations of limited size, but, for large FGTs, sampling surveys have become the common practice. It is emphasized that, in an FGT survey, the greatest cost element generally derives from the organization of field surveys and the location of sampling units on the ground. Reducing the number of units on which to measure the attributes of interest almost always means reducing survey costs in a consistent manner. Further, a complete enumeration typically takes much longer than a sample-based inventory – so much so that it can lose effectiveness from an operational point of view; the time required to carry it out can make the results obsolete by the time they are available.

A general practical reference for structuring a survey strategy can be found in the manual for integrated field data collection produced by FAO (2012). Assessment methods, variables and tools need to be tailored and adapted to each individual situation, taking into account local contexts, social and ecological environments, and information requirements. Involvement of all stakeholders is essential in this process to ensure that results will meet the expectations of the information users. A set of appropriate indicators should be agreed upon and should capture information on FGT productivity, diversity and health at the plot and landscape scales (e.g. Muhtaman, Siregar and Hopmans, 2000). Core variables to be assessed, with their definitions and options, may be selected in accordance with international standards to facilitate reporting at various levels and encourage harmonization between data-collection initiatives among countries.

The sampling strategy traditionally recommended for FGT surveys on a local scale (e.g. a given estate) is based on one-phase systematic grid design (SGS). Pre-stratification may be adopted in situations where feasible strata are deemed to improve the design. The use of a stratified sample ensures the spreading of samples throughout the survey area in accordance with the stratification criteria and can provide greater estimation precision with respect to non-stratified sampling of equal sample sizes. The number of sampling units to be surveyed is determined by the required statistical reliability of the estimations (Gregoire and Valentine, 2008) (Box 11) and the available financial and human resources for the assessment, and it must be chosen in such a way to enable periodic monitoring.

For large-scale assessment of FGTs within agricultural farms, Marcelli *et al*. (2020) proposed a two-phase sampling strategy. The first phase can be performed semi-automatically or manually on screen using remote sensing imagery and is sufficient to estimate the total area of FGTs. A second phase is necessary to reduce the sample size, achieving a stratified sampling of units to be visited on the ground. Once a given attribute (e.g. wood volume) is recorded for the units selected in the second phase, a two-phase estimator of total wood volume was proposed by Baffetta, Fattorini and Corona (2011). Regarding the scheme for locating points in the first phase, tessellation stratified sampling (TSS) can be advised instead of the more common SGS. Tessellation stratified sampling involves covering the survey area by a grid of regular polygons of equal sizes, selecting a point at random in one polygon, and repeating this in the remaining polygons. However, from a theoretical point of view, the superiority of TSS over SGS is proven (Barabesi and Franceschi, 2011).

The sampling scheme must be described in detail so that the staff responsible for making it operational can easily understand its characteristics and application methods. The sample size must be explicitly predetermined, as well as the procedures for selecting the sample units. In addition, possible sources of non-sampling errors must be defined, along with ways to at least limit or overcome them.

Discussion and conclusion

The status of FGTs at a given point in time can be known through efficient surveys, which are rapidly evolving as new information needs arise and new techniques and tools become available. The exploitation of the latter, as well as their implementation within operative management processes, should be evidence-based (Corona, 2018). Practical examples of dedicated surveys can be found in Rawat *et al*. (2003), Lister, Scott and Rasmussen (2009), Gavran and Parsons (2010), Social Forestry and Extension Division (2019), and Corona *et al*. (2020).

A fundamental feature of FGT monitoring and assessment is making sure the information produced is clear and can be easily retrieved. There is no "one-size-fits-all" solution across diverse geographical areas and different environmental, institutional and socioeconomic settings. However, some common guidelines can be suggested. The general strategy for FGT monitoring and assessment involves:

- acknowledging the multiplicity of relevant stakeholders and the heterogeneity of their perceptions to determine a common vision for designing and implementing an effective survey process;
- developing a hierarchy of attributes to be monitored and related indicators to be assessed;
- selecting the right tools and methods for a proper survey design, to be kept as simple as possible but not too simple;
- developing an operationalization plan to conduct the survey: this includes defining tasks, costs and staff roles, among other things;
- testing the design to understand its gaps and weaknesses and finalizing the survey design implementation.
- conducting the survey; and
- producing and presenting the results.

Take-home message

- Fast-growing tree monitoring and assessment is not an end *per se*. It is a critical and essential part of the FGT management cycle. Strategies for success include involving relevant stakeholders and participants, asking the right questions and defining the right survey objectives, adopting a survey design that is as simple as possible but not too simple, and applying the results to fine-tune management actions.

Box 11. SAMPLING INTENSITY FOR FAST-GROWING TREE MONITORING

A rigorous statistical procedure can be adopted to define the survey sample size.[a] For instance, to estimate the mean of a given attribute under simple random sampling, with a confidence interval that is *W* units in total in width (*W/2* on each side of the sample mean, the so-called margin of error), the following sample size *n* should be adopted:

$$n = \frac{4Z^2 s^2}{W^2}$$

where *Z* is a standard Z-score for the desired level of confidence (1.96 for a 95 percent confidence interval) and *s* is the standard deviation of the attribute of interest for which the mean is estimated. Practical guidelines may also be available at country or local level, such as shown in the table below (reported as an example), adopted by the Department of Forests and Park Services of Bhutan, for monitoring survival percentages in forest plantations, with sample units represented by plots of 225 square metres (m^2).[b]

Area (ha)	*Number of sample plots*
Up to 4	1–3
5–10	5–9
11–15	10–13
16–20	14–18
21–25	19–22
26–30	23–27
31–35	28–31
36–40 and above	32–36

Sources:

[a] **Gregoire, T.G. & Valentine, H.T.** 2008. *Sampling strategies for natural resources and the environment*. Applied environmental statistics. Boca Raton, Chapman & Hall/CRC. 474 pp.

[b] **Social Forestry and Extension Division.** 2019. Guidelines for Monitoring and Evaluation of Plantation and Forest Nursery. Department of Forests and Park Services, Ministry of Agriculture and Forests, Royal Government of Bhutan, Bhutan.

Case study 16

THE ASSESSMENT OF POPLAR PLANTATIONS IN ITALY

A two-phase sampling strategy is adopted to monitor and assess poplar (*Populus* L.) plantations in Italy, which cover 300 000 square kilometres (km^2). In the first phase, the sampling scheme is based on a grid of 500 metre (m) quadrats covering the whole territory, with one sampling point randomly selected within each quadrat. Sampling points are photo-interpreted on high-resolution airborne imagery – digital orthoimages with geometric resolution less than or equal to 50 centimetres (cm) – supported by Google Earth© images and tools (Google Street View©). All poplar plantations with a minimum area of 5 000 m^2 and at least one side longer than 20 m are selected and mapped. Canopy cover and corresponding age class (determined by the level of canopy cover) are assessed on the orthoimages. In the second phase, the selected plantations are partitioned into strata coinciding with the administrative regions of Italy. Then, within each stratum, a subset equal to 3 percent of the plantations selected in the first phase is drawn by means of simple random sampling without replacement. The plantations selected in the second phase are visited on the ground, and information such as year of plantation, clone type and tree spacing is recorded. Each tree in the selected plantations is enumerated and diameter at breast height is recorded. A sample of tree heights is measured. The total wood volume of second-phase plantations is calculated as the sum of the volumes of single trees (determined by means of allometric equations). The mean annual increment (MAI) of wood volume is calculated for each plantation by dividing the total wood volume by the age of the plantation. Estimation is carried out according to Marcelli *et al*. (2020). Over 46 000 ha of hybrid poplar plantations were recorded in 2017, with an average age of 8 years, an average wood volume of 153 m^3/ha and an average wood volume MAI of 17 m^3/ha. Details of the assessment are reported by Mattioli *et al*. (2019).


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6.4 Credit and financial support for farmers

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Summary

The poplar market in Italy is experiencing growth after years of decline, and there is renewed interest in poplar farming among farmers. But they can only get funding to help cover the substantial costs of new poplar (*Populus* L.) plantings if more environmentally sustainable clones are used and if the plantations are certified according to sustainable management standards.

Keywords: Fast-growing species; hybrid poplar; financial support; Italy; France

Introduction

Poplar (*Populus* L.) wood prices in Italy have remained unattractive for many years, which has adversely affected the development of poplar cultivation in the country. However, since 2018, prices have recovered and remained at a sustainable level. An increase in the price of both standing trees and assortments is indicative of the recovery of industrial production, mainly in the panel sector. In Italy, specialized poplar cultivation currently covers less than 50 000 hectares (ha) (Mattioli *et al*., 2019), and about 4 000–5 000 ha of new poplar plantations are established on agricultural land every year (Coaloa and Chiarabaglio, 2019). This contrasts with the figures recorded in 1980, with 7 000–8 000 ha of annual plantings.

Incentives for sustainable management of poplar in Italy

Figures for the annual area planted in poplar can be estimated using information on annual production of nursery material, supported by inventory monitoring with remote sensing and mapping of poplar plantations (UNIFI, 2020). Predictions can then be made on the potential availability of poplar roundwood for industry based on rotation. Many variables significantly impact planting cost, which on average makes up 30–40 percent of the total cost of poplar wood cultivation and production. The main variables influencing planting cost are the number of trees per unit area (150–330 trees/ha), the vegetative development of the planting material, the commercial value of the poplars, mulching, and the use of individual protection systems. These variables also affect planting operations, including tracking, digging and closing potholes, and labour. In general, the costs of hybrid poplar plantation establishment are estimated at between EUR 1 650/ha and EUR 4 000/ha (data from hybrid poplar plantations under Measure 8.1, Afforestation Measures, of the European Rural Development Programme 2014–2020).

The regions of Italy support and encourage the afforestation of agricultural land through specific measures under Rural Development Programmes (RDPs). These plantations, though varying in modalities among the regions most interested in poplar cultivation, such as Emilia-Romagna, Friuli Venezia Giulia, Lombardy, Piedmont and Veneto, can benefit from a planting subsidy provided that the principle of polyclonality is followed, meaning that plantations should consist of two or more clones depending on the size of the poplar grove, especially if more sustainable clones are used or if a process of sustainable management certification is initiated (Table 8). In this regard, the above-mentioned regions have adopted a list of more sustainable poplar clones, known as Maggior Sostenibilità Ambientale (MSA) clones, for greater environmental sustainability (Coaloa *et al*., 2016). Subsidies provided for plantations containing MSA clones are adjusted according to the percentage of clones used (Corona *et al*., 2018). Establishment of new poplar plantations containing MSA clones has recently reached 30 percent of total annual nursery production.

Table 8. Subsidy requirements for poplar plantations

Region	Percentage of contribution to eligible costs	Minimum percentage of MSA[a] clones	Sustainable management certification scheme
Lombardy	60	50	No
		0	Yes
	80	100	No
		50	Yes
Emilia-Romagna	70 / 80	50	Yes
	40	0	No
Veneto	80	10 / 20 depending on field size	No
Piemonte	60	10 / 40 depending on field size	No
		10 / 20 depending on field size	Yes
	80	30	Yes
		50	No
Friuli Venezia Giulia	80	Preferable MSA clones	Yes

Note: [a] MSA = Maggior Sostenibilità Ambientale (greater environmental sustainability).

Sustainable management certification of poplar groves has now been active for about 15 years in Italy under the Forest Stewardship Council (FSC) and the Programme for the Endorsement of Forest Certification (PEFC), representing about 10–15 percent of the national poplar surface area. Sustainable management of poplar groves is a fundamental tool for the enhancement and traceability of wood production. It is necessary to obtain recognition of productive and sustainable excellence, even if it not always rewarded by premium prices on the market.

Less than 20 percent of all newly planted poplar groves have benefited from planting aid, as shown by comparing the inventory data of arboriculture for woodland and region-supplied data on annual planting areas that have benefited from aid. Based on the most recent provisions at the regional level, in the case of the Lombardy region, arboriculture for wood and poplar plantations in nature reserves and parks (where permitted by relevant plans) is funded only if carried out in farms certified as sustainably managed. The same condition applies to concessions in the public estate and their renewal for poplar plantings (Lombardy regional law r.l. 13/2020). Box 12 provides an example from France, where support is unavailable through the common agricultural policy and where stakeholders are obtaining incentives through another mechanism.

Box 12. CHARTE MERCI LE PEUPLIER IN FRANCE

In France, which is the largest producer of poplar wood in Europe, interest in poplar cultivation has diminished, and the annual area planted in poplar has fallen by about half. Land under poplar plantations is not classified as "agricultural land" as it is in Italy, which is why French poplar farmers cannot receive economic and financial support through the common agricultural policy. To address the dwindling interest in poplar farming that is also affecting the French sector, stakeholders, including nurseries, poplar growers, and users and wood-processing companies, have embarked on a virtuous path to support and promote poplar production with incentives through La Charte Merci le Peuplier (the Thank You Poplar Charter), which is of great importance at the European level (CNP, 2021). The objectives of the charter are to:

- promote reforestation of poplar after harvesting;
- develop the use of PEFC-certified wood, from grower to consumer;
- ensure a sustainable stock of standing poplars for the future; and
- strengthen the cohesion of the value chain, particularly through transparency on the results of this operation.

The principle of the charter is to provide financial support to poplar grove owners for replanting. To receive support, poplar farmers must comply with two requirements, which are that the replanting should take place within 2 years of cutting and that the sustainable management of the plantation should be certified by the Programme for the Endorsement of Forest Certification. The support provided covers 50 percent of the cost of the planting material.

Discussion and conclusion

The monitoring system recently adopted in Italy at various levels and using different inventory tools provides reliable information on raw-material availability. It also makes it easier to plan investments along the entire wood chain, from farming to industrial processing, if used on a continuous basis.

The nursery sector, particularly for poplar, will be able to better plan production based on the outlook of the wood market and industrial activity. The shortfall in domestic poplar production, which will continue into the medium term, may effect a favourable wood market and encourage new poplar plantations.

There is a need for greater awareness and consistency on the part of government agencies and departments in promoting and supporting sustainable production of the poplar resource through the use of MSA clones and certification of plantations in accordance with sustainable management standards.

Take-home messages

- The Italian wood industry is increasingly relying on the production of poplar wood from environmentally sustainable plantations.
- The development of sustainable poplar cultivation should be supported by appropriate national and community policies.

Case study 17

LINKING FARMERS AND INDUSTRY THROUGH POPLAR PLANTINGS

R.C. Dhiman

In the Indo-Gangetic Plain south of the Indian Himalayas, agroforestry based on poplar (*Populus* L.) has gradually developed over the last 50 years to supply raw materials for industrial wood production. This a new geographical location outside the natural distribution range of poplar species. In 1976, a poplar plantation programme in the area was initiated by WIMCO Ltd, a company manufacturing safety matches. Today, the production of matchwood on farmer fields has reached maturity, and wood is being supplied to numerous industrial units. The programme has been highly successful due to the commitment and foresightedness of this company in promoting and developing its vision for industrial wood production integrated with poplar-based agroforestry. The success of this well thought-out and dynamic strategy can be attributed to multiple components in the initial stages of the programme, as follows:

- The programme began by engaging an integrated team of extension workers trained in agriculture, forestry, and legal and marketing aspects.
- Initially, plantation establishment costs were covered by the company. Saplings were supplied for free and then at subsidized rates.
- Financial arrangements were made, including insurance for trees and contracts with farmers for wood to be purchased at a guaranteed price.
- Research support was provided for developing new clones and technologies.
- Saplings were supplied for cash payments, without contracts, at the establishment of the programme.

This success story, achieved by providing solutions for poplar-based agroforestry, has inspired other wood-based industries and government institutions to follow suit and is being extended to other fast-growing species. Models such as the one presented here are contributing to shifting sustainable wood production and supply from forests to agroforests while also improving net returns to farmers. Such models also create jobs in rural locations, improve environmental quality and help provide greater crop diversity in moving away from monocropping.

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7 Fast-growing trees in the landscape

7.1 Forest and landscape restoration

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Summary

Using fast-growing trees (FGTs) in forest and landscape restoration (FLR) can support faster land cover, root expansion and soil formation. Fast-growing trees can be associated with a wide range of restoration interventions, providing the multifunctionality that landscape recovery programmes require to mitigate land degradation while building sustainable livelihoods and the resilience of communities and developing value chains at the local and national levels.

Keywords: Forest and landscape restoration; landscape dynamics; land degradation neutrality; landscape rehabilitation, reconstruction, reclamation and replacement

Introduction

Forest and land degradation is a major concern worldwide, particularly in developing countries. According to United Nations statistics (UNSD, 2021), in 2019, approximately 1 billion people, that is, nearly 15 percent of the world's population, lived in areas considered to be degraded while one-third were affected by land degradation. The loss of forests and trees is one of the biggest concerns for countries seeking to combat desertification, land degradation and drought. The United Nations Convention to Combat Desertification (UNCCD) has set a framework of action on land degradation neutrality (LDN), which is defined as:

> a state whereby the amount and quality of land resources, necessary to support ecosystem functions and services and enhance food security, remain stable or increase within specified temporal and spatial scales and ecosystems (UNCCD, 2019).

Forests and trees are essential for making progress towards LDN. Deforestation and the removal of trees from agricultural and pastoral landscapes have been key drivers of degradation for centuries. While deforestation trends have slowed in recent decades, the conversion of forest cover to other land uses continues to be the main source of land degradation (FAO and UNEP, 2020).

Among the main approaches for achieving LDN, FLR is crucial. The term forest and landscape restoration is new, dating back to 2001, but most of its components are not (Laestadius *et al*., 2015). It combines adaptive management, participatory techniques, and innovative procedures and technologies into a flexible and creative approach for establishing trees in degraded landscapes.

Forest and landscape restoration provides a complementary framework – to both sustainable forest management and the ecosystem approach – in landscapes where forest loss and land degradation have caused a decline in the quality and quantity of the supply of ecosystem services. However, FLR is not a set of design, management and implementation actions aiming to re-establish pristine forest (Maginnis, Rietbergen-McCracken and Sarre, 2006). It aims to restore forest cover at a particular site by considering the site within the context of the wider landscape, encompassing all land uses and the people within it (Stanturf *et al*., 2016).

Forest and landscape restoration aims to strengthen the resilience of landscapes to ever-changing patterns of ecosystems in which physical, biotic and anthropogenic components coexist. Further, FLR aims to support communities as they strive to increase and sustain the benefits that they derive from the management of their land while also maintaining the ecological resilience of the environment.

How landscapes are perceived matters. Discourses on landscape design and management often reflect conservation issues related to particular landscapes. These landscapes are often viewed according to a static representation that does not consider their ever-changing dynamics. But the perception of landscapes should encompass the complex and ever-changing relationships of a community with the surrounding environment. The Council of Europe (2000) provides a better definition of *landscape*: "'Landscape' means an area, as perceived by people, whose character is the result of the actions and interactions of natural and/or human factors".

The nexus between fast-growing tree plantations and forest and landscape restoration

Fast-growing trees as we know them today appear in masterpieces by the Impressionists who painted outdoors from nature, capturing scenes of modern life in rural, suburban and urban settings. In *Les Peupliers* (Poplars) painted in 1879–1880, Paul Cézanne depicted a clump of tall trees on the banks of the Viosne in Île-de-France. Cézanne, like Pissarro earlier, represented trees planted by human activities rather than trees that grew "naturally". The signs of human activity organizing the landscape were thus apparent in his paintings.

Ten years later, Vincent van Gogh (1890) wrote to his brother Theo about the painting *Undergrowth with two figures* (Figure 7):

> Then undergrowth, violet trunks of poplars which cross the landscape perpendicularly like columns. The depths of the undergrowth are blue, and under the big trunks the flowery meadow, white, pink, yellow, green, long russet grasses and flowers.

Van Gogh was struck by the contrast between the geometric sequence of the poplars and the chromatic – and biological – diversity of the undergrowth.

Poplars were a distinctive element in the landscapes represented at the end of the nineteenth and beginning of the twentieth centuries. Throughout the twentieth century, poplars continued to be widely used in land rehabilitation programmes across Europe. The IPC was founded in 1947 to facilitate the restoration of severely *degraded landscapes* in Europe after the Second World War. As such, the concept of FLR permeated the IPC's vision well before the term was invented.

Although there is a natural connection between FGTs and FLR programmes, this relationship often seems to be overlooked. Consider the high number of contributions on FLR in the scientific and technical literature. A quick search on Google Scholar for "forest landscape restoration" yields nearly a million results. But if the terms FLR and FGTs are associated, the results drop to 96, a number that increases slightly to 546 results when using "forest restoration" instead of "forest landscape restoration".

Fast-growing trees meet a wide range of needs and objectives towards FLR. This is due both to FGTs' intrinsic characteristics (e.g. enhanced growth rates and thus rapid establishment of soil cover and expansion of root systems) and the modularity of FGT planting systems, compared to traditional reforestation. This means that FGTs can be associated with a wide range of restoration interventions. Implementing FGT plantations for FLR programmes can also provide the multifunctionality that landscape recovery programmes require. Because FLR has both ecological and social dimensions, it is important to create win–win situations by interconnecting four pillars: (1) mitigating land degradation; (2) protecting biodiversity; (3) building resilience; and (4) developing sustainable livelihoods for communities. Fast-growing trees are often a good option for balancing all these aspects.

According to Stanturf, Palik and Dumroese (2014), forest restoration objectives can be broadly classified into four overarching strategies, namely:

1. **rehabilitation**, meaning the restoration of desired species, structures or processes in an existing ecosystem;
2. **reconstruction**, meaning the restoration of native plants on land that is in another use;
3. **reclamation**, meaning the restoration of severely degraded land devoid of vegetation; and
4. **replacement**, in which species or provenances ill-suited to a given location and unable to migrate are replaced with introduced species in the interest of climate-change adaptation.

Forest and landscape restoration can be interpreted in relation to the stages of forest transition. Rehabilitation is normally carried out to restore the productivity of a forest in the degraded stage, while reconstruction or reclamation are carried out in forests that are so degraded they have ceased to function as effective forests. In many parts of the world, abandoned agricultural land will regenerate naturally to form secondary forests, which are different in their nature and composition from the forests that preceded them. Active management and enrichment planting of FGTs can accelerate this process or change the trajectory of the succession so that the structure or composition better achieves management objectives.

In the eastern ridge of Bogotà in Colombia, plantations of *Eucalyptus* L'Hér and other FGTs established for commercial purposes have fulfilled a protective role against land degradation well beyond their given purpose, which was to create wood-producing landscapes. These plantations are now being managed as the initial stages of a long-term process of native forest rehabilitation.

Natural disasters, including wildfires and wind-storms, may cause the loss of forest cover over large areas. Restoration may then be required to accelerate natural regeneration processes and a return to a more productive condition. Following an El Niño-related wildfire event about 30 years ago, the landscape in northern Sabah (Pulau Jambongan, Malaysia) has been invaded by imperata grassland (*Imperata cylindrica* L.) and fern cover. In 2011, part of the degraded area was planted with FGT species as a first step to re-establishing productive forest cover. Without intervention, the entire area would likely still look as degraded as the unmodified surrounding areas (Stanturf, Mansourian and Kleine, 2017).

Approach to socioeconomic systems and their governance

Community-based forest management is widely recognized as one of the more effective means of combating deforestation while also supporting the livelihoods of local communities. However, the effectiveness of community-based management is dependent upon the broader socioeconomic context including tenure type, community governance, local capacity, opportunity costs and incentives.

Six key questions (Figure 8) can help stakeholders understand:

- landscape dynamics; and
- the ways in which information about, and awareness of, the effects of tree-cover change can elicit feedback that drives change (Van Noordwijk and Sunderland, 2014).

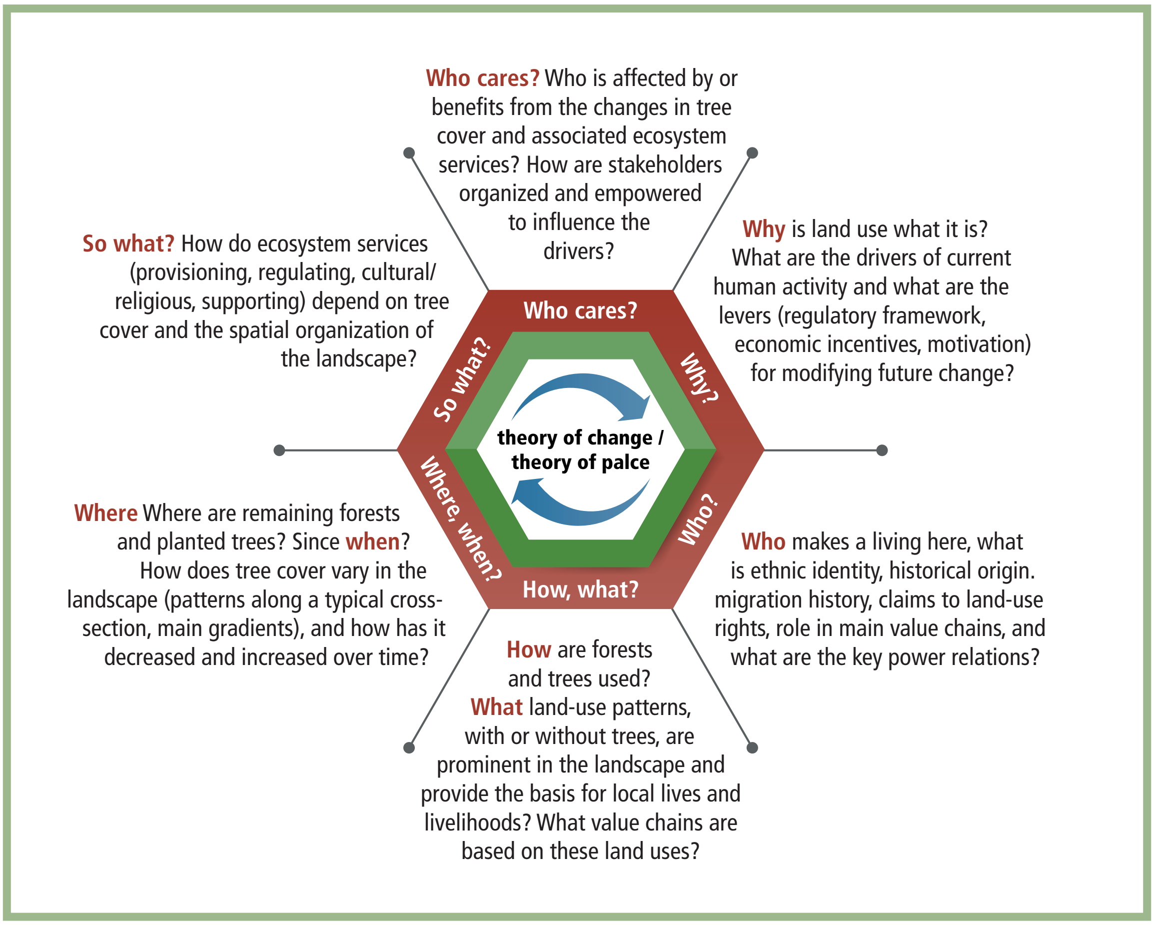
Take-home message

- The use of well-designed, properly implemented and sustainably managed FGT plantations is recommended to create win–win situations in which FLR, biodiversity protection, climate-change adaptation and the development of income alternatives for local communities are interconnected.

Figure 8. *Undergrowth with two figures* by Vincent van Gogh

Source: **van Gogh, V.** 1890. *Undergrowth with Two Figures*. Cited 17 April 2021. https://commons.wikimedia.org/wiki/File:Vincent_van_Gogh_-_Undergrowth_with_Two_Figures_-_Google_Art_Project.jpg

Figure 9. Six questions to support stakeholders in forest landscape restoration programmes



Source: **Van Noordwijk, M. & Sunderland, T.** 2014. Productive landscapes: what role for forests, trees and agroforestry? In: J. Chavez-Tafur, R. Zagt, Tropenbos International & European Tropical Forest Research Network, eds. *Toward productive landscapes*. ETFRN news No. 56. Wageningen, Tropenbos International.

Case study 18

FAST-GROWING TREES AS A MEANS FOR REHABILITATION, RECONSTRUCTION AND RECLAMATION IN ARID DRYLANDS UNDER DESERTIFICATION

Advection fog is the sole source of water for many coastal arid drylands worldwide, such as the lomas. These drylands are fog-dependent landscapes of the coastal zone of Peru and northern Chile, where deforestation has occurred since the sixteenth century, leading to progressive and severe desertification. A forest and landscape restoration (FLR) programme in fogscapes (Salbitano *et al.*, 2010) was initiated in the mid-1990s in the coastal hills close to Meija (Arequipa department, southern Peru). Trees of native species (*Caesalpinia spinosa* (Feuillée ex Molina) Kuntze and *Prosopis pallida* (Humb. & Bonpl. ex Willd.) Kunth) and exotic species (*Acacia saligna* (Labill.) H.L. Wendl., *Casuarina equisetifolia* L., *Parkinsonia aculeata* L.) were planted in 1996 to test the FLR potential of the degraded lomas ecosystems under desertification. Among the selected trees, *C. equisetifolia* and *A. saligna* were planted as FGTs in clusters mixed with native species to speed up forest-cover rehabilitation and enhance soil formation. *C. spinosa* demonstrated the highest rate of survival, while *A. saligna* and C. *equisetifolia* exhibited the greatest height, diameter and crown volume increments.

Habitat conditions of the area in terms of diversity and frequency of plant and animal populations, and plant cover, have changed substantially over the years. Overall, the tree-covered soil showed more diversity and frequency of both types of populations than the non-forested areas, thus demonstrating the efficiency of the intervention in terms of combating the greenhouse effect. The various tree species planted, however, showed a highly variable capacity to promote carbon sequestration at the soil level.

Irrigation of the plantings was carried out through water harvesting by large fog collectors. From the third year onwards, all trees relied only on fog water collected by their canopies. Survival rates, heights and root collar diameters were monitored until 2016, when the soil carbon and nitrogen stocks were also measured. Fifteen years after planting, about 65 percent of trees were still alive and growing, and reforestation had induced substantial carbon sequestration both above and below the ground. Of the tree species, *A. saligna* had the best performance, with most of the aboveground carbon stored in its biomass, leading to its consequent high efficiency as a natural fog collector (Certini *et al.*, 2019).

Sources:

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Certini, G., Castelli, G., Bresci, E., Calamini, G., Pierguidi, A., Villegas Paredes, L.N. & Salbitano, F. 2019. Fog collection as a strategy to sequester carbon in drylands. *Science of The Total Environment*, 657: 391–400. https://doi.org/10.1016/j.scitotenv.2018.12.038

Case study 19

FAST-GROWING TREES AS A MEANS FOR REHABILITATING ECONOMIC AND ECOLOGICAL CONDITIONS UNDER FOREST AND LANDSCAPE RESTORATION PROGRAMMES

Plantations of fast-growing tree (FGT) species should be considered to accelerate the return of economically and ecologically valuable forest stands on land no longer used for agriculture. Besides producing wood, FGTs provide cobenefits such as ecological restoration and the cultivation of non-wood products (NWPs) in the understorey. However, few studies have directly compared the habitat created by plantations with the natural forest habitat that develops on former croplands. The effects of FGT plantations in terms of soil characteristics and understorey vegetation communities were assessed in experimental plantations of two poplar hybrid clones ('915303', a hybrid of *Populus maximowiczii* A. Henry and *Populus balsamifera* L.; and '131', a hybrid of *Populus deltoides* Bartr. ex Marsh. and *Populus nigra* L.). Results from FGT plantations were compared with the neighbouring unmanaged abandoned fields and older secondary forests at eight sites in the Eastern Townships region of Québec, Canada (Boothroyd-Roberts, Gagnon and Truax, 2010).

The FGT plantations did not have significant effects on soil chemical properties, but greater effects on shade and leaf litter were observed. Greater leaf litter and denser shade were observed in the M×B plantations than in the D×N plantations, while the more productive plantations of both clones were similar to the forests in terms of these characteristics. Both plantation types favoured the colonization of the sites by tree species compared to the unmanaged fields, while the herb and shrub communities remained similar to those of the abandoned fields. Hybrid poplar plantations of either clone can accelerate the restoration of certain understorey attributes, particularly at recently abandoned sites.

Another key aspect refers to cultivating forest understorey species in hybrid poplar plantations. This could provide an interesting alternative to the cultivation of understorey species in naturally regenerated woodlots and can help avoid any harvest from natural populations. The changes produced by hybrid poplar plantations in terms of light and leaf litter are sufficient to create a habitat suitable for colonization by tree species and for the adult life stages of certain forest herb species.

Source:

Boothroyd-Roberts, K., Gagnon, D. & Truax, B. 2010. En sous-bois de plantations de peupliers hybrides: Une nouvelle vie pour les plantes forestières. *Progrès Forestier*: 12–16.

Case study 20

ECONOMIC NURSE TREES: *EUCALYPTUS* FOSTERING THE RESTORATION OF HIGH-DIVERSITY TROPICAL FORESTS

Nino Tavares Amazonas, Carina Camargo Silva, Pedro H.S. Brancalion and Ricardo Ribeiro Rodrigues

Ecosystem restoration has become a global priority, and commitments to restore degraded lands have reached millions of hectares throughout the world. This creates a major challenge for governments and landowners, who need to finance restoration initiatives. Restoring degraded lands is expensive and provides little or no economic return. In many cases, the high costs discourage landowners from carrying out restoration. This is one of the main obstacles to achieving large-scale restoration. To overcome this barrier, high-diversity mixed forests were created that temporarily intercropped exotic *Eucalyptus* L'Hér with 30 tree species native to the Brazilian Atlantic Forest. Native tree species and fast-growing commercial varieties of *Eucalyptus* were planted to be harvested within 5 years and sold to the pulp and paper industry, while the native tree species would grow at a slower pace. The fast-growing varieties of *Eucalyptus* were used as economic nurse crops, playing the role of a pioneer species and providing an early economic return to offset the high costs of reforestation. Intercropping was found to be a viable option from an ecological and silvicultural perspective and confirmed the financial viability of this type of forestry system. These transient, high-diversity mixed forests are at the interface between traditional restoration systems and traditional commercial silviculture. The adoption of this strategy has the potential to offset the total costs of reforestation and to generate net revenue, which varies from case to case. *Eucalyptus* should be intercropped with native tree species for one rotation, or a few rotations, until the intended economic return is reached. After that, only native tree species should remain in the restored forest. This forestry system can be easily adapted to other parts of the globe, using another species as the economic nurse tree along with a variety of local native tree species. High-diversity mixed forests that temporarily intercrop an economic nurse tree with a wide range of native tree species are a viable way of offsetting the high costs of tropical forest restoration.

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7.2 Agroforestry and trees outside forests

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Summary

Agroforestry, that is, combining trees with crops, grazing animals or both, is a traditional land-use system that was neglected during the Green Revolution but is being re-evaluated as a way of addressing the trilemma of ensuring wood and food security while safeguarding the environment. Agroforestry develops complex agroecosystems that are potentially more resilient to abiotic and biotic stress factors than commercial agriculture, but which are also labour intensive. Many fast-growing tree (FGT) species are integrated in diverse, traditional and innovative agroforestry systems combining the production of food and construction materials. These tree species vary greatly depending on site conditions but are often allowed to regenerate naturally. Innovations may involve the introduction of mechanical or cultural operations to reduce the complexity of management, as well selecting FGT species and cultivars resistant to stress factors and adapted to changes in climatic conditions, or to complement agricultural land productivity.

Keywords: Agroforestry; trees outside forests; multifunctional systems; ecological intensification

Introduction

Agroforestry is a collective name for land-use systems and technologies in which woody perennials such as trees, shrubs, palms or bamboos are deliberately used on the same land-management units as agricultural crops, animals, or both these, in some form of spatial arrangement or temporal sequence (Nair, 1993). More recently, agroforestry also involves natural tree regeneration practices known as farmer-managed natural regeneration (FMNR), whereby native tree stumps are allowed to regenerate and are managed on farms and pastoral lands for tree products, soil carbon and nutrient cycling, shade and biodiversity benefits (Larwanou, Abdoulaye and Reij, 2006; Haglund *et al*., 2011; Reij and Garrity 2016). Agroforestry systems worldwide are extremely varied. Traditional agroforestry systems include pasture or arable land with scattered trees, windbreaks, tree hedges along field margins, and grazing in forest plantations or orchards. Examples of innovative agroforestry systems with FGTs are:

- alley cropping;
- buffer strips along field edges or water bodies for phytoremediation and bank protection against soil erosion and pollution (Borin *et al*., 2010); and
- modern silvopastoral systems for animal thermoregulation and well-being, and for the balancing of climate-altering animal emissions (Torres *et al*., 2017).

The most important benefit of agroforestry systems with FGTs is using agricultural land whose soil fertility sustains high tree growth rates. Such systems address the trilemma of producing wood products and agricultural commodities while preserving the environment (e.g. through biodiversity conservation, reducing agricultural pollutants and soil erosion, and carbon sequestration for mitigating climate change). With this approach, agroforestry systems and FGTs are a modern form of smart agriculture.

Fast-growing tree species most frequently used in agroforestry systems are poplars (*Populus* L.) in temperate areas, poplars and eucalypts (*Eucalyptus* L'Hér) in the subtropics, and gliricidia (*Gliricidia* Kunth) and leucaena (*Leucaena* *leucocephala* [Lam.] de Wit) in the tropics (Wolz and DeLucia, 2018). Short-rotation Australian acacias (*Acacia* Mill.) involving *Acacia auriculiformis* A. Cunn. Ex Benth. and *Acacia mangium* Willd. and its hybrids offer crucial wood contributions when plantation-managed under smallholder systems, as in Viet Nam and India (Dinh Kha *et al*., 2012). Overall, there is an increased use of diverse tree species that are well adapted to specific site conditions in different areas of the world (Figure 9), thereby contributing a huge reservoir of on-farm biodiversity (Wolz and DeLucia, 2018).

Different types of agroforestry systems

Based on different site conditions and socioeconomic contexts, it is possible to distinguish among several agroforestry systems that include FGT species, as described below.

<u>Tree alley cropping</u>

Tree alley cropping is a form of cultivation of FGTs mostly for timber production, in which widely spaced tree rows are alternated with alleys that are 20–40 metres (m) wide containing agricultural crops on fertile, alluvial soils. Tree density is generally low, less than 100 trees per hectare (ha), in order for sufficient solar radiation to penetrate through the tree canopy and reach the ground floor for the intercrops. Total productivity of the system, considering the timber and the crop yields, is very high. Expressing this total productivity as the land equivalent ratio (LER) according to Mead and Willey (1980), simulations show LER values that are often greater than 1, reaching a maximum value of 1.4. The maximum of 1.4 means that 1 ha of tree alley cropping produces 40 percent more than equivalent areas with tree and crop monocultures (Graves *et al*., 2007). Tree alley cropping is widely practised in northern India, mostly with local clones of hybrid poplars. Small farmers are particularly attracted to this cultivation system due to its high profitability (Chavan and Dhillon, 2019), as the local price for poplar timber is very high.

Innovative activities with pilot experiments on tree alley cropping are conducted in many parts of the world. In Europe, hybrid poplars and paulownia (*Paulownia* Siebold & Zucc.) are used, while in Canada, hybrid poplars and hardwoods with moderate growth (e.g. *Fraxinus americana* L., *Quercus rubra* L. and *Quercus macroamericana* L.) are alternated within rows (Carrier *et al*., 2019). In Brazil, tree alley cropping is also studied with clones of hybrid eucalypts (Alves Barbosa *et al*., 2019). Overall, tree spatial arrangements within the tree row greatly affect system profitability, and wider arrangements with the highest allocation of tree biomass for timber (40 percent for sawing) are preferred. Thus, a key element of tree alley cropping for successful adoption by farmers is wood prices, for which it is necessary to maximize the quantity and quality of the timber produced. For this reason, experiments on tree alley cropping are often conducted with valuable hardwood timber species like walnut (*Juglans* L.) and cherry (*Prunus avium* L.), which have moderate growth (Morhart *et al*., 2014). Research is also exploring the possibility of mixing these species (within rows) with fast-growing woody species that have coppice management for bioenergy production, like poplars, willows (*Salix* L.) and alders (*Alnus* Mill.).

A possible variation of the above system is <u>coppice alley cropping</u>, in which trees are managed as coppice with short rotations (less than 5 years) and to produce wood chips for energy conversion. Trees are densely planted (> 5 000 stems/ha) in rows or strips alternated with alleys (9–35 m wide) of arable crops or grassland (Kanzler *et al*., 2019). Again, FGT species used in coppice alley systems are poplars and robinia (*Robinia pseudoacacia* L.) and are grown to produce wood chips for energy conversion. This system is mostly studied in northern or continental European areas with wet climates, as water availability is a strong limiting factor for trees under short-rotation coppice (SRC) management (Paris *et al*., 2018). Additionally, intercropping between timber trees with moderate growth (e.g. walnut and cherry trees with 30- to 40-year rotations) and fast-growing SRC trees (2- to 5-year rotation) is also studied in Europe, and this system is called <u>alley coppicing</u> (Morhart *et al*., 2014). Its main advantage is combining tree species with different growth rates and ecophysiological niches. However, the competitive interactions between timber and SRC species require careful management.

Riparian forest buffers

Similar to tree buffer strips planted along field margins for runoff and agricultural pollution control, riparian forest buffers are recognized by the United States Department of Agriculture (USDA) as conservation strips of trees, shrubs or perennial plants located adjacent to watercourses (USDA, 2012). Riparian forest buffers are managed to prevent pollution of streams, lakes and wetlands through interception and mitigation of constituents such as nutrients, pesticides, animal waste and suspended sediment. In the United States of America, multiple conservation programmes currently provide financial support for the establishment of riparian forest buffers (Cunningham, Stuhlinger and Liechty*,* 2009; Cartwright *et al*., 2017). Suitable FGT species include poplars, willows, robinias, alders, eucalypts, plane trees (*Platanus* L.), *Acer negundo* L. and *Acer pseudoplatanus* L. In addition to providing invaluable ecosystem services (e.g. pollutant mitigation [Pavlidis and Tsihrintzis, 2018], bank stabilization [Schultz *et al*., 2004], enhanced resilience to climate change [Seavy *et al*., 2009]), FGTs grown in this manner are also suited to on-farm use as fuelwood, livestock fodder, mulch and conversion into wood chips for bioenergy, while also enabling management for game and the provision of waterfowl habitat (Christen and Dalgaard, 2013; Fortier *et al*., 2016).

Windbreaks

Windbreaks, also known as shelterbelts, are linear plantings of trees and shrubs that have been implemented in agricultural settings for centuries to manage wind and snow. The favourable microclimate created by windbreaks can markedly improve crop and livestock production as well as enhance human quality of life. Worldwide, eucalypts, poplars and willows have been the main FGTs implemented in windbreaks (Jacobs, 1979; Matthews *et al*., 1993; Peri and Bloomberg, 2002; Kuhns, 2012; Isebrands and Richardson, 2013), as well as acacias to a lesser extent (Nuberg, 1998). Given that windbreaks are a well-established practice worldwide, the greatest potential for FGT innovation regards the development of new clones that do not require canopy spraying. Another possible innovation is using windbreaks formed by strips of FGTs as SRCs. In this manner, FGTs have lower total tree height than standard, non-coppiced trees (Kanzler *et al*., 2019), whose high and large canopy might shade adjacent crops.

Boundary plantings and hedgerows

Tree planting on smallholder farms involves line planting designs that minimize competition with agricultural crops while serving as farm boundary markers, windbreaks and fodder banks. Additionally, trees planted along contour lines to help stabilize soil conservation structures in combination with grasses such as *Pennisetum purpureum* Schumach. (napier grass) for livestock are widespread throughout the mixed-cropping systems of East Africa. Common timber tree species used to serve in this role include *Grevillea robusta* A. Cunn. Ex R. Br., *Alnus acuminata* Kunth, *Cordia africana* Lam., *Markhamia lutea* (Benth.) K. Schum., and *Faidherbia albida* (Delile) A. Chev. Integration of *Calliandra calothyrsus* Meissn., *Gliricidia sepium* (Jacq.) Walp. and legumes to support maize and bean intercrop systems contribute to available farm biomass, soil fertility, water infiltration and water-use efficiency. In traditional parkland agroforestry systems, maize biomass and yields have been shown to be significantly greater under tree canopies compared to crop-only plots (Dilla *et al*., 2019).

Perennial tree or shade crop systems

Multistory tree–crop systems involve rubber, cocoa, oil palm or coffee agroforests with tree components such as *Grevillea robusta*, *Cordia africana*, *Albizia gummifera* (Gmelin) Smith, *Artocarpus heterophyllus* Lam., species of *Macadamia* F. Muell., *Persea americana* Mill. and others scattered on the farm. Banana and horticultural crops such as vanilla and cardamom are also included to add profitability in African and Asia contexts. Available evidence suggests that win–win relationships for biodiversity and yields can be realized in appropriate circumstances and that small farms can greatly contribute to the maintenance of species richness.

Farmer-managed natural regeneration

Farmer-managed natural regeneration is based on the systematic regrowth of existing trees or self-sown seeds and is possible wherever there are living tree stumps or roots with the ability to coppice (resprout) or seeds in the soil that can germinate. Farmers have many different objectives in mind when they practice FMNR, including soil fertility, windbreaks, woodfuel and building poles for home consumption and sale, fruit, edible leaves, fodder, erosion control, reversal of land degradation, aesthetics, medicines, income generation and social acceptance. Farmer-managed natural regeneration is now being considered as a promising climate-smart agroforestry practice that represents an affordable means of enhancing rural livelihoods. Further, FMNR may contribute to the conservation of biodiversity, as well as climate-change mitigation by sequestering carbon in tree biomass and soil.

Take-home messages

- Agroforestry systems with FGTs play an important role in the development of multifunctional and resilient farming systems that can help feed the world while protecting the biosphere.
- Research innovations involving FGTs can be implemented in improved (novel) systems as well traditional ones.

Case study 21

TREE ALLEY CROPPING WITH NOVEL HYBRID POPLAR CLONES ON ALLUVIAL SOILS OF SOUTHERN EUROPE

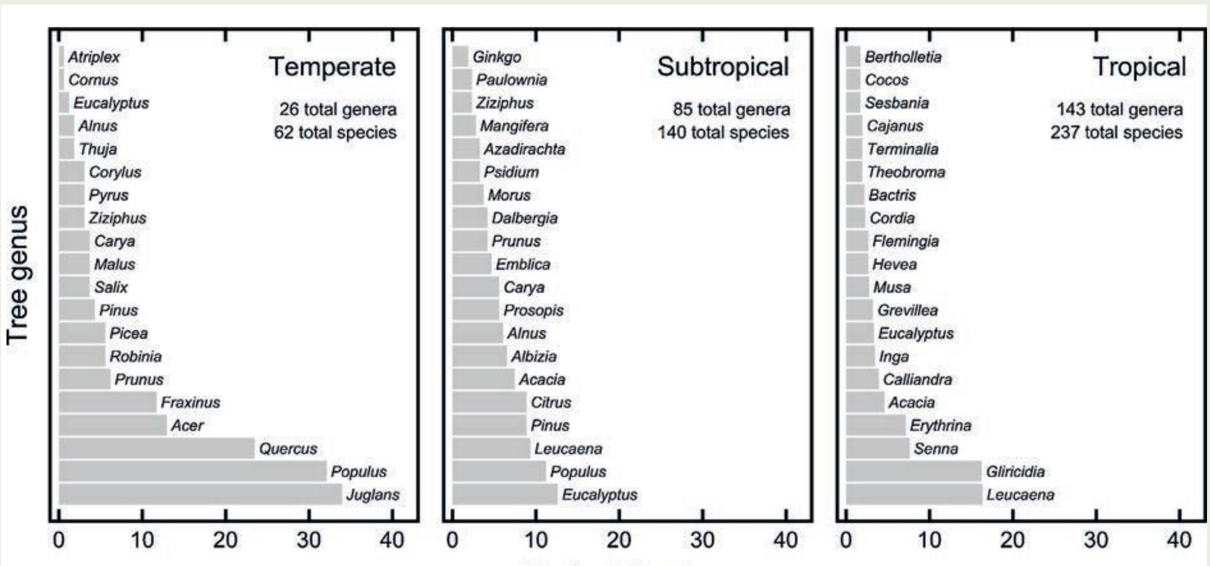
The intercropping of crops with poplar trees for timber production was largely practised in southern Europe during the twentieth century until the late 1970s (Paris *et al*., 2019). This practice was then almost abandoned because tree canopy spraying for pest/disease control often hindered the management of intercrops. Nowadays, tree alley cropping is again being studied for its important environmental and productive values for mitigating climate change and the environmental emergencies of modern agrimonoculture (Kay *et al.*, 2019) In Europe, public institutions provide funding for the establishment of tree alley cropping. For example, in Italy, new poplar clones are now available that do not require canopy spraying, known as Maggior Sostenibilità Ambientale (MSA) clones (Coaloa *et al*., 2016). A network of three experimental sites was recently established in Italy with the aim of optimizing the tree alley cropping system according to the criteria of modern agriculture. Research is currently in progress. The first experimental results of one site (10 ha) established in 2014 are very encouraging in terms of tree growth, intercrop yield and financial profitability. Tree rotations are expected to be 10 years. The key element for financial profitability is the final timber quality of the harvested trees. In the context of a modern market economy, the final timber produced should have very high standards for plywood processing and should be able to fulfil the requirements of the furniture industry. Thus, trees with fast growth rates that produce high-quality timber and do not require canopy spraying are essential for successful management of tree alley cropping in areas of southern Europe with intensive agriculture.

Case study 22

ECOSYSTEM SERVICES AND PROFITABILITY OF AGROFORESTRY PHYTOBUFFERS WITH COVER CROPS AND ENDOPHYTES

Industry and conventional agriculture have led to increased degradation of the soils and waters of the Great Lakes region, United States of America, which limits social, environmental and economic progress. These impacts have caused subsequent losses of on-farm profits and, in many cases, a decrease in the quality of life for farmers, ranchers and growers. There is a need for plant-based systems that enhance the ecosystem services of degraded agricultural lands and waters. To address this need, the Great Lakes Restoration Initiative (GLRI) was established in 2010 (GLITF, 2014). One of the GLRI's five main focus areas is non-point source pollution impacts on nearshore health, which specifically aims to mitigate pollution of the Great Lakes. With funding from the GLRI, a regional network of specialized poplar (*Populus* L.) phytotechnology installations was established in 2017–2019 on lands contaminated with inorganic and organic pollutants. The main objective is to reduce potentially contaminated runoff and subsurface water flow that can impact the ecosystem services on which agriculture depends. Continuing efforts of this endeavour include the integration of cover crops and soil endophytes with existing trees to establish a replicated research and demonstration network of 16 agroforestry phyto buffers in the Lake Michigan and Lake Superior watersheds. This project seeks to enhance quality of life, stewardship of ecosystem services and profitability for regional growers. The efficacy of these systems for implementation in an agricultural setting will be measured specifically as they relate to:

- reducing health risks from water and soil pollution by developing best management practices;
- enhancing ecosystem services such as water quality and soil health, along with carbon sequestration and biomass productivity of the trees; and
- decreasing grower costs and increasing land productivity for bioenergy, biofuels and bioproducts.



Frequency of genus occurrence in the tree component of agroforestry field experiments in temperate, subtropical and tropical climate zones.

Source: **Wolz, K.J. & DeLucia, E.H.** 2018. Alley cropping: global patterns of species composition and function. *Agriculture, Ecosystems & Environment*, 252: 61–68. https://doi.org/10.1016/j.agee.2017.10.005

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7.3 Urban and peri-urban forests

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Summary

Fast-growing trees (FGTs) are frequently used in urban greening projects worldwide, where they can help mitigate the increasing effects of climate change for city dwellers and can also be used to rehabilitate brownfield sites. Studies show that tree species used in urban environments have accelerated growth rates, meaning that they can provide benefits in a shorter time, but their faster ageing needs to be taken into account by urban planning and management.

Keywords: Urban forests; peri-urban forests; urban greening; phytoremediation

Fast-growing trees (FGTs) include several species that are considered in urban forestry and are relevant for the establishment of urban and peri-urban forests at the global level. In boreal and temperate zones, FGT genera such as poplar (*Populus* L.), maple (*Acer* L.), eucalypt (*Eucalyptus* L'Hér), willow (*Salix* L.), cedar (*Thuja* L.) and birch (*Betula* L.), and species such as *Liriodendron tulipifera* L., *Cupressus* × *leylandii* A.B. Jacks & Dallim. and *Paulownia tomentosa* (Thunb.) Siebold & Zucc. are frequently found in the green areas of cities and implemented in urban greening projects. There are several reasons for using FGTs in urban and peri-urban greening.
First, several FGT genera and species that are typical of rural landscapes in many countries have found their place in numerous urban and peri-urban greening projects. In European cities, for example, poplars and particularly *Populus alba* L. and *P. nigra* L. have been used successfully. In the greening of the streets of Barcelona, especially after the adoption of the Barcelona Green Spaces Plan in 1995, *P. alba* var. *pyramidalis* Bunge, also called *P. bolleana*, was used to rapidly increase canopy cover (Ajuntament de Barcelona, 2017). In 2009, about 11 000 out of 200 000 trees managed by the municipality of Barcelona were specimens of this species. *P. alba* is a tree that can achieve the canopy-cover objectives set out in the 2017–2030 strategic plan (Chaparro and Terradas, 2009; Ajuntament de Barcelona, 2017). Although there are some critical issues with the low mechanical resistance of its branches, *P. alba* lends itself to being used in Mediterranean climate zones as a valid alternative to eucalypts. In areas with a more continental climate, *P. nigra* var. *italica* Moench, also called Lombardy poplar, is more commonly used. In the metropolitan area of Milan, this species has frequently been used to create tree rows, specifically in plantations in Parco Nord Milano and in the recovery of the Falck landfills in the municipality of Cologno Monzese. Poplars are not always the preferred species for an urban environment. Research into urban areas of Portugal has shown that people who live near poplar rows tend to underestimate the health benefits of trees. This probably stems from the perception of poplar as a disturbance, with the potential to cause respiratory allergies and produce waste (Fernandes *et al*., 2019).

Second, FGT species can provide many ecosystem services, such as shading to reduce heat in urban areas, improved air quality (Muftakhova *et al*., 2020), absorption and storage of carbon dioxide (Chaparro and Terradas, 2009) and atmospheric particulate matter (Nguyen *et al*., 2015), and water flow regulation, all of which can help mitigate the increasingly devastating effects of climate change in urban areas. Indeed, the canopies of FGTs are particularly efficient in intercepting water, thus effectively managing storm waters (Van Stan II, Levia and Jenkins, 2015).

Third, any FGT species can improve the quality of soils through phytoremediation processes. In doing so, FGTs are able to rehabilitate urban areas that have previously been affected by industrial settlements (brownfields) or radioactive fallout through environmentally sustainable technologies (Laćan, McBride and De Witt, 2015).

The practice of phytoremediation can be combined with biomass production, which is one of the main uses of FGTs. Using short-rotation forestry (SRF), hybrids of poplar, willow and locust (*Robinia* L.) can help manage contaminated urban areas economically and effectively as they combine the added value of biomass production with landscape benefits (Padoan *et al*., 2019). Poplar clones, for example, have demonstrated their effectiveness in decreasing the concentrations of polychlorinated biphenyls (PCBs) and heavy metals in contaminated soils near the industrial centre of Taranto in the vicinity of residential settlements (Ancona *et al*., 2017).

Despite the advantages of FGTs, the use of these species and the changes that they produce in the peri-urban and rural landscape are not always well accepted by residents. In a study carried out in Hamburg, Germany, citizens reacted negatively to biomass plants using FGTs as an energy source. People showed a significantly more negative reaction towards the addition of trees to open landscapes characterized by *Erica* L. and meadows than to landscapes with a higher share of forests and fields (Boll von Haaren and Albert, 2014).

In addition to considering the growth rates of the species listed above, it is worth noting that various studies have highlighted how trees in urban areas grow faster than in their natural environment but also that trees in cities sometimes die earlier than trees in forests, thus losing the ability to provide ecosystem services such as carbon storage. Global and local studies in different climates have shown accelerated tree growth in urban areas, along with increased carbon sequestration and anticipated provisioning of many other ecosystem services. However, this biomass increase also means quicker tree ageing, especially for FGTs, indicating the need for early replacement and replanting (Pretzsch *et al*., 2017; Smith *et al*., 2019). To support green infrastructure and related ecosystem functions, urban planning and management must account for the enhanced rate of tree growth in urban environments. In FGTs, accelerated tree growth reduces mechanical stability and biotic resistance, thus elevating risks associated with planting in urban areas.

Fast-growing trees give citizens the opportunity to realize the benefits of a mature tree sooner. In some contexts, FGTs, including shade trees and fast-growing hedges, are used to provide quick benefits in urban landscapes. A factor to be considered is water availability in urban substrates, which are often very poor in physical, chemical and biological components. Many FGTs are water-demanding species that can fail when planted without an irrigation support.

Fast-growing trees are particularly suitable for reviving newly built neighbourhoods and for introducing new buildings into the urban fabric, especially in urban–rural interface areas. The use of FGTs requires careful planning of monitoring and maintenance activities, including, in the long term, the replacement of the tree.

A further aspect to consider is the role that FGTs (and trees in general) play in delivering provisioning ecosystem services and improving livelihoods in urban areas, particularly slums and poor outskirts. There are often sentiments among governments and research agencies that urban forestry is not important other than for recreation, landscaping, climate-change mitigation and, possibly, improving biodiversity. In the case of Zeerust (South Africa), households in the township planted intensively managed FGTs to improve informal family incomes (Paumgarten *et al*., 2005).

Take-home messages

- Fast-growing plantations in cities deliver a wide range of benefits for the well-being and livelihoods of urban dwellers.
- The quality of design, planning and management of FGT plantations in cities is a key issue to address for multiscale capacity-building programmes and awareness-raising interventions.

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7.4 Partnerships

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Summary

In the fast-growing tree (FGT) sector, partnerships are seen as instruments for facing specific problems, depending on the socio-environmental and economic context. This section shows different examples of the forms, methods and objectives of partnerships worldwide. All these examples, though radically different from each other, have some common elements, which have been identified. Finally, the section shows real examples of existing partnerships, highlighting the main characteristics but also factors of success and failure.

Keywords: Partnership; cooperation; value added; empowerment; certification

Introduction

There are over 570 million farms worldwide. Most can be classified as small, covering less than 2 hectares (ha), and family operated. Small farms account for about 12 percent and family farms for about 75 percent of the world's agricultural land (Lowder, Skoet and Raney, 2016). For many forest and plantation smallholders, establishing partnerships is the most effective way to access specific markets. Therefore, there has been increased experimentation in recent years with the use of partnerships, alliances and networks throughout the public, private and non-profit sectors to produce and deliver goods (and services).

Partnership is generally promoted both as a solution to reaching effectiveness and efficiency objectives and as the most appropriate relationship according to value-laden principles (Brinkerhoff, 2002a). According to Brinkerhoff (2002b), the ideal type of partnership can be defined as:

> a dynamic relationship among diverse actors, based on mutually agreed objectives, pursued through a shared understanding of the most rational division of labour based on the respective comparative advantages of each partner. Partnership encompasses mutual influence, with a careful balance between synergy and respective autonomy, which incorporates mutual respect, equal participation in decision-making, mutual accountability, and transparency.

The definition of partnership usually reveals an emphasis on mutual legitimation, commitment to cooperative processes, and joint decision-making or consultation (Haynes and Allen, 2001). This definition and these considerations apply to all types of partnerships in every sector, including primary production. In these contexts, smallholder forest producer organizations continuously evolve to meet new demands from their constituents, and based on external pressures, such as those deriving from climate change (Rantala, 2017).

Partnership for fast-growing tree cultivation and management

In the FGT sector, partnerships are established to reach different objectives and to solve specific problems, depending on the socio-environmental and economic context.

Existing partnerships worldwide demonstrate how cooperation among actors can enable them to solve common problems. As stated by the Collaborative Partnership on Forests (CPF),[1] many drivers of deforestation and threats to forests lie outside the forest sector. To enable countries to make progress and achieve globally agreed goals and

[1] The Collaborative Partnership on Forests (CPF) is an informal, voluntary arrangement among 15 international organizations and secretariats with substantial programmes on forests. These agencies share their experiences and build on them to produce new benefits for their respective constituencies.

targets for forests, intersectoral collaboration and coordination is needed at all levels, including among its member organizations (CPF, 2020). For example, in Asia and South America, there are many instances of vast plantations causing misalignment between people's needs, safeguarding the environment and developing economic activity. In Africa, FGT plantations have been accused of being a part of land-grabbing.

Agroforestry systems to produce raw materials and food, and related initiatives, which were widely taken up in India, for example, represent a great example of effective partnership and finding a balance between different needs (see Case study 23 – India). Also, in the Philippines, communities are encouraged through their organizations to grow agroforestry crops and engage in other livelihood activities in addition to the production of wood and wood products to provide an alternative source of income while the trees mature (Calderon and Nawir, 2006).

In Europe, cooperation and partnerships among smallholders and with public and private entities can facilitate access to markets and increase the incomes of owners. In Italy, owners of small poplar (*Populus* L.) plantations cooperate to implement "additional" best management practices and sell the ecosystem services generated, such as carbon credits, to large retail firms. This has also been possible thanks to smallholder group certification initiatives implemented by forest certification schemes that enable smallholders to group together, pool their resources and work as a team to achieve certification, making forest certification affordable and practical for small-forest owners. In South America, there are examples of how sustainably managed FGT plantations can also enable owners to establish ancillary activities, thereby creating additional incomes (see Case study 24 – Uruguay).

Although the forms, methods and objectives of partnerships can be radically different from context to context, there are some common elements that can be identified in all partnership examples around the world:

Careful selection of species to plant. The tree species to plant should be selected based on a careful assessment of the markets and site–species compatibility.
Adoption of outgrower schemes. Most of the risks in timber growing fall on the tree growers. An outgrower type of arrangement involving buyers and sellers early on would spread the risk.
Environmental impact of FGTs. All organizations involved in a partnership inevitably have to deal with issues related to environmental hostility, both internally and externally. Tree plantations with exotic species established on land to produce paper or pulp or biomass for energy conversion are considered by environmental groups all over the world to have negative effects on the environment (e.g. on soil fertility, biodiversity and water quality), the climate and people (e.g. because of the use of pesticides and other pollutants). This issue has to be considered to avoid the failure of relationships between partners.
Improving and promoting reinvestment mechanisms to ensure continuity and financial sustainability. Organizations should ensure that part of their earnings is reinvested in livelihood activities and in tree plantations.
Linking to markets and value-added products. Second- and third-party certification systems, participatory guarantee systems and internal control systems are all voluntary market tools that aim to provide a credible assurance for markets seeking sustainable or legal products, thus playing a role in the production of value-added products, which can generate higher incomes. In the case of FGT systems, especially with the involvement of smallholder farmers, this type of assurance should be a tool to increase smallholder access to markets.

Take-home messages

- Partnerships among stakeholders involved in FGT management, just like any other relationship, are based on dynamic agreement. Empowerment, active participation of stakeholders, knowledge sharing and relationship building are key themes for a successful partnership.
- Regardless of the trees that are used for plantations, a successful partnership should help alleviate poverty and improve livelihoods, especially if there are additional incomes from non-wood tree products, such as honey, foliage for fodder and bark tannins.

Assessing and classifying partnerships

According to the literature (Brinkerhoff, 2002a), there are five general areas for assessing and classifying partnerships: (1) compliance with prerequisites and success factors in partnership relationships; (2) the degree of partnership practice; (3) outcomes of the partnership relationship; (4) partner performance; and (5) efficiency.

The main prerequisites and facilitating factors for establishing strong and lasting partnerships are related to tolerance for sharing power and \ the willingness to adapt to meet partnership needs, which translates into receptivity to new solutions, flexibility in taking corrective action where needed, accommodation of special requests, and responsiveness to unforeseen situations. The presence of a "partnership champion" is another facilitating factor, considering that championing capacity not only entails strong capacity for negotiation and communication but also organizational skills and perceived legitimacy among partners and stakeholders.

In fact, legitimacy and trust, together with an existing senior management role, support the ability to meet performance expectations. The setting of clear goals and partner compatibility are identified in the literature as the main success factors in building and running partnerships.

Another key area for evaluating and classifying partnerships is the degree of partnership itself. This can be assessed through its defining dimensions: mutuality and organizational identity.

The first dimension (mutuality) includes equality in decision-making, transparency in the process, and the type of resource exchange, both monetary and non-monetary (e.g. soft resources like managerial and technical skills, information and legitimacy). Moreover, partnership mutuality also depends on reciprocal accountability. Specifically, within a partnership, partners have access to information on the performance of the overall partnership as well as of the related individual partners, upon request or on a regular basis. As shown by Brinkerhoff (2002a), this concept is directly connected to the concept of transparency: "Partners do not need to know everything about each other, but in partnerships, they should be open and honest about areas of common concern or any information that can potentially influence partnership effectiveness and efficiency". With regard to mutuality, another aspect that must be taken into consideration is the full participation of all members according to their needs and assigned tasks.

As mentioned above, the degree of partnership is also determined and affected by organizational identity, in which a series of elements play a crucial role, related to determining partner organization identities; extent and quality of organizational change; influence on the service quality and responsiveness of partners to core constituencies; perception of threats or compromises; influence on and use of core constituencies; nature of organizational adaptations or adjustments; perceptions of mutual adaptation; perception of the partners' adjustments in response to expressed concerns; and perceptions of overall impact on identity. In terms of the outcomes of the partnership relationship, three main aspects can be identified: the value added by partnership, whether the partners meet their own objectives, and the partnership identity.

The concept of "value added" is related to the confirmation that a partnership as a whole bears more fruit than the single partner organizations would on their own. Under partnership agreements, the concept of value added refers to qualitative and quantitative synergistic programme outcomes but also to linkages with other programmes and actors and to enhanced capacity and influence. Another key element related to the effectiveness and outcomes of a partnership is the extent to which individual partners meet their own objectives by being a member of the partnership. Enhanced performance in pursuing their own mission while satisfying the needs of constituencies contributes to the overall satisfaction of partners within a partnership. Finally, a successful partnership relationship is one that has developed its own partnership identity in terms of partnership organization and culture, mission, values, name recognition and partnership constituencies.

Partner performance is characterized by four main dimensions: (1) partner roles enacted as prescribed or adapted for strategic reasons; (2) compliance with expected and agreed roles; (3) satisfaction with the performance of partners; and (4) partner performance beyond the call of duty.

The last identified area for describing and assessing partnerships is efficiency. All organizations involved in a partnership in FGTs will inevitably have to deal with issues related to environmental hostility, both internally and externally. The identification of critical factors that could influence a partnership's success, and the extent to which these are continuously monitored and managed, are key aspects to evaluate the efficiency of a partnership.

In any case, it must be taken into consideration that partnerships, just like any other relationship, are based on dynamic agreement.

Case study 23

GROWTH OF FARM FORESTRY AND AGROFORESTRY IN INDIA – ITC

Suneel Pandey

The National Forest Policy 1988 emphasized the need for conservation of forests and for increasing forest and tree cover in India through extensive afforestation and major social forestry programmes. Given the raw-material needs of industry, the policy recognized that raw materials could no longer be sourced from forests and suggested that industry should take care of their sourcing needs by collaborating with farmers and other entities.

This prompted ITC to encourage and enable farmers to grow trees through farm forestry and agroforestry. To enable farmers to adopt these types of plantations, ITC initiated a tree improvement programme (TIP) focusing on genetic improvement of planting stock, which led to the development of site-specific, highly productive, disease-resistant clones of *Eucalyptus* L'Hér, *Subabul* (Lamarck) de Wit and *Casuarina* L. Along with these clones – also called ITC or Bhadrachalam clones – effort was also made to develop site-specific best management practices for each of the operational agroecological regions, in order to make the plantations competitive compared to agricultural crops.

Once the TIP was successfully transferred and established in the field, which took almost ten years, farmers began to realize its economic benefits, mainly in terms of the increased productivity of these clonal plantations, compared to the option of seed-based plantations. This development brought about the exponential growth of farm forestry and agroforestry plantations in the states of Andhra Pradesh, Madhya Pradesh, Karnataka and Uttar Pradesh. It also generated a huge wave of productive plantation creation in other states, with the support of agencies such as forest development corporations, forest departments and other pulp and paper mills, which contributed immensely to an increase in tree outside forests between 2001 and 2015.

Farm forestry plantations benefit from *in situ* soil and moisture conservation, groundwater recharge, soil enrichment due to accumulation of leaf litter and (leguminous) intercropping, and direct sequestration of carbon in trees. Farm forestry and agroforestry have the potential to reduce the vulnerability of the agriculture sector and rural livelihoods to climate variability and climate change.

Case study 24

CERTIFIED HONEY FROM SUSTAINABLY MANAGED PLANTATIONS

Gabriela Malvárez, PEFC Urugay Technical Secretary

Every fall in Uruguay, honey producers set their hives in eucalypt (*Eucalyptus* L'Hér) plantations, native forests and natural areas for the flowering season. Forest management in Uruguay is certified everywhere; beekeepers thus have the opportunity to get chain-custody certification for their product. The final product, certified honey, is guaranteed to have been produced in a forest area under sustainable management and where plants are not genetically modified. This adds value to the product and strengthens the partnership between tree-growers and local communities. The environment generates the ideal framework for promoting the development and professionalization of the sector, which helps optimize use of the productive area. Honey producers and certified forest companies agree to coordinate their work to allow honey production alongside other activities that take place in the forests, such as plantation management and grazing. The relationship between forest owners and honey producers is established through an annual contract in which the terms are agreed by both entities. Honey producers pay for each productive unit set in the forest, but marketing of the product is entirely up to the producers. Chain-of-custody certification in accordance with the Programme for the Endorsement of Forest Certification standard for honey and products from the beehive increases value added and demonstrates that the supply chain is managed sustainably in compliance with legislation and traceability requirements.

Case study 25

NCT FORESTRY COOPERATIVE WORKING WITH PARTNERS TO IMPROVE LIVELIHOODS IN RURAL COMMUNITIES

Craig Norris and Steve Germishuizen

In KwaZulu-Natal (South Africa), the NCT Forestry Cooperative, the Sustainable African Forestry Assurance Scheme (SAFAS), the South African National Biodiversity Institute and the Global Environment Facility are working together to:

- improve the productivity and sustainable management of plantations and woodlots in communal areas; and
- assist with market access by developing systems to make certification accessible to small-scale timber growers.

The project partnership has developed a new certification system (SAFAS) endorsed by the PEFC. This system is risk-based and will make certification more accessible to these small-scale timber operations. Certified products include *Acacia mearnsii* De Wild. timber for woodfuel, pulpwood and building poles and bark for tannin production, and eucalypts (*Eucalyptus* L'Hér) for pulpwood, poles and woodfuel. Timber is sold to the NCT Forestry Cooperative at depots or mills. The NCT cooperative pays timber farmers for the tonnes of wood that they deliver over the weighbridge (assisting with organizing loading and transport of the timber). The NCT cooperative then places the timber on the market, and any excess revenue generated through trading is paid back to the farmers through price enhancements or bonuses. Thanks to the project, numerous small-scale timber growers are generating cash income that is used for education, health and improving quality of life. The farmers are also benefiting from improved genetic material, forestry advice, plantation protection, and a new risk-based certification system that will help them access international markets. An awareness of sustainability and environmental issues has also been fostered.

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8 Conclusion

Although fast-growing trees (FGTs) can be found in different types of forests, they make up most of the 131 million hectares (ha) of intensively managed plantation forests around the world, as seen in previous chapters.

Fast-growing trees have been cultivated for millennia to provide wood and non-wood products for rural and urban communities. Today, multiple FGT species represent a widespread resource throughout the world and an important economic sector for many countries. Due to their rapid growth and high adaptability FGTs can help support the industrial bioeconomy and the livelihoods of local communities and also have huge potential for combating climate change and providing other ecosystem services. However, to obtain the greatest ecological and socioeconomic benefits, FGTs need to be carefully and sustainably managed, avoiding the replacement of natural forests with FGT plantations and counteracting the invasive capacity of many of these species when introduced outside their natural ranges.

The collection of studies in this publication has highlighted innovative practices in FGT management as well as the need to improve current knowledge on the genetics, physiology and ecology of FGTs. It raises awareness of the need to strengthen understanding of the enabling factors of sustainable management, such as governance, partnership, livelihoods facilitation, certified and balanced value chains, and socioecological issues.

The publication has provided an overview of FGTs based on the work of the IPC and its collaborators, introducing the main genera and species, summarizing the state-of-the-art in sustainable management, describing the factors affecting plant of vulnerability, resilience and health, and discussing exploration and characterization of genetic resources as a means for providing the knowledge base for their conservation and management.

Fast-growing trees include a wide variety of tree species in temperate, subtropical and tropical biomes throughout the world, belonging to the genera *Populus*, *Salix*, *Paulownia*, *Pinus*, *Acacia*, *Casuarina*, *Eucalyptus* and *Tectona*, among others. Most FGT plantations consist of trees of the same age, species and even clones, making them vulnerable to abiotic, biotic and anthropogenic disturbances. This vulnerability has been worsened by globalization and climate change, which have exacerbated the spread of new biotic threats from introduced FGT species, the resurgence of existing pests and diseases, and abiotic stress. Well-defined monitoring and protection strategies are required to mitigate these risks, both at the reproductive material level and in plantation implementation and management. Preventive management is the most desirable form of protection from diseases and pests. The use of material certified as healthy is key to protecting plants from pests and diseases in the context of international exchanges of vegetative material and relies on quarantine strategies.

Fast-growing trees are the most domesticated of forest trees, and genetic improvement focuses on increasing yield, wood quality and pest resistance. Breeding programme objectives should include environmental adaptability and tolerance to emerging pests. The conservation of genetic resources *in situ* should be sustained while *ex situ* collections should be expanded with new germplasm to counter current threats to genetic resources. The dynamic gene conservation of FGTs *in situ* requires the definition of gene conservation units, the implementation of genetic monitoring and better international coordination, while germplasm collections and common gardens need investments for long-term maintenance and monitoring. Interspecific hybrids will continue to be the main road for the improvement of some FGTs, and genomics, phenomics and modelling should continue to be implemented in future genetic improvement programmes. Trade and deployment of forest reproductive material (FRM) at the global scale would benefit from the wider participation of countries in the OECD Scheme for the Certification of Forest Reproductive Material Moving in International Trade, which is open to OECD and United Nations members.

This publication has discussed the ecological benefits of FGTs and their contributions to environmental sustainability. Fast-growing trees have a long history of use for the production of biomass, bioenergy and bioproducts but are increasingly being used to enhance or re-establish ecosystems services, such as carbon sequestration and climate-change mitigation and adaptation, biodiversity enhancement in degraded ecosystems and rural and urban landscapes, alleviation of desertification, water management innovations such as the remediation of soils and water, including through novel plant–microbe partnerships, and soil fertility enhancement.

The pivotal role of FGTs in providing socioeconomic benefits and contributing to livelihoods and production for the bioeconomy is consubstantiated by several contributing authors. This role is particularly expressed through smallholder systems for forestry, agroforestry and the well-being of human communities.

Technological innovations in the wood-processing industry have brought up opportunities for wood from FGT plantations to be used in the manufacturing of high-value structural products for the construction sector, contributing to addressing the performance and sustainability challenges of modern society. This resource from FGT plantations could be complementary to softwood-based products with the added benefit of local production and livelihood options.

In the last four decades, FGT species have been increasingly used for the establishment of bioenergy plantations to reduce the use of fossil fuels in developed countries and to slow deforestation while maintaining the livelihoods of local communities in tropical and subtropical areas. Recent research focuses on combining energy woody crops with cereals or other agricultural crops, including nitrogen-fixing tree species in energy plantations, and identifying microbial communities capable of improving tree resistance to abiotic stresses such as limited nutrients and drought. Such research is key for enhancing the sustainability of bioenergy plantations.

With the need for increased circularity and carbon storage capacity for all materials, business opportunities for small and medium-sized enterprises (SMEs) linked to the FGT sector are flourishing. In developed countries, small businesses formalized as legal entities are focusing on value-added products providing benefits for entrepreneurs, whereas, in less-developed countries, the lack of formalization can limit opportunities for innovation. This publication has presented some success stories that demonstrate the possibilities for diversifying and re-purposing main and sidestream products to increase SME incomes.

Several aspects of sustainable management of FGTs are highlighted, including innovative nursery techniques, permanent polycyclic plantations, plantation monitoring and assessment strategies, and credit and financial support to smallholders.

Innovative nursery techniques can help meet the demand for high-quality seedlings necessary for achieving worldwide forest restoration goals to mitigate climate change, protect watersheds, improve livelihoods, re-establish habitats, stabilize soils and generate wood products. These techniques include high-tech advances but also basic upgrades in low-tech nurseries, which can have dramatic impacts on plant quality and programme success in many places in the world.

Fast-growing trees can be implemented as part of permanent polycyclic plantations. These are mixed plantations with two or more production cycles on the same plot, providing continuous land cover and benefits. Permanent polycyclic plantations provide economic benefits for farmers, and environmental and landscape benefits for communities and the planet, such as fewer changes to the landscape and habitats, continuous carbon storage and increased biodiversity in areas otherwise under intensive agricultural management.

A key requirement for the planning and sustainable management of FGTs characterized by relatively short rotations is reliable information. Frequently updated, accurate and spatially detailed information on tree attributes is required for the area of interest to adequately plan, design and implement FGT management. Strategies for FGT surveys should be based on involving all relevant stakeholders in the survey process and should capture key information on productivity, diversity and health at the plot and landscape scale.

Well-designed credit and financial support tools can help the FGT sector in moving towards more sustainable management, such as the subsidies available for the establishment of new poplar plantations in Italy, which encourage polyclonality and the use of more sustainable clones and environmental management certification schemes.

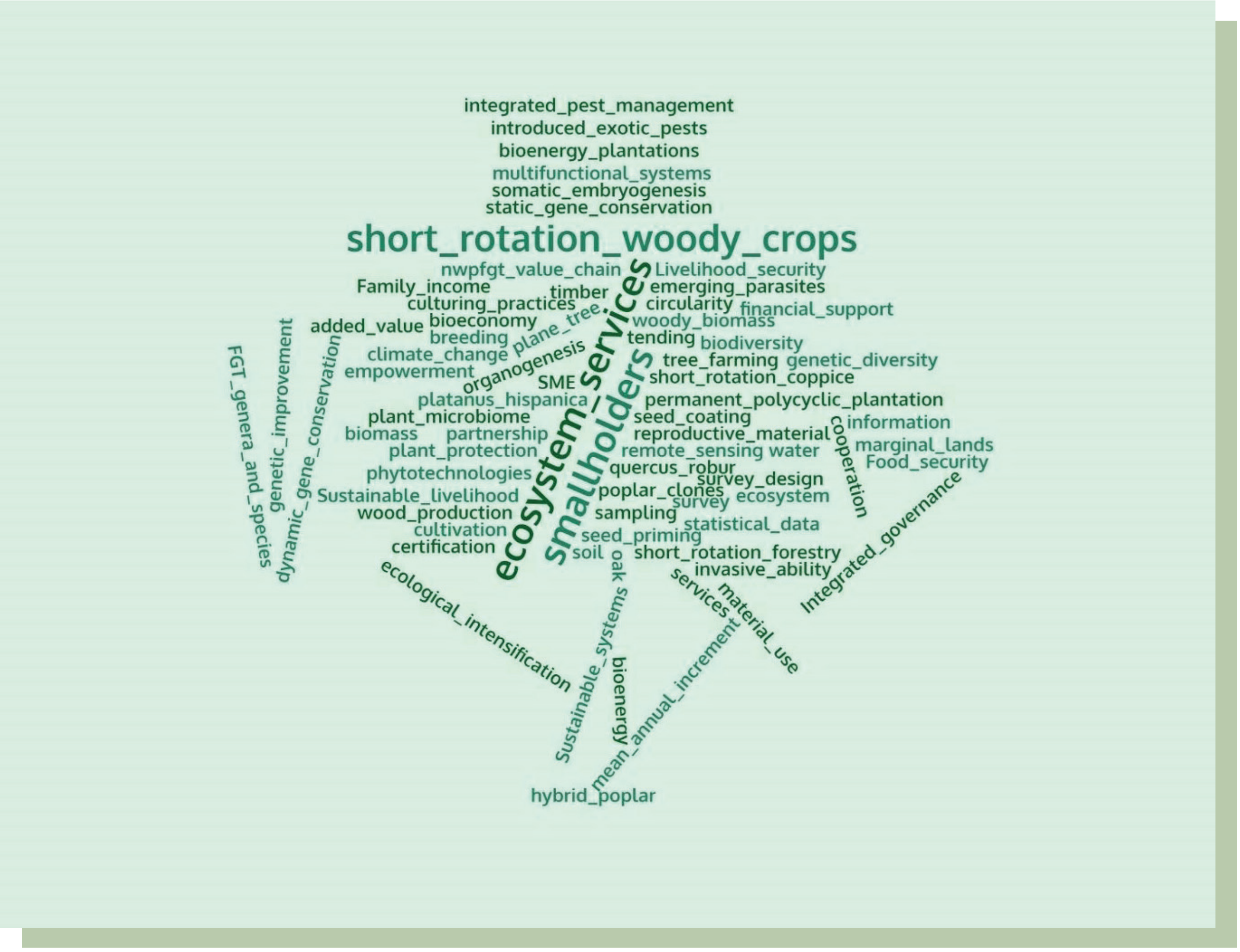
Because of their enhanced growth rates, efficient root expansion and rapid soil formation, FGTs meet a wide range of forest and land restoration (FLR) needs and objectives and so can be used in many types of restoration interventions. Fast-growing trees can help mitigate land degradation while also contributing to protecting biodiversity, building community resilience and developing sustainable livelihoods.

Another way forward is provided by agroforestry systems, where agricultural crops or livestock, or both, are deliberately integrated with trees or shrubs on farmland to provide environmental, economic and social benefits to farmers, communities and the planet. Many FGTs are ideal trees to consider for maximizing the benefits from traditional and innovative agroforestry systems. The latter include tree alley cropping, riparian forest buffers, windbreaks, boundary plantings and hedgerows, perennial tree or shade crop systems, and farmer-managed natural regeneration. Such systems address the trilemma of producing wood products and agricultural commodities while preserving the environment; they are a modern form of smart agriculture.

Fast-growing trees in cities can deliver a wide range of benefits for the well-being and livelihoods of urban dwellers. To support ecosystem functions over time, urban planning and management must account for the enhanced rate of tree growth, and sometimes earlier death of trees, in urban environments.

For many forest and plantation smallholders, cooperation and partnerships at the landscape scale are the obliged route for accessing markets and opportunities. In the FGT sector, partnerships are established to reach different objectives, depending on the context. This publication has highlighted some common desirable elements that can be identified for successful partnerships in the FGT sector, including careful selection of species for planting, adoption of outgrower schemes, dealing with hostility about perceived environmental impacts, improving and promoting reinvestment mechanisms, and linking to markets and value-added products.

This publication has addressed knowledge and the current and potential development of FGTs. A complex picture emerges, both in terms of the experiences developed and the prospects for future development, as shown in the keyword infographic shown in Figure 10. The publication has reported on consolidated achievements and highlighted gaps in research and applications. There is a need for in-depth knowledge to support and promote the role of FGTs in the broader context of planted forests, sustainable landscape design and management, and wood production, as well as in relation to the fundamental issues of livelihoods and equity and the socio ecological sustainability of land use.



Word cloud based on the keywords in this publication.

Glossary

Definitions of the following terms were based on FAO (2020).

Aboveground biomass
All biomass of living vegetation, both woody and herbaceous, above the soil including stems, stumps, branches, bark, seeds and foliage.

Afforestation
Establishment of forest through planting or deliberate seeding, or both, on land that, until then, was under a different land use. Implies a transformation of land use from non-forest to forest.

Agroforestry
"Other land with tree cover" with temporary agricultural crops, or pastures or animals, or both.

Belowground biomass
All biomass of live roots. Fine roots of less than 2 millimetres (mm) in diameter are excluded because these often cannot be distinguished empirically from soil organic matter or litter.

Canopy cover
The percentage of the ground covered by a vertical projection of the outermost perimeter of the natural spread of the foliage of plants.

Carbon in aboveground biomass
Carbon in all living biomass above the soil, including stems, stumps, branches, bark, seeds and foliage.

Carbon in belowground biomass
Carbon in all biomass of live roots. Fine roots of less than 2 mm diameter are excluded, because these often cannot be distinguished empirically from soil organic matter or litter.

Conservation of biodiversity
Forest where the management objective is conservation of biological diversity. Includes but is not limited to areas designated for biodiversity conservation within the protected areas.

Deforestation
The conversion of forest to another land use independently whether human-induced or not.

Disturbance
Damage caused by any factor (biotic or abiotic) that adversely affects the vigour and productivity of the forest and which is not a direct result of human activities.

Disturbance by diseases
Disturbance caused by diseases attributable to pathogens, such as bacteria, fungi, phytoplasma or viruses.

Disturbance by insects
Disturbance caused by insect pests.

Disturbances by severe weather events
Disturbances caused by abiotic factors, such as snow, storm, droughts, etc.

Forest
Land spanning more than 0.5 hectares (ha) with trees higher than 5 metres (m) and a canopy cover of more than 10 percent, or trees able to reach these thresholds *in situ*. It does not include land that is predominantly under agricultural or urban land use.

Forest expansion
Expansion of forest on land that, until then, was under a different land use. Implies a transformation of land use from non-forest to forest.

Forest ownership
Generally refers to the legal right to freely and exclusively use, control, transfer or otherwise benefit from a forest. Ownership can be acquired through transfers such as sales, donations and inheritance.

Forest policy
A set of orientations and principles of actions adopted by public authorities in harmony with national socioeconomic and environmental policies in a given country to guide future decisions in relation to the management, use and conservation of forest for the benefit of society.

Growing stock
Volume over bark of all living trees with a minimum diameter of 10 centimetres (cm) at breast height (or above buttress if higher). Includes the stem from ground level up to a top diameter of 0 cm, excluding branches.

Introduced tree species
A tree species occurring outside its natural range (past or present) and dispersal potential (i.e. outside the range it occupies naturally or could occupy without direct or indirect introduction or care by humans).

Multiple use
Forest where the management objective is a combination of several purposes and where none of them is significantly more important than the other.

National stakeholder platform
A recognized procedure that a broad range of stakeholders can use to provide opinions, suggestions, analysis, recommendations and other input into the development of national forest policy.

Native tree species
A tree species occurring within its natural range (past or present) and dispersal potential (i.e. within the range it occupies naturally or could occupy without direct or indirect introduction or care by humans).

Natural expansion of forest
Expansion of forest through natural succession on land that, until then, was under a different land use. Implies a transformation of land use from non-forest to forest (e.g. forest succession on land previously used for agriculture).

Naturally regenerating forest
Forest predominantly composed of trees established through natural regeneration.

Non-wood forest product
Goods derived from forests that are tangible and physical objects of biological origin other than wood.

Other land
All land that is not classified as "forest" or "other wooded land".

Other land with tree cover
Land classified as "other land", spanning more than 0.5 ha with a canopy cover of more than 10 percent of trees able to reach a height of 5 m at maturity.

Other wooded land
Land not classified as "forest", spanning more than 0.5 ha; with trees higher than 5 m and a canopy cover of 5–10 percent, or trees able to reach these thresholds *in situ*; or with a combined cover of shrubs, bushes and trees above 10 percent. It does not include land that is predominantly under agricultural or urban land use.

Plantation forest
Planted forest that is intensively managed and meets ALL the following criteria at planting and stand maturity: one or two species, even age class and regular spacing.

Planted forest
Forest predominantly composed of trees established through planting or deliberate seeding, or both.

Primary forest
Naturally regenerated forest of native tree species, where there are no clearly visible indications of human activities, and the ecological processes are not significantly disturbed.

Private ownership
Forest owned by individuals, families, communities, private cooperatives, corporations and other business entities, religious and private educational institutions, pension or investment funds, non-governmental organizations, nature conservation associations and other private institutions.

Production
Forest where the management objective is production of wood, fibre, bioenergy or non-wood forest products, or a combination of these.

Protection of soil and water
Forest where the management objective is protection of soil and water.

Reforestation
Re-establishment of forest through planting or deliberate seeding, or both on land classified as forest.

Shrub
Woody perennial plant, generally more than 0.5 m and less than 5 m in height at maturity and without a single main stem and definite crown.

Soil carbon
Organic carbon in mineral and organic soils (including peat) to a specified depth chosen by the country and applied consistently through the time series.

Sustainable forest management
A dynamic and evolving concept, intended to maintain and enhance the economic, social and environmental value of all types of forests, for the benefit of present and future generations.

Tree
A woody perennial with a single main stem, or in the case of coppice with several stems, having a more or less definite crown.

Trees in urban settings
"Other land with tree cover" such as urban parks, alleys and gardens.

Tree orchards
"Other land with tree cover" predominantly composed of trees for production of fruits, nuts or olives.

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FAO. 2020. *Global forest resources assessment 2020: terms and definitions*. Forest Resources Assessment Working Paper 188. Rome. 26 pp.

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ISBN 978-92-5-139579-0

9 789251 395790

CD4104EN/1/02.25