Food and Agriculture Organization of the United Nations

Forestry for a low-carbon future

Integrating forests and wood products in climate change strategies

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FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS
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Foreword

Climate change is one of the key challenges of present and future generations. The impact of increased global temperature will affect all regions and countries, but will hit hardest those already living in poverty and food insecurity.

By June 2016, 178 countries had already signed the Paris Agreement adopted at the end of 2015, in clear recognition of the urgency of global action to respond to the climate change challenge. A majority of the signatories included agriculture and forests in their Intended Nationally Determined Contributions for mitigation of climate change, some highlighting forests' importance also for adaptation.

Forests are at the heart of the transition to low-carbon economies. Forests and forest products have a key role to play in mitigation and adaptation, not only because of their double role as sink and source of emissions, but also through the potential for wider use of wood products to displace more fossil fuel intense products. Indeed, a virtuous cycle can be enacted in which forests increase removals of carbon from the atmosphere while sustainable forest management and forest products contribute to enhanced livelihoods and a lower carbon footprint.

Forestry for a low-carbon future: Integrating forests and wood products in climate change strategies brings together contributions from more than 100 experts on the different mitigation options offered by forests and wood products and on the enabling conditions for realizing their potential. The publication is a follow-up to the International Online Conference on the Economics of Climate Change Mitigation Options in the Forest Sector, held by FAO in February 2015. The book is designed primarily for policymakers, negotiators and other experts contributing to climate change strategies, but will also be of interest for professionals in such fields as energy, architecture and construction. Its aim is to provide elements for decisions on a policy mix that will optimize carbon emission reduction (less carbon content per unit of output) and socioeconomic benefits with the needed urgency.

FAO will continue to support countries in their climate strategies, and we hope that readers of this publication will come away with a better understanding of the importance of forests in the climate change framework and new insights on the use of forests and wood products in achieving climate change objectives and the Sustainable Development Goals.

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Acronyms and abbreviations

AFOLU	agriculture, forestry and other land use
A/R	afforestation and reforestation
ARD	afforestation, reforestation and deforestation
CDM	Clean Development Mechanism
CER	Certified Emission Reduction
CHP	combined heat and power
CLT	cross-laminated timber
CO_2e	carbon dioxide equivalent
COP	Conference of the Parties
EJ	exajoule
EPD	Environmental Product Declaration
EU	European Union
EU ETS	EU's Emissions Trading System
FCPF	Forest Carbon Partnership Facility
FM	forest management
FMRL	Forest Management Reference Level
FREL	Forest Reference Emission Level
FRL	Forest Reference Level
FSC	Forest Stewardship Council
GGWSSI	Great Green Wall for the Sahara and the Sahel Initiative
GHG	greenhouse gas
Gt	gigatonne
HWP	harvested wood product
INDC	Intended Nationally Determined Contribution
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
JI	Joint Implementation
LCA	life-cycle assessment
lCER	long-term Certified Emission Reduction
LEED	Leadership in Energy and Environmental Design
LULUCF	land use, land-use change and forestry
Mg	megagram
Mt	megatonne
NAMA	Nationally Appropriate Mitigation Action
NAPCC	National Action Plan on Climate Change (India)
NDC	Nationally Determined Contribution
OECD	Organisation for Economic Co-operation and Development
PEFC	Programme for the Endorsement of Forest Certification
PES	payment for ecosystem services
ppm	parts per million

R&D	research and development
REALU	Reducing Emissions from All Land Uses
REDD	Reducing Emissions from Deforestation and Forest Degradation in Developing Countries
REDD+	positive incentives and policy approaches for reducing emissions from deforestation and forest degradation, including conservation, sustainable management of forests and enhancement of forest carbon stocks
RIL	reduced-impact logging
SALM	sustainable agricultural land management
SOC	soil organic carbon
tCER	temporary Certified Emission Reduction
Tg	teragram
TPES	total primary energy supply
UNFCCC	United Nations Framework Convention on Climate Change
USGBC	United States Green Building Council
VCS	Verified Carbon Standard
VCU	Verified Carbon Unit

Executive summary

The Paris Agreement, adopted by 195 Parties to the United Nations Framework Convention on Climate Change (UNFCCC) in 2015, recognizes the urgency of climate change and calls for limiting the increase in global temperatures to well below 2°C compared with pre-industrial levels, with an ambition to limit the increase to 1.5°C. It recognizes the key role of forests in meeting this challenge, not only for their mitigation potential, but also for their contribution to adaptation.

In order to meet the ambition of the Paris Agreement, countries are called to contribute to emission reduction within their different capabilities, on the basis of voluntary commitments expressed through Intended Nationally Determined Contributions (INDCs). More than 70 percent of the countries that submitted INDCs to UNFCCC included forests in their planned contributions to mitigation, with many also recognizing their role in adaptation.

The INDCs are country driven in nature and create room for more flexible policy approaches, requiring policymakers to decide on the optimal mix of options for delivering climate change mitigation and meeting national development goals. Forests and wood products offer both developed and developing countries a wide range of options for timely and cost-effective mitigation. This publication assesses some of these options and highlights the enabling conditions, opportunities and potential bottlenecks to be considered in policymaking.

Net emissions from forests occur mostly in the Southern Hemisphere, in developing countries, while boreal forests have acted as carbon sinks. The most recent consolidated global forest cover data show a net loss of 129 million hectares of forest between 1990 and 2015, resulting in a 1 percent reduction in forest land as a proportion of the global land area. However, the rate of annual net loss of forest has slowed from 0.18 percent in the 1990s to 0.08 percent in the period 2010–2015.

Mitigation potential and costs differ greatly by activity, region, system boundaries and time horizon. Afforestation/reforestation offers the best mitigation option because of its short timescale and ease of implementation. Reducing deforestation, forest management and forest restoration also offer good mitigation potential, especially because of the possibility for immediate action. Forest contributions to mitigation go beyond forest activities, however. Wood products and wood energy can replace fossil-intense products in other sectors, creating a virtuous cycle towards low-carbon economies. However, technological limitations and concerns regarding potential negative impacts on forest resources have been barriers to increased use of wood energy and wood products to substitute for more emission-intensive energy sources and materials.

FOREST-BASED MITIGATION ACTIVITIES

Global estimates indicate that the total economic mitigation potential of afforestation, reducing deforestation and forest management could range from 1.9 to 5.5 Gt CO_2e per year in 2040 at a carbon value of less than US$20 per tonne CO_2e. By region, the combination of these forest activities has the largest economic potential in the Caribbean and Central and South America, followed by Africa, South Asia and North America.

Forests have potential for climate change mitigation in both developed and developing countries, through a range of activities. While in developed countries, especially in Europe and North America, abandoned lands can provide for high mitigation potential through afforestation and reforestation, reducing emissions from deforestation and degradation in developing countries also presents a highly cost-effective option. The inclusion of the land-use sector under the Kyoto Protocol, agreed in 1997, was limited, with very complex rules for offsetting fossil emissions by forest emission reductions on the compliance market. Recently, however, the possibilities for mitigation from forests have broadened significantly under UNFCCC. Notably, positive incentives and policy approaches for reducing emissions from deforestation and forest degradation, including conservation, sustainable management of forests and enhancement of forest carbon stocks (REDD+), agreed in 2011, have emerged as an avenue for supporting developing countries in their contribution to mitigation through the forest sector.

Forest management practices that can increase carbon sequestration and storage and reduce emissions include modification of rotation length; avoiding losses from pests, disease, fire and extreme weather; managing the soil carbon pool; and maintaining biodiversity. Fire management, in particular, is an important part of mitigation strategies in the forest sector, as annual global emissions from wildland fires are around 7.34 Gt CO_2.

WOOD ENERGY AND WOOD PRODUCTS: LOWER-CARBON SUBSTITUTES

Wood energy accounts for 7 percent of total global carbon emissions. However, its share in total emissions varies significantly among regions, with the highest share in Africa. Bioenergy's share in total primary energy supply (TPES) in 1990 was estimated to be about 10 percent. In 29 countries, mostly in Africa, wood energy provides more than half of all energy consumption. Solid biofuels, mainly wood, constitute the largest renewable energy source, accounting for 69 percent of the world's renewable energy supply. Woodfuel from forests accounts globally for about 6 percent of TPES (roughly two-thirds coming from fuelwood and charcoal and one-third from the forest processing industry).

One-third of households worldwide (about 2.4 billion people) use wood as their main fuel for cooking and for boiling drinking water. About three-quarters of the 2.4 billion tonnes of annual global CO_2 emissions from woodfuel come from the use of woodfuel for cooking. The introduction of improved cookstoves could make a meaningful contribution to emission reductions, especially in Africa.

Use of modern wood energy could be expected to become economically viable first in regions that have large quantities of forest resources and existing coal-fired power plants where woody biomass could be co-fired. Areas with abundant forest resources located relatively close to population centres may also offer opportunities for development of new stand-alone biomass electricity generation or ethanol production facilities with reasonable transportation costs. Clearly, wood energy will become more competitive with fossil fuels when there is a carbon price applied.

The carbon neutrality of wood energy is a controversial issue. Burning wood – or transforming it into other forms of solid, liquid or gas fuels such as charcoal, pellets, briquettes, pyrolysis bio-oil, cellulosic ethanol and combustible wood gas – releases CO_2 into the atmosphere (as well as other GHGs such as methane and nitrous oxide). The emission reduction potential of wood energy rests in part on whether the carbon released is recaptured by subsequent plantations; wood energy should be closest to carbon neutral if the wood is drawn from a sustainably managed forest or system of growing forests, which would sequester an amount of CO_2 close to or equivalent to the amount emitted in producing wood energy.

Harvested wood products are not really carbon sinks, but carbon storage. FAO has estimated the total annual greenhouse gas (GHG) emissions from the value chain of wood products as 0.89 Gt CO_2e, excluding the sequestration accomplished in the value chain. In 2007, the net emission and removal effect for CO_2 in wood products constituted 424 million tonnes of CO_2e – enough to offset 86 percent of the GHG emissions related to manufacturing wood products, and almost 50 percent of the value chain's total emissions.

Evidence from numerous life-cycle assessments (LCAs) of wood-based products in the construction sector indicates that, typically, wood-based materials have a lower emission footprint than competing materials over the complete life cycle of the product (including use and disposal), and the production stage of wood-based materials results in lower GHG emissions than the production stage of functionally comparable non-wood materials. Responsible management of end-of-life wood products, as well as of biomass residues generated along the wood-product value chain, is critical for high GHG displacement from wood products.

In the construction sector, technological lock-in might prevent more substantive mitigation. Generally, acceptance of wood as a green building material has been low despite growing documentation regarding the benefits and competitiveness of wood-based products and buildings compared with alternative building systems.

Sustainable management of forests and forest plantations is the cornerstone for using wood to substitute for other materials and energy sources. In those countries where sustainable forest management is well established and close attention is paid to developing forest stocks for the long term – particularly developed countries and some other forest-rich countries – a sustainable wood supply is feasible. In general, the future supply of industrial roundwood will mostly come from managed and planted forests rather than natural forests. Improving recycling and reuse of wood could aid in meeting the demand for sustainable and affordable raw material. Recycling efforts are already on a positive trend. For example, in Europe in 2010, 9.2 percent of the market volume of wood was recovered as material and 12.1 percent as energy. More effective use of harvest and processing residues could help meet the demand for some energy options (e.g. combined heat and power generation or extending feedstock for biofuels).

MOVING AHEAD WITH A MIX OF OPTIONS

By 2030, forestry mitigation options could contribute to reductions of 0.2 to 13.8 Gt CO_2e per year at carbon prices up to US$100 per tonne CO_2e and to reductions of 0.01 to 1.45 Gt CO_2e per year at prices below US$20 per tonne CO_2e.

Establishment of carbon prices can accelerate the transition to low-carbon economies and would incentivize increases in forest area and use of wood products. At the moment, market incentives for forest mitigation are almost non-existent. The Kyoto Protocol has fostered a carbon market; its accounting rules and project guidelines for generation of carbon credits defined the activities eligible for mitigation and hence shaped the main investments in mitigation in developed and developing countries. Globally, however, the combined value of the regional, national and subnational carbon pricing instruments was less than US$50 billion in 2015, of which almost 70 percent was attributed to emission trading systems and the rest to carbon taxes. Carbon prices vary significantly, from less than US$1 to US$130 per tonne CO_2e. About 85 percent of emissions are priced at less than US$10 per tonne CO_2e. This is considerably lower than the price estimated as needed to meet the recommended 2°C climate stabilization goal.

Almost 20 years after the Kyoto Protocol was agreed, the UNFCCC framework has only recently begun to provide more opportunities for unlocking forest mitigation potential. Both developed and developing countries can now contribute to mitigation, and financial support to the latter can be provided not only through transaction of emission reductions but also through other instruments of climate and development finance. The Paris Agreement has not yet defined the role of markets for achieving its goals, and therefore carbon prices are currently low and volatile. It is expected, however, that carbon prices will be introduced, at least at the national and regional levels, as all countries seek policy instruments to incentivize climate mitigation actions.

From this assessment of the full mitigation potential of the forest sector, it is clear that the positive impact of increased forest area through afforestation, reforestation, forest management and reduced deforestation can be amplified by increased use and management of wood products. Forestry offers possibilities for policymakers in developing and developed countries to decide on different activity mixes, adapted to local circumstances, to reduce emissions. While reducing emissions through REDD+ may seem to have the highest mitigation potential for a tropical developing country, reforestation, forest management and harvested wood products might seem more attractive for a developed country. Maximizing the mitigation potential of forests involves not only enhancing their capacity as a carbon sink and reducing their human-induced emissions, but also striving to promote cost-efficient technologies with low carbon intensity and implementing proper and sustainable forest management that can provide forest products without driving deforestation or forest degradation. Not all decisions rely on the forest sector: For the creation of an enabling environment, policies are crucial to break lock-in of technologies and to establish carbon prices.

Key messages

- Forests are critical to mitigation, having a dual role; they function globally as a net carbon sink but are also responsible for about 10 to 12 percent of global emissions. More than 70 percent of Intended Nationally Determined Contributions submitted to UNFCCC indicate countries' intentions to undertake forest-based mitigation actions.
- According to IPCC, forest management offers the best mitigation option owing to its ease of implementation and short timescale, followed by afforestation and reforestation. Reducing deforestation, forest management and forest restoration also offer good mitigation potential, especially because of the possibility of immediate action. While afforestation and reforestation offer the highest forest mitigation potential in developed countries, developing countries' largest potential lies in reduction of deforestation and forest degradation.
- In recent years, agreement on REDD+ and changes in accounting for forest management and harvested wood products under the Kyoto Protocol have increased opportunities to benefit from forests' full mitigation potential. Reporting on forest management has become mandatory, and carbon storage in harvested wood products can now be accounted, paving the road for increased use of wood products as part of low-carbon strategies.
- Wood energy represents a high mitigation potential. Key opportunities lie, among others, in using wood residues effectively, improving the conversion efficiency of woodfuel and improving the combustion and heating efficiency of end-use devices and facilities. Challenges include sustainable wood supply, feedstock accessibility, combustion efficiency, issues of scale and technological and institutional barriers.
- Increased use of wood offers important mitigation potential when it displaces fossil-fuel intense products. Production of wood-based materials and products results in lower greenhouse gas emissions than production of other materials such as concrete, metal, bricks and plastic. Responsible management of end-of-life wood products, as well as of other biomass residues generated along the wood product value chain, is critical to ensuring a low carbon footprint.
- A virtuous cycle can be enabled if at the global level reforestation, afforestation and reduced deforestation and sustainable forest management provide for increased carbon sequestration while augmenting the supply of sustainable wood products that can replace more carbon-intense products in the different supply chains.

- The potential of different mitigation options varies considerably among countries and regions, and their prioritization depends on local considerations. Options pertaining to the post-harvest use of wood seem promising in countries where an appropriate processing sector is present, industrial forestry operates under sustainability guidelines (e.g. sustainable forest management practices) and chain-of-custody is certified.
- Forests contribute to important policy objectives such as enhancement of livelihoods, climate change adaptation, biodiversity conservation, outdoor recreation and water regulation. Although the value of these co-benefits has not generally been included in estimates of the cost effectiveness of mitigation options, it should be considered in assessing forest mitigation options in climate-change strategies.

1. Introduction

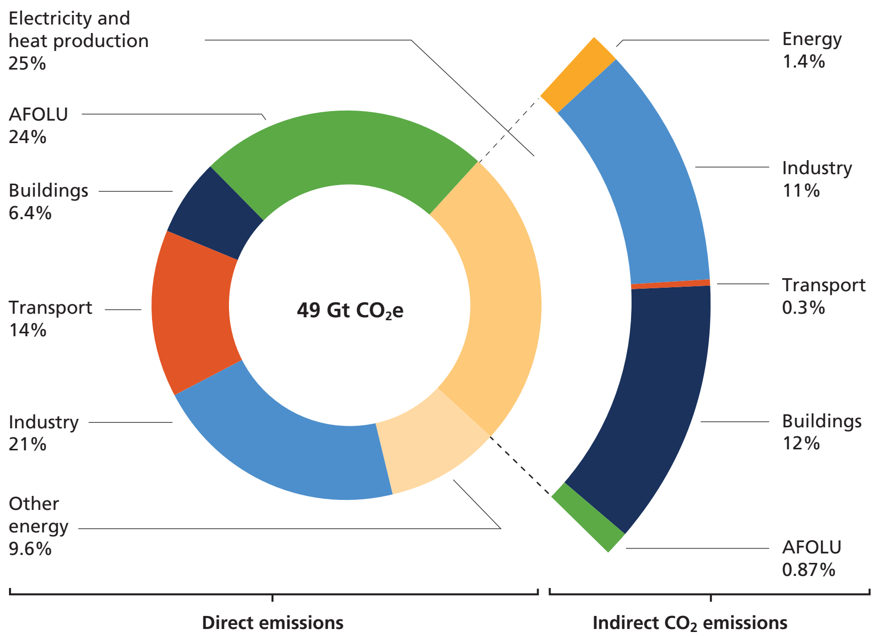
Human-induced climate change poses one of the greatest challenges of the twenty-first century. Current atmospheric concentrations of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) are unprecedented in at least the last 800 000 years. The daily average concentration of CO_2 in the atmosphere rose above 400 parts per million (ppm) for the first time on record in 2013, up from 280 ppm before the Industrial Revolution and 315 ppm when continuous observations began at Mauna Loa in the United States in 1958 (Stocker *et al.*, 2013). Greenhouse gas (GHG) emissions continue to increase (see UNFCCC, 2016 for links to organizations that track these emissions). As the CO_2 concentration in the atmosphere rapidly approaches 450 ppm, it has become clear that limiting the global temperature increase to a maximum of 2°C requires urgent and comprehensive actions from most important sectors in the major emitting countries, irrespective of their current economic status. Parties to the United Nations Framework Convention on Climate Change (UNFCCC) have recognized this urgency, and the Paris Agreement adopted at the twenty-first Conference of the Parties (COP 21) in 2015 brought commitment for keeping within the 2°C goal and for pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels.

Climate change mitigation (hereafter referred to simply as "mitigation") actions from the land-based sector, comprising agriculture, forestry and other land use (AFOLU), are of utmost relevance to this challenge. Forests have a key role in climate change mitigation, as they act as both sinks and sources of carbon. According to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), the AFOLU sector is responsible for 24 percent of global GHG emissions (Figure 1), while vegetation and soil account for approximately 30 percent of the sequestration of carbon (IPCC, 2014b). Although the contribution of the AFOLU sector to global emissions has remained constant, the mitigation potential in land-based activities is extremely important. Within the AFOLU sector, forestry and other land-use change activities (of which forestry accounts for the greatest part) were responsible annually for net emissions amounting to 4.3 to 5.5 gigatonnes (Gt) CO_2 equivalents (CO_2e) in the period 2000–2011, roughly 40 to 50 percent of overall annual emissions from AFOLU and 10 to 12 percent of global emissions.

Net emissions from forests mostly occur in the Southern Hemisphere, in developing countries, while boreal forests act as carbon sinks. The most recent consolidated data for global forest cover show a net loss of 129 million hectares of forest between 1990 and 2015, resulting in a 1 percent reduction in forest land as a proportion of the global land area. However, the rate of annual net loss of forest has slowed from 0.18 percent in the 1990s to 0.08 percent in the period 2010–2015 (FAO, 2016a).

Forests' dual role as carbon sink and source of emissions offers mitigation options that could be cheaper than those in other sectors while contributing to sustainability

FIGURE 1
Global carbon emissions budget by sector, 2010



Source: IPCC, 2014b

and development goals (Bruckner *et al.*, 2014). Globally, forests provide wood, food and income to billions of people. Over 3 billion cubic metres of wood are harvested from forests annually (FAO, 2016a). About 2.4 billion people cook with woodfuel, and at least 1.3 billion people rely on forest products for shelter. Forests also support vibrant industries, formally employing about 13.2 million people across the world and informally employing at least another 41 million (FAO, 2014).

While forests' role in regulating global climate has always been recognized in the international climate change regime, until recently the use of forest emission reduction to offset emissions from other sectors remained controversial (IPCC, 2000). Inclusion of the land-use sector under the Kyoto Protocol to UNFCCC (adopted in 1997) was limited, and compliance market mechanisms involving offsets of fossil emissions by forest emission reductions were never agreed. Recently, however, the possibilities for mitigation from forests have broadened significantly under UNFCCC. Notably, positive incentives and policy approaches for reducing emissions from deforestation and forest degradation, including conservation, sustainable management of forests and enhancement of forest carbon stocks (REDD+), agreed in 2011, emerged as an avenue for supporting developing countries in their contribution to mitigation through the forest sector (Sanz and Penman, 2016). REDD+ is expected to generate large emission reductions. The recent decline in forest sector CO_2 emissions as a result of decreased rates of deforestation (FAO, 2016a; IPCC, 2014a), notably in the Brazilian Amazon, is a sign of the potential of mitigation from reducing deforestation in developing countries.

While mitigation action in the forest sector has been widely promoted and assessed, the use of forest products in mitigation has received little emphasis. Evidence from numerous life-cycle assessments (LCAs) indicates that, typically, wood-based materials have a lower emission footprint than competing materials. However, technological limitations and concerns regarding potential negative impacts on forest resources have been barriers to increased use of wood energy and wood products to substitute for more emission-intensive energy sources and materials. Until recently, emission accounting rules under UNFCCC considered harvested wood products (HWPs) as instantaneously oxidized, and thus not as carbon stores – another factor hindering in-depth assessment of the potential mitigation impacts of increased use of wood products across different value chains.

The complexity of emission accounting in land use, land-use change and forestry (LULUCF) has driven away much potential investment in mitigation in the forest sector. However, a 2013 change in IPCC guidelines for LULUCF accounting under the Kyoto Protocol allows for accounting of carbon storage in wood products, bringing a new perspective to their consideration in mitigation strategies. This revision, together with growing awareness regarding the use of forest products to reduce emissions from other sectors and the availability of more accurate and accessible methodologies for tracking wood and accounting for carbon storage, is instrumental in supporting a societal shift towards low-carbon sustainable consumption and production patterns, including the cascading use of wood (i.e. employing wood in successive uses, extending its lifetime) from legally and sustainably managed forestry. The potential contribution of wood products to low-carbon economies and tackling climate change becomes even more relevant in light of the Sustainable Development Goals agreed in 2015 and global commitments to more sustainable production and consumption, cleaner energy, sustainable forest management and an end to deforestation.

This book focuses on the potential contribution from forests and wood products to climate change mitigation. It explores the mitigation potential, opportunities and challenges for forest activities, wood energy and building sectors, with an emphasis on the economic feasibility and institutional instruments to make action concrete. Moreover, it offers insights into the use of woodfuel and wood products to substitute fossil fuels and more energy-intensive materials. Designed for forest policymakers, decision-makers and managers involved in mitigation-related efforts, this assessment provides critical information necessary for informed policy decisions that could help bring out the full potential of forest and forest-product based mitigation.

OPTIONS FOR MITIGATION IN THE FOREST SECTOR: ENCOURAGING A MULTIPLE-USE PERSPECTIVE

Some countries are working through the challenges of refining their land-use and forest policy, agricultural commodity production goals and investments patterns in light of the need to identify and commit to mitigation policies. Many have formulated low-carbon development strategies and actions. The challenge is for policymakers to identify combinations of options that provide optimal social, environmental and economic outcomes.

Considering the potential of REDD+, afforestation, reforestation, forest management and wood products, for many countries the forest sector can offer mitigation options that are more time and cost effective than options in other sectors (Table 1). The various options are not mutually exclusive and can indeed be complementary.

Given their ability to store carbon in standing trees and long-lasting wood products, as well as to avoid CO_2 emissions when wood is substituted for fossil fuels, sustainably harvested forests have the potential to surpass the carbon storage benefits provided by conserved forests over the long term (Lippke *et al*., 2011). Conservation-oriented management of forests for biodiversity and carbon benefits, for example through payment for environmental services, can be compatible with efficient wood use.

The existing information about the benefits and costs of various mitigation options has many gaps, varying with the activity (e.g. forest management, afforestation, agroforestry), the scale of the activity, the system boundaries and the period across which options are compared. This publication is designed to help fill some of these gaps.

ABOUT THIS PUBLICATION

Aimed at policymakers, investors and all those committed to transition to low-carbon economies, this publication sets down information on why the forest sector is relevant for mitigation and the conditions that can enable optimal results. The publication assesses forest activities and products in the context of climate change mitigation following the UNFCCC framework. To the extent possible, costs of the different options are included in the analysis.

Following this introduction, Chapter 2 provides an overview of mitigation in the forest sector, addressing the handling of forests under UNFCCC, clarifying the complex rules that guide mitigation accounting and assessing the overall mitigation potential in the sector.

Chapters 3 to 5 focus on forest-based mitigation options – afforestation, reforestation, REDD+ and forest management – and Chapters 6 and 7 focus on wood-product based options – wood energy and green building and furnishing. The publication describes these activities in the context of UNFCCC rules, assessing their mitigation potential and economic attractiveness as well as opportunities and challenges for implementation. Country cases and projects offer supporting evidence and lessons learned. These chapters make evident the multiple approaches and different scales possible for mitigation from forests. Interestingly, most of the contributors focused on the project level, which suggests that there is potential for a deeper investigation of economic results and means of implementation at the jurisdictional or national level.

The ultimate objective of this book is to enable decision-makers to put forest-based mitigation actions into practice. Thus Chapter 8 discusses the different considerations involved in choosing the right mix of options as well as some of the instruments and means for implementation. As the different options are considered together, it becomes clear that the forest sector should be viewed as a continuum of activities including sustainable forest management and wood products. Maximizing the mitigation potential of forests involves not only enhancing their capacity as a carbon sink or reducing deforestation, but also

TABLE 1
Key forest-sector mitigation options assessed in this publication

Activity	Mitigation action	Examples	Carbon benefits
Aimed at enhancing carbon stocks (i.e. sinks)			
Afforestation and reforestation	Increasing the forest area	Planting new forests	Increases atmospheric CO_2 removal from long-term forest stocks and tree plantations Augments the availability of HWPs, including for bioenergy use
Forest management	Increasing the carbon density/stock in forests	Optimizing the use of appropriate fertilizers and irrigation Restoring degraded forests and soils Optimizing harvest systems and implementing reduced-impact harvesting Managing impacts of forest disturbances under a changing climate	Maximizes CO_2 removal and storage Enables long-term production of HWPs for bioenergy or other uses
Green building and furnishing	Replacing high-energy products with industrial wood products	Using wood and forest-based materials for green buildings, infrastructure and furniture	Increases carbon storage potential off-site through the use of HWPs
Aimed at reducing GHG emissions (i.e. sources)			
Reduced deforestation and degradation (REDD)	Maintaining forest area and site- and landscape-scale carbon stocks/density	Preventing forest loss Suppressing forest disturbance via better management of fires, pests and diseases Improving management of soil carbon	Helps avoid GHG emissions and maintain CO_2 removal and optimal forest stock
Use of wood energy	Improving practices related to bioenergy	Using sustainably produced wood products and residues for energy Promoting improved cookstoves	Avoids CO_2 emissions through substitution of fossil-fuel-based energy Avoids emissions from microbial decomposition of biomass
Green building and furnishing	Improving use and uptake of wood-based products	Using climate-smart products following a cascading principle, including increased use of wood in construction	Avoids CO_2 emissions through substitution of fossil-fuel-based products by green buildings and bio-based materials and chemicals Avoids emissions from microbial decomposition of biomass

Note: Options may not be mutually exclusive.

Source: Adapted from Nabuurs *et al.*, 2007 implementing proper sustainable forest management that can ensure that forest products are offered without driving deforestation or forest degradation. Chapter 8 also highlights the co-benefits generated by forest mitigation (contributions to income and livelihoods, energy, air quality and health, adaptation and water) and emphasizes that economic assessment of forest mitigation options needs to take these benefits into account.

It is clear that it is possible to scale up forests' contribution to tackling climate with the necessary urgency. Making this contribution concrete depends on much more than carbon markets. Technical capacity for managing forests, good forest governance and policy instruments for addressing market barriers are crucial for successful forest-sector mitigation and generation of co-benefits. Carbon storage is one important environmental service provided by forests, but not the only one. Considering forests in climate change strategies contributes to unlocking their full potential to support sustainable development.

An innovative collaborative process

Growing out of the well-received International Online Conference on the Economics of Climate Change Mitigation Options in the Forest Sector, held by FAO in 2015, this publication was prepared as an "open book", written through the online collaboration of 113 worldwide experts. An advisory committee devised the outline and reviewed the voluntary contributions. The process brought together different and sometimes divergent perspectives related to mitigation in the forest sector. The transparent collaboration platform encouraged interaction among contributors. Through the process of gathering, integrating and editing of inputs, revision by contributors, expert review and final editing, care has been taken to avoid factual errors and misleading statements to the extent possible. The opinions and data presented here, having been provided by so many contributors, do not necessarily reflect the opinions, views and positions of the publication team, FAO or its member countries. Having kept the diverse perspectives in the book, FAO aims to stimulate continuous investigation of forests' and wood products' contributions to mitigation and to bring a range of potential options to the attention of policymakers.

Key messages: overview

- Technological limitations and concerns about potential negative impacts on forest resources have been barriers to increased use of wood energy and wood products to substitute for more emission-intensive energy sources and materials.
- Recent changes in IPCC guidelines allows for accounting of carbon storage in wood products, bringing a new perspective to their consideration in mitigation strategies.
- Given their ability to store carbon in standing trees and long-lasting wood products, sustainably harvested forests have the potential to surpass the carbon storage benefits provided by conserved forests over the long term.

2. Mitigation in the forest sector

FORESTRY IN THE CLIMATE CHANGE FRAMEWORK

The United Nations Framework Convention on Climate Change, launched at the 1992 United Nations Conference on Environment and Development (UNCED), is the principal multilateral body in charge of cooperative action on climate change. It calls for cooperation based on countries' "common but differentiated responsibilities and respective capabilities". This principle is the pillar for all agreements under the convention and has driven different approaches to mitigation by developed and developing countries. The first instrument agreed in UNFCCC, the Kyoto Protocol, adopted in 1997, committed developed countries (also known as Annex I countries) to legally binding CO_2 emission-reduction targets. In the Kyoto Protocol's first commitment period (2008–2012), Annex I countries committed to cut their emissions on average by 5 percent with respect to 1990 levels. In 2012, parties to the UNFCCC agreed to a second commitment period of the Kyoto Protocol (2013–2020), during which Annex I countries will cut their emissions to at least 18 percent below 1990 levels.

Through the rules guiding its implementation mechanisms and the possibility of transacting emission reduction credits, Kyoto has fostered a carbon market and has been the guiding framework for mitigation actions in developed and developing countries. Its accounting rules and project guidelines for generation of carbon credits defined the activities eligible for mitigation and hence shaped the main investments in mitigation. From 2008, however, with the introduction of such concepts as REDD and Nationally Appropriate Mitigation Actions (NAMAs), new opportunities for mitigation in developing countries were created beyond those in the Kyoto Protocol.

In 2020, the Kyoto Protocol will be superseded by a new global agreement, the Paris Agreement, adopted in 2015; it is universal in nature and replaces the Kyoto Protocol's legally binding Annex I targets with Nationally Determined Contributions (NDCs) from all countries, by which countries determine their contributions to climate change mitigation based on their highest ambition.

Forest-based mitigation options under the Kyoto Protocol

The Kyoto Protocol is a legally binding instrument for mitigation in developed countries, as those have historically contributed a larger share of global emissions. Understanding the role of forests in the Kyoto Protocol demands consideration of the context in which it was created.

Awareness of the urgency of tackling climate change and the need for a quick transition to low-carbon economies underpinned the legally binding agreement. The Kyoto Protocol provides for three market-based mechanisms: international emissions trading, which allows a country to buy Assigned Amount Units (AAUs) from another country that might have overachieved its target; Joint Implementation (JI), by which Emission Reduction Units (ERUs) can be earned from an emission-reduction or emission-removal project in another Annex I country (usually one of the so-called "economies in transition"); and the Clean Development Mechanism (CDM), which allows for acquiring credits called Certified Emission Reductions (CERs) from emission reduction or removal projects in developing countries. These mechanisms are aimed at achieving the target at the lowest cost possible. The concern has always existed that allowing fossil fuel emissions to be offset by forest emission removals sends the wrong message, especially because most of the net removals from forests happen in Annex I countries. Additionality is also a fundamental principle under the Kyoto Protocol (Box 1). Mitigation can only be accounted for when it represents a reduction of anthropogenic emissions in reference to an established baseline. UNFCCC is focused on mitigation beyond business as usual, and increased net removals from forests do not always represent additionality. Issues related to permanence and leakage also jeopardized a more robust role for forests in the Kyoto Protocol, as conformance to those principles is methodologically costly to demonstrate and address at a project level. In short, forest mitigation options were long perceived as a potential threat to the environmental integrity of the overall mitigation framework.

BOX 1

Key challenges in accounting for carbon in forest-sector mitigation

Additionality. Additionality is the most fundamental principle of the climate change framework. Mitigation should be additional to what would happen in a business-as-usual scenario, i.e. without the need for the proposed intervention. In other words, the only activities that should count are those that reduce atmospheric CO_2 above and beyond what would occur in the absence of carbon market incentives. This is not always easy to prove in practice.

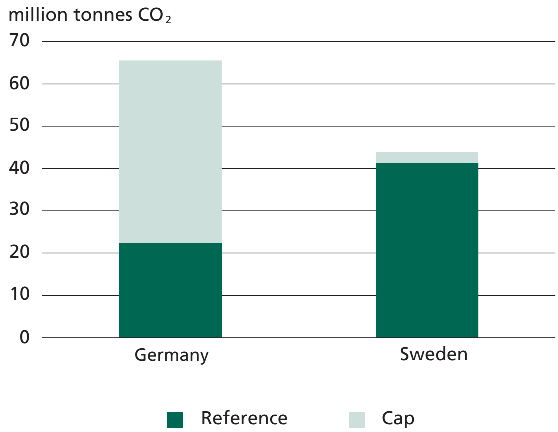
Permanence. Carbon sequestered and stored in trees or forests is eventually emitted back to the atmosphere after trees are harvested or lost to natural mortality or disturbances such as pest outbreaks and fires. After harvesting, carbon is stored in harvested wood products throughout the lifetime of the product but is eventually lost to decay. This intrinsic characteristic of mitigation in the forest sector, referred to as non-permanence, is critical to address. Mitigation projects necessarily entail a long-term land-use commitment, which makes some options less financially attractive (e.g. afforestation or reforestation projects where land may be converted back to non-forest uses).

Leakage. Leakage refers to the potential that direct changes in land use for the purpose of carbon sequestration may result in carbon releases elsewhere, i.e. a displacement of the emissions. Leakages of 43 to 85 percent have been documented, and a failure to account for leakage can underestimate the costs of CO_2 uptake by one-third (van Kooten, 2013).

In order to ensure that the Kyoto Protocol would respect environmental integrity, emission reductions from LULUCF were subject to special rules. Caps were established on the amount of forest emission reduction that Annex I countries could consider for mitigation purposes, and forest CERs generated within the CDM were determined to be temporary. According to Articles 3.3 and 3.4 of the Kyoto Protocol, Annex I countries must account for CO_2 emissions from deforestation and CO_2 removals from afforestation and reforestation. In the first commitment period, accounting for emissions or removals from forest management (FM) was optional, up to a limit or "cap" of 3 percent of 1990 emissions or 15 percent of actual net removals. Emissions and removals from cropland management and grassland management were also optional. Harvested wood products were not included in the accounting, as the carbon pool in HWPs was assumed to be constant; all harvested wood was considered instantly oxidized (IPCC, 2014a).

Progress in science and lessons learned from implementation paved the way to improvements in emission accounting under the Kyoto Protocol, favouring forest activities. In the second commitment period, the accounting rules for the treatment of FM and HWPs changed. FM accounting became mandatory, and instead of a simple cap, an individual Forest Management Reference Level (FMRL) was agreed for each Party as the benchmark or business-as-usual scenario against which future action (emissions and removals) would be measured. To retain the Kyoto Protocol's goal of incentivizing permanent mitigation through national measures in all key sectors, removals from FM were capped at 3.5 percent of a country's overall 1990 emissions. The cap is intended to curb the consequences of underestimating the forest management reference level, while still giving incentives for additional action. However, the cap is likely to be limiting for countries with a large forest sector relative to other sectors, where the potential for additional mitigation action exceeds the value of the cap. An example is shown in Figure 2.

FIGURE 2
Influence of the cap on incentive for mitigation through forest management: Sweden has little incentive to increase the forest sink, whereas for Germany the cap has no practical consequences



Source: Based on data from FAO, 2015a; UNFCCC, 2008, 2011

The guidance for the second commitment period established that net emissions and removals resulting from changes in the HWP carbon pool originating from domestic forests are to be counted and included in the FMRL. The method for estimating the HWP pool combines data on annual production of sawnwood, wood-based panels, paper and paperboard and their assumed average service life, using an exponential decay function. HWPs obtained through deforestation or illegal practices continue to be accounted for on the basis of instantaneous oxidization (Box 2).

In the view of many authors, the cap on accounting emissions from FM has prevented consideration of the full mitigation potential of forests under the Kyoto Protocol. The difference between the actual emission reduction from FM and the portion accounted under the Kyoto Protocol has been referred to as "the incentive gap" (Ellison *et al.*, 2013). In the first commitment period a total of 86 percent of forest-based net removals in Annex I countries arose from FM (Figure 3), with only the remaining 14 percent resulting from afforestation, reforestation and deforestation (ARD) activities. Nevertheless, some countries, such as Iceland, Ireland, Italy, New Zealand and Spain, have invested significant resources in afforestation and reforestation (A/R).

Although not having a legal obligation, developing countries can contribute to emission reduction within the Kyoto Protocol through the CDM. In this mechanism only A/R project activities are allowed. These activities generate particular kinds of CERs, called temporary or long-term CERs (tCERs and lCERs). They count as emission reductions in the Annex I country that buys the credits, but they need to be replaced by other units at the end of the subsequent commitment period (for tCERs) or the lifetime of the project (for lCERs). In addition, Kyoto Protocol rules limit the use of A/R credits to 1 percent of a country's emission reduction times the number of years in the commitment period (Box 3).

BOX 2

Consideration of HWPs under the Kyoto-Protocol

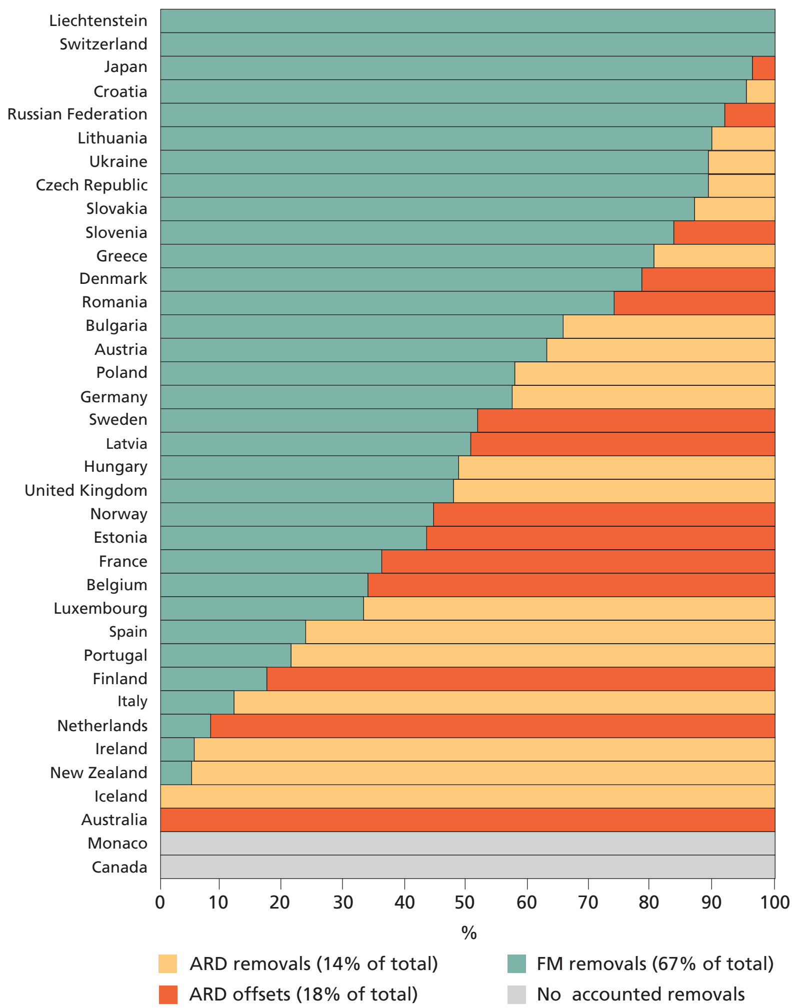
In the first commitment period, the contribution of HWP was assumed to be zero: the carbon pool in HWP was assumed to be constant and was thus not included in the reporting since "the mere presence of carbon stocks" was to be excluded from accounting (IPCC, 2014a).

For the second commitment period, various approaches were proposed for estimating and reporting the HWP contribution to carbon storage and the delayed release of stored biogenic carbon (IPCC, 2014a).

To determine the storage effect of the material use of wood within a country, in principle it is necessary to assess the carbon flows associated with the consumption of wood in the country. Consumption is calculated from the production and foreign trade of wood product commodities. The stock-change approach calculates the HWP pool from calculated consumption, thus estimating the emissions and removals that take place within a country. For the purpose of accounting, however, this approach could result in an unintended inclusion of wood originating from forests that are not sustainably managed in terms of their carbon stock. To avoid this pitfall, the international community agreed in 2011 that the second commitment period of the Kyoto Protocol should consider the mitigation role only of those HWPs that originate from domestic forests whose carbon balance is also considered in the binding international climate agreement.

FIGURE 3

Accounted removals: ARD net removals plus ARD offsets from FM plus FM net removals up to the cap (% of total), 2008–2012 (average values)



Note: For the purposes of this illustration, any emissions under ARD have been set to zero. Hypothetical offsets and removals were estimated for countries that did not elect to account FM under the first commitment period. Furthermore, all non-accountable FM net removals measured in the incentive gap (the difference between the actual emission reduction from FM and the portion accounted under the Kyoto Protocol) are not included here.

Source: Adapted from Ellison *et al.*, 2013, based on 2014 Annex I Party GHG inventory submissions under UNFCCC; for parties not electing FM, data on forest land remaining forest land reported to UNFCCC have been used as a proxy.

Forestry's place in UNFCCC beyond the Kyoto Protocol: REDD+

Recognizing that conservation of natural forests offers important mitigation potential, in the 2010 Cancun Agreements Parties to UNFCCC agreed on policy approaches and positive incentives for reducing emissions from deforestation and forest degradation,

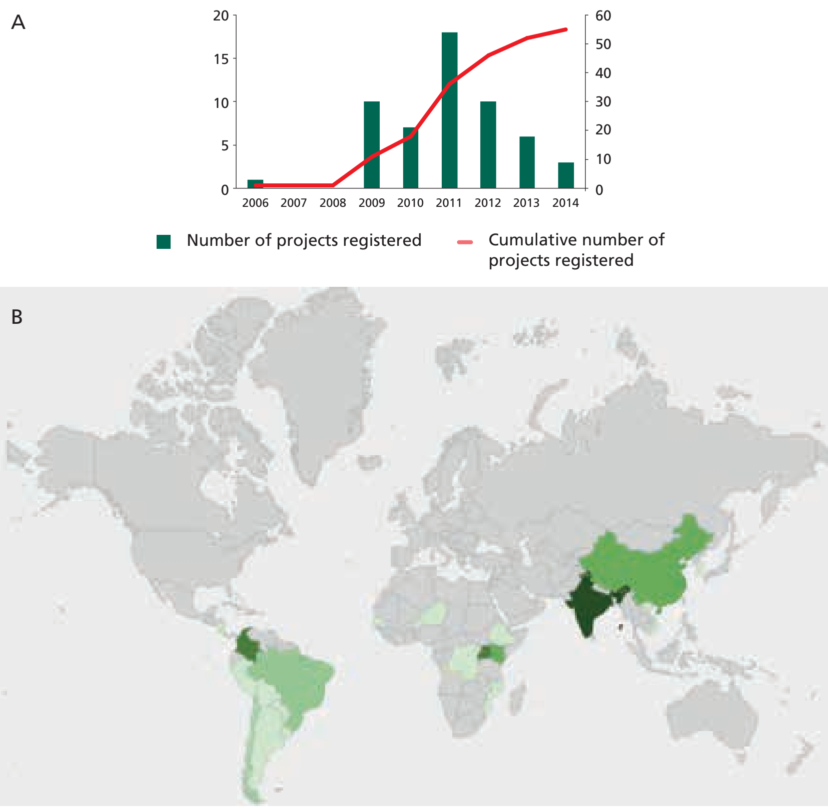
BOX 3

Mitigation from A/R project activities under the CDM

Data from the online database of CDM projects (CDM, 2015b) indicate that only 57 (0.7 percent) of the 8 022 registered CDM projects under the Kyoto Protocol were A/R-related projects, representing a total emission-reduction target of around 140 megatonnes (Mt) CO_2e (as of November 2015). One key factor explaining the small share of A/R projects is the severe restriction on the demand side. Several developed countries, including the European Union, have excluded forestry credits from their emission trading schemes. The 57 A/R CDM projects span 23 countries, with the greatest number concentrated in India (nine), Colombia (seven), China (five) and Kenya (five) (Figure 4).

FIGURE 4

Status of A/R projects in the CDM: (A) trends in A/R project registration; (B) geographical distribution of registered A/R projects



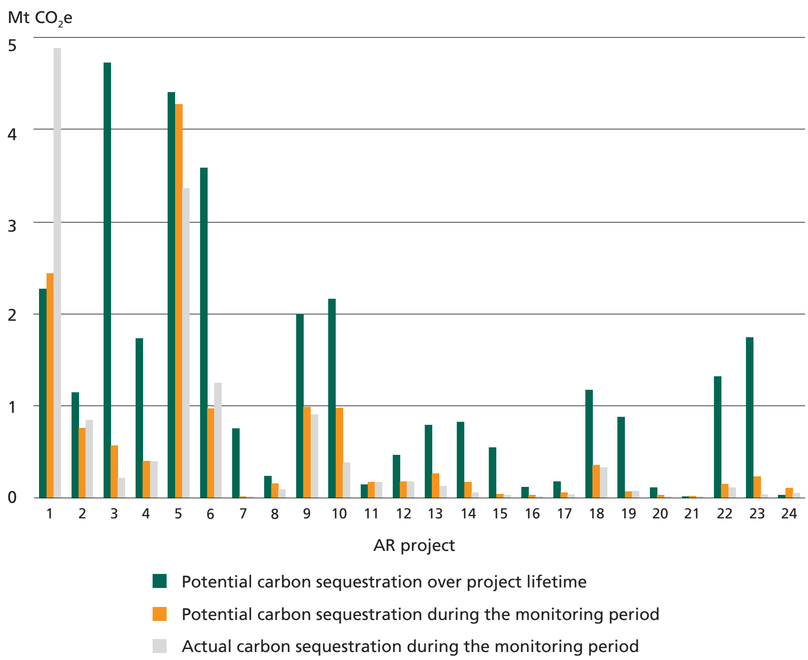
Note: Number of projects ranges from 1 (lightest green) to 9 (darkest green).

Source: Data from CDM, 2015b

Based on monitoring reports submitted by 24 of the projects (CDM, 2015b), A/R projects under the CDM have generally not fully achieved emission abatement targets on the ground (Figure 5). However, the collective deficit is only 2 Mt CO_2e, and five projects have actually exceeded sequestration expectations. The apparent success of the first project in Figure 5 (Project 2569, Reforestation as Renewable Source of Wood Supplies for Industrial Use in Brazil), with net verified CO_2 removals 66 percent higher than expectations for the first years, can be attributed to conservative mean annual increment figures adopted in the ex-ante estimations, and to harvesting of only 50 percent of planned amounts because of reduced industrial demand due to the 2008 global economic crisis. The 23 remaining reports indicate that 87 590 ha were planted and approximately 82 percent of the expected 11 Mt CO_2e of emission reductions were achieved during the monitoring periods.

FIGURE 5

Emission-reduction success of CDM A/R projects: projected CO_2 mitigation potential against actual achievements from 24 projects that submitted monitoring reports



Source: Data from CDM, 2015b

sustainable forest management, conservation and enhancement of carbon stacks in developing countries – REDD+. Focused on developing countries, REDD+ has a national rather than project scope, with a subnational approach possible as an interim measure to lead towards the national scale, in a way that non-permanence and leakage risks can be consistently and more cost-effectively addressed.

The set of key decisions adopted between 2010 and 2014 defines REDD+ as a mitigation mechanism with a robust approach to measuring emission reduction from reduced deforestation and forest degradation and from conservation and enhancement of carbon stocks, while acknowledging the need to safeguard the multiple functions of forests, to enhance livelihoods and to respect the rights of indigenous peoples and forest-dependent communities. The possibility for both large-scale emission reduction and the generation of non-carbon benefits makes REDD+ one of the greatest opportunities for mitigation. Multilateral initiatives and bilateral cooperation have been building capacity for delivering REDD+ in more than 60 countries.

So far, REDD+ is not included in the compliance carbon market, as the Kyoto Protocol encompasses only Annex I activities, and no other compliance mechanism has been established. In order to get access to results-based payments, developing countries need to have in place a national REDD+ strategy; a national (or subnational, on an interim basis) forest monitoring system; national (or subnational, on an interim basis) forest reference levels or forest reference emission levels (Box 4); and a report on how safeguards are being respected and addressed.

REDD+ implementation is advancing in several countries, and some international organizations are getting ready to make payments based on results, notably the Carbon

BOX 4

Forest Reference Emission Levels (FRELs) and Forest Reference Levels (FRLs)

Forest Reference Emission Levels (FRELs) and Forest Reference Levels (FRLs) are benchmarks for assessing the performance of each country in implementing REDD+ activities.

Some initiatives, such as the Forest Carbon Partnership Facility Carbon Fund, currently use FRELs/FRLs (called simply "Reference Levels" by the Carbon Fund) to provide results-based payments for demonstration activities (pilot testing). UN-REDD Programme (2014) provides an overview of emerging country approaches to FREL/FRLs.

How is an FREL/FRL constructed?

UNFCCC Decision 4/CP.15 established that FREL/FRLs should be constructed transparently, taking into account historical data and adjusting for national circumstances. Accordingly, Decision 12/CP.17 provides guidance on FREL/FRL construction, and its annex provides guidance on the information to include in an FREL/FRL submission to UNFCCC. Decision 13/CP.19 details technical assessment of FRELs/FRLs. In the context of results-based payments, they should be reported in a technical annex to the biennial update report (Decision 14/CP.19).

Box 4, continued

Countries need to make choices about the following elements:

- scale (area covered by the FREL/FRL),
- scope (REDD+ activities, pools and gases included in the FREL/FRL),
- forest definition,
- historical data (selection and analysis of activity data and emission factors),
- national circumstances and FREL/FRL construction approach.

UN-REDD Programme (2015) describes possible benefits and risks associated with the different choices for each element to facilitate decision-making.

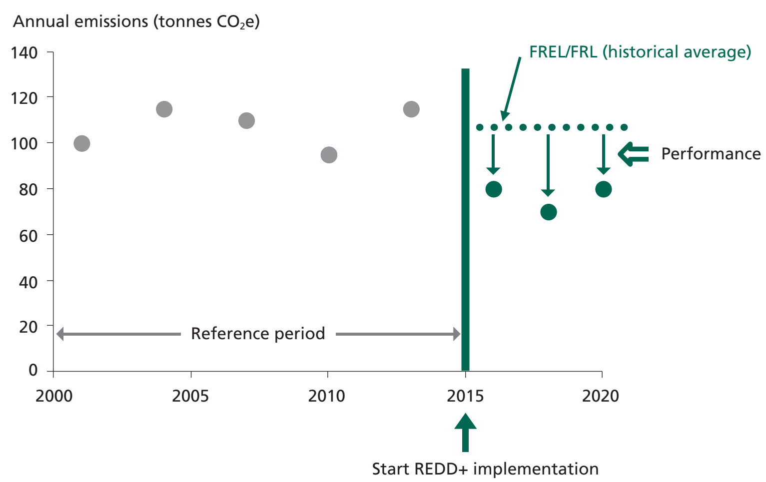
Figure 6 gives a graphical example of a possible FRL based on a simple historical average of forest emissions.

FREL/FRL submissions to date

From June 2014 to April 2016, 15 countries submitted FRELs/FRLs to UNFCCC: Brazil, Chile, Colombia, Congo, Costa Rica, Ecuador, Ethiopia, Guyana, Indonesia, Malaysia, Mexico, Paraguay, Peru, Viet Nam and Zambia. The six FREL/FRLs submitted in 2014 and 2015 have undergone a technical assessment, and the remaining nine will be technically assessed by November 2016.

The deadline for submission for the technical assessment in 2017 is January 2017. FREL/FRL submissions, technical assessments and modified submissions are published on the UNFCCC website: http://redd.unfccc.int/fact-sheets/forest-reference-emission-levels.html

FIGURE 6
Example of a Forest Reference Level using only historical data



Source: UN-REDD Programme, 2015

Fund of the Forest Carbon Partnership Facility (FCPF) managed by the World Bank; Germany's REDD Early Movers Programme; and the Green Climate Fund, which is the official financial entity of UNFCCC.

Forests in the Paris Agreement

While the Kyoto Protocol defined legally binding responsibilities only for industrialized (Annex I) countries, the Paris Agreement, although not legally binding, calls all countries to contribute to the mitigation effort, respecting their different capabilities and responsibilities. The commitments to emission reduction are now voluntary and nationally determined. Once a country signs the Paris Agreement, the Intended Nationally Determined Contributions (INDCs) become Nationally Determined Contributions. The agreement notes that the INDCs that supported the Paris decisions were well below the contributions needed to achieve the envisaged limit in temperature increase, and that more ambitious measures will be incentivized in accordance with future global stocktaking.

Forests had an important role in mobilizing UNFCCC parties towards an agreement. REDD+ attracted developing countries to negotiations and allowed for a new approach to the principle of common but differentiated responsibilities. Under the Kyoto Protocol, developing countries had no role in mitigation (and therefore no support), apart from offering mitigation projects to industrialized countries in the cumbersome CDM. Under the Paris Agreement, developing countries are also invited to advance mitigation and to be supported in their efforts by industrialized countries. Developing countries can formulate not only REDD+, but the full range of cross-sectoral mitigation strategies, and they may seek financial support from the Green Climate Fund or other donors.

Noteworthy in the Paris Agreement is the recognition of the importance of forests for both mitigation and adaptation. The finance section singles out REDD+ activities in particular, calling on countries to support REDD+ and alternative policy approaches such as joint mitigation and adaptation approaches for the integral and sustainable management of forests. The Paris Agreement text also affirms the importance of non-carbon benefits, which could pave the way for reflection of the multiple benefits from forests in future carbon prices.

Of the 197 Parties to UNFCCC, 175 (174 countries plus the EU) signed the agreement by May 2016. In their statements at the signature ceremony held in May, more than 40 developing countries highlighted their mitigation actions in the forest sector, and in REDD+ in particular. An assessment of 185 INDCs submitted to UNFCCC by May 2016 illustrates how countries have considered forests in their climate change plans (Box 5).

MITIGATION POTENTIAL IN THE FOREST SECTOR

The potential and cost-effectiveness of mitigation options depend on a number of factors including the type of forest, the potential for additionality, and the feasibility and timescale of implementation.

As described by Smith *et al.* (2014), economic potential refers to mitigation that could be realized at a given carbon price over a specific period, but does not take into consideration any socio-cultural or institutional barriers to practice or technology adoption. Economic potentials are expected to be lower than the corresponding technical potentials, but higher than market potentials.

BOX 5
An analysis of forestry in INDCs

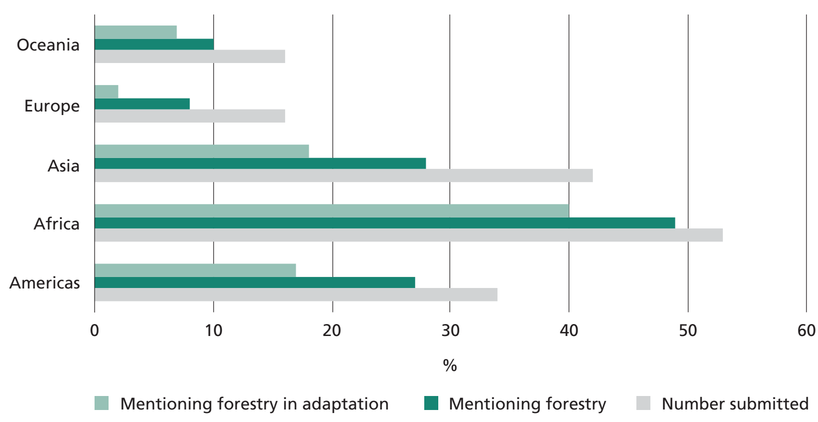
Of 185 INDCs submitted to UNFCCC up to 10 May 2016, 122 countries (76 percent) mentioned forests (including mangroves). Forests were mentioned in INDCs for all regions but most frequently in Africa, where forests were mentioned in mitigation by 92 percent of countries and in adaptation by 75 percent of countries (Figure 7). REDD or REDD+, contributing to both adaptation and mitigation, was mentioned specifically by 28 countries; many more (69) list actions that would fall under REDD such as avoiding emissions from deforestation and land degradation through sustainable forest management or the enhancement of carbon sinks.

Forestry is mentioned in 82 percent of INDCs submitted by developing countries and in 100 percent of those submitted by the least developed countries, indicating the important role of forests in bringing developing countries to the global Paris Agreement.

Decreased consumption of woodfuel for cooking has also been significantly included in developing countries' INDCs, with calls to support alternatives to wood energy and charcoal; 20 submissions (of which 17 are in Africa) state goals to distribute fuel-efficient cookstoves. At the same time, 15 countries (with no strong regional trend) refer to mitigation through forest-related biomass energy.

The vast majority of developing countries make their INDCs contingent on financial and technical support from developed countries. In most cases, the projected costs of adaptation exceed those of mitigation. Many submissions include both unconditional and conditional targets, while others propose entirely conditional efforts. Regarding possible funding sources across various sectors, one-third of the parties intend to approach the Green Climate Fund, with a preference

FIGURE 7
Mention of forestry in submitted INDCs, by region



continues

Box 5, continued

for direct access, country ownership of the financial resources and their allocation to national priority needs. Some countries state the need for international assistance as they lack an institutional framework and human capacity for dealing with the complexity involved in obtaining funding. Some countries call for immediate increased contributions to the Green Climate Fund and state that international sources should include reliable, new and additional official development assistance (ODA), and not redirected flows.

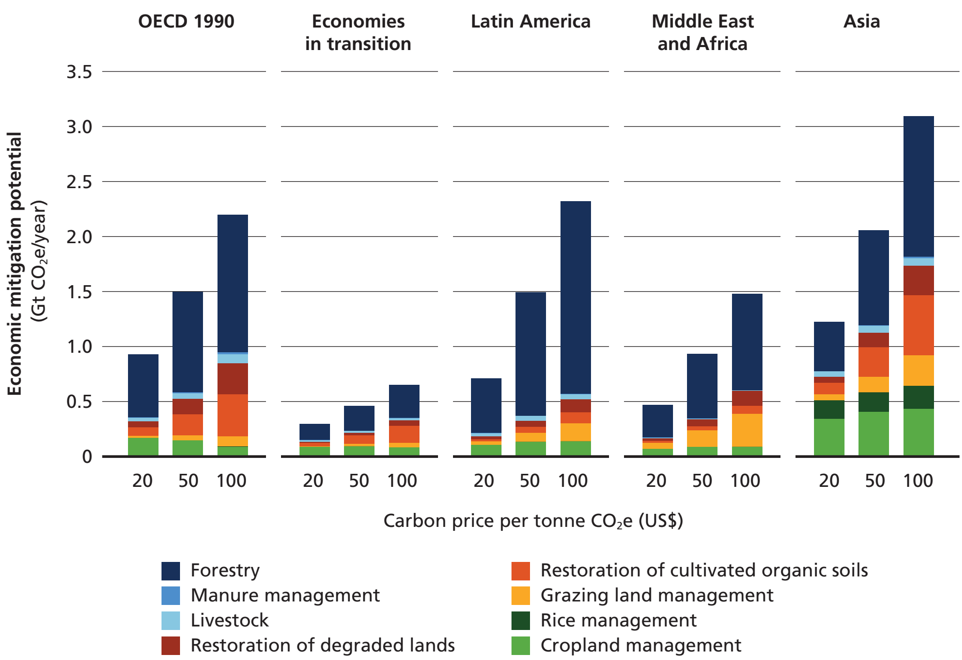
Mitigation potential of forest activities

According to IPCC (2014b), A/R offers the best mitigation option because of its short timescale and ease of implementation. Reducing deforestation, forest management and forest restoration also offer good mitigation potential, especially because of the possibility for immediate action.

By 2030, forestry mitigation options could contribute to reductions of 0.2 to 13.8 Gt CO_2e per year at carbon prices up to US$100 per tonne CO_2e and to reductions of 0.01 to 1.45 Gt CO_2e per year at prices below US$20 per tonne CO_2e (Smith *et al.*,

FIGURE 8

Economic potentials of forestry relative to other supply-side mitigation options in the agriculture, forestry and other land use (AFOLU) sector by region by 2030



Source: Smith *et al.*, 2014

2014) (Figure 8, Tables 2 and 3). While potentials and costs differ greatly by activity, region, system boundaries and time horizon, estimates from the bottom-up global model (Table 3) indicate that the total economic mitigation potential of afforestation, reducing deforestation and forest management could range from 1.9 to 5.5 Gt CO_2e per year in 2040 at a carbon value of less than US$20 per tonne CO_2e. By region, these combined options

TABLE 2

Economic potential for forest-based mitigation options in 2030, from global models

Region/group	Afforestation				Reduced deforestation				Forest management				Total[b]
	Potential at cost up to US$100 (*Mt CO_2e/year*)	% of total potential at different cost ranges in US$/tonne CO_2			Potential at cost up to US$100 (*Mt CO_2e/year*)	% of total potential at different cost ranges in US$/tonne CO_2			Potential at cost up to US$100 (*Mt CO_2e/year*)	% of total potential at different cost ranges in US$/tonne CO_2			
		1–20	20–50	50–100[a]		1–20	20–50	50–100[a]		1–20	20–50	50–100[a]	
Africa	665	70	16	14	1 160	70	19	11	100	65	19	16	1 925
Central and South America	750	39	33	28	1 845	47	37	16	550	43	35	22	3 145
United States of America	445	30	30	40	10	20	30	50	1 590	26	32	42	2 045
East Asia (non-Annex I)	605	26	26	48	110	35	29	36	1 200	25	28	47	1 915
Other Asia	745	39	31	30	670	52	23	25	960	54	19	27	2 375
Middle East	60	50	26	24	30	78	11	11	45	50	25	25	135
OECD Pacific	115	24	37	39	30	48	25	27	110	20	35	45	255
Europe	115	31	24	45	10	17	27	56	170	30	19	51	295
Countries in transition	545	35	30	35	85	37	22	41	1 055	32	27	41	1 685
Total	**4 045**	**40**	**28**	**32**	**3 950**	**54**	**28**	**18**	**5 780**	**34**	**28**	**38**	**13 775**

[a] Calculated from the two columns to the left.

[b] Top-down global estimates of mitigation from wood energy and green building are not available in Nabuurs *et al.*, 2007.

Source: Nabuurs *et al.*, 2007

TABLE 3

Economic potential for forest-based options in 2040, from regional bottom-up estimates

Region/group	Combined economic potential of afforestation, reducing deforestation and forest management[a] (*Gt CO_2/year*)	
	Low	High
Africa	0.300	0.875
Caribbean and Central and South America	0.500	1.750
North America	0.400	0.820
East Asia (non-Annex I)	0.150	0.400
South Asia (non-Annex I)	0.300	0.875
OECD Pacific	0.085	0.255
Europe	0.090	0.180
Russian Federation	0.150	0.300
Total	**1.975**	**5.455**

[a] Economic potentials of green buildings were not provided in Nabuurs *et al.*, 2007.

Source: Nabuurs *et al.*, 2007

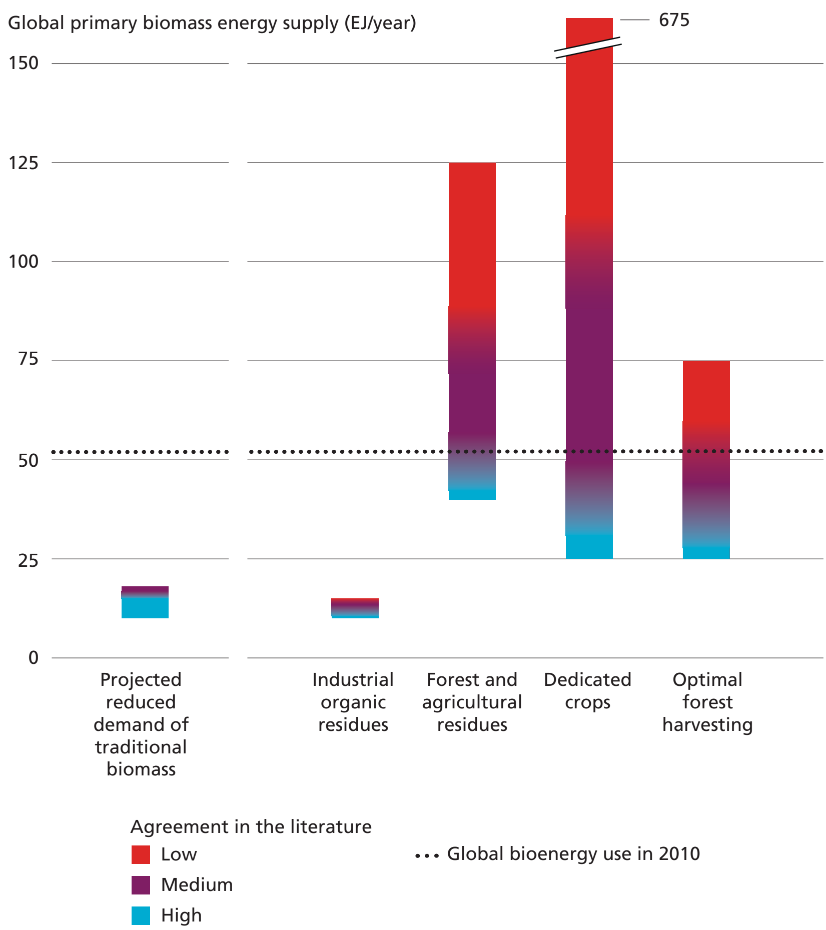
have the largest economic potential in the Caribbean and Central and South America, followed by Africa, South Asia and North America.

The forest sector also contributes to the technical mitigation potential of bioenergy (Figure 9).

Mitigation potential of wood products

HWPs are not really carbon sinks but carbon storage. The wood product value chain (from the forest to the end of the product's life) contributes to the removal of CO_2 from the atmosphere, because CO_2 removed by trees is stored as carbon in products in use and in well-managed landfills. FAO (2010b) estimated the total annual GHG emissions from the value chain of forest products as 0.89 Gt CO_2e, excluding the sequestration

FIGURE 9
Global technical potential of bioenergy, 2050



Source: Smith *et al.*, 2014

accomplished in the value chain. This figure decreases to 467 million tonnes CO_2e annually when sequestration is considered. In 2007, the net emission and removal effect for CO_2 in forest products constituted 424 million tonnes of CO_2e – enough to offset 86 percent of the GHG emissions related to manufacturing forest products, and almost 50 percent of the value chain's total emissions (FAO, 2010b).

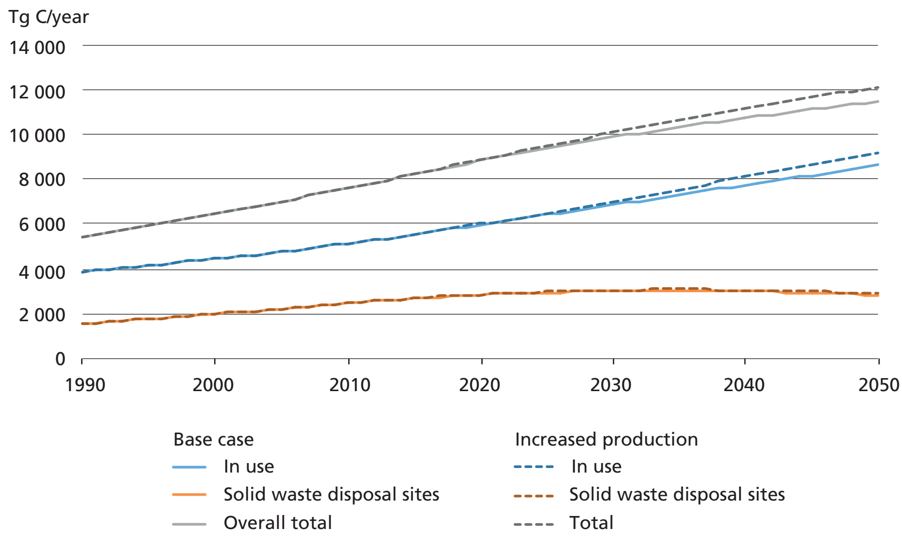
Further, FAO (2010b) calculated that the use of wood-based building materials avoids emissions of 483 million tonnes CO_2e annually, via substitution effects. In addition, by displacing fossil fuels, the burning of used products at the end of the life cycle avoids the emission of more than 25 million tonnes CO_2e annually, which could be increased to 135 million tonnes by diverting material from landfills. Estimates indicate that forest biomass-derived energy could reduce global emissions by between 400 million and 4.4 billion tonnes CO_2e per year (IPCC 2006 estimates cited in FAO, 2010b). The market for wood incentivizes landowners to retain forests and thereby avoid carbon losses to the atmosphere through land-use change (FAO, 2010b).

A background study for this publication (Miner and Gaudreault, 2016) estimated the net impact on the atmosphere of additions to stocks of carbon in three primary products – sawnwood, wood-based panels, and paper and paperboard – from 1990 to 2050 (Figures 10 and 11). To estimate future stocks of carbon in HWP, the authors examined two scenarios: a baseline scenario in which it was assumed that the annual average increase in production from 1990 to 2013 would apply into the future, and a second scenario in which this annual increase was adjusted upward by 25 percent reflecting unspecified policies or market conditions promoting the production and use of wood and paper products. In the case of sawnwood, the increased production scenario assumed that instead of slowly declining into the future (as reflected in recent trends), sawnwood production would remain constant from 2013 forward. The study estimated that the global stock of carbon in HWPs in use in 2013 was approximately 5 360 teragrams (Tg) C (19 671 Gt CO_2e). The net annual addition to stocks of carbon in HWPs in use was estimated to be 85.9 Tg C per year (315.3 Gt CO_2e). When the HWP carbon in solid waste disposal sites was considered, the total HWP carbon stock in 2013 was estimated to be 7 960 Tg C (29 213 Gt CO_2e), and the net addition to stocks in 2013 was estimated to be 128 Tg C per year (469.8 Gt CO_2e).

Another background study (Palma, Rüter and Federici, 2016) used a different method to examine trends in the carbon pool in the same three commodities. The authors followed the stock-change method proposed in IPCC (2006) as modified by IPCC (2014a). The study showed that sawnwood alone accounted for about 73 percent of the global carbon pool in HWPs in use from 1990 to 2013, followed by wood-based panels (21 percent) and paper and paperboard (6 percent) (Figure 12). The carbon pool in wood-based panels and paperboard generally followed an increasing trend over the 24 years (Figure 13). The carbon stock changes in these two HWP categories were comparatively higher than those in sawnwood, which has been in decline from the 1990s. A sharp drop in carbon stock during the financial crisis of 2008–2009 is also evident in Figure 13. Note that the simplified calculation, which does not account for annual increases in stocks, results in a higher estimate of carbon stocks and a lower estimate of stock increases than those in Miner and Gaudreault (2016).

FIGURE 10

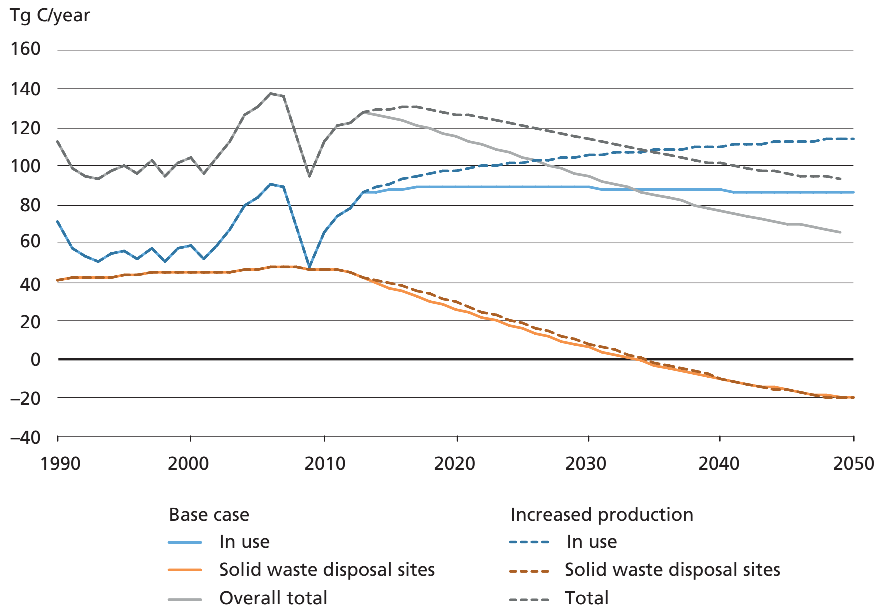
Global carbon stock in harvested wood products



Source: Miner and Gaudreault, 2016

FIGURE 11

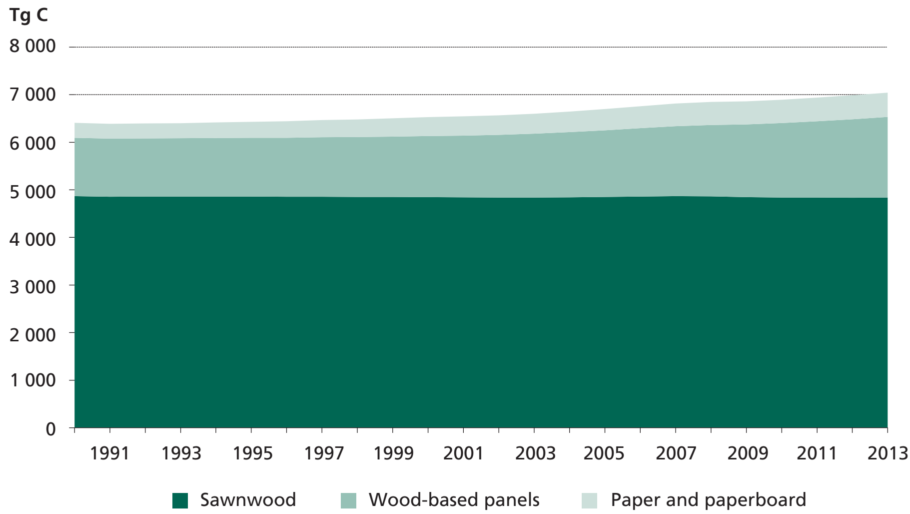
Annual change in carbon stock in harvested wood products



Source: Miner and Gaudreault, 2016

FIGURE 12

Development of the global carbon pool in harvested wood products, 1990–2013

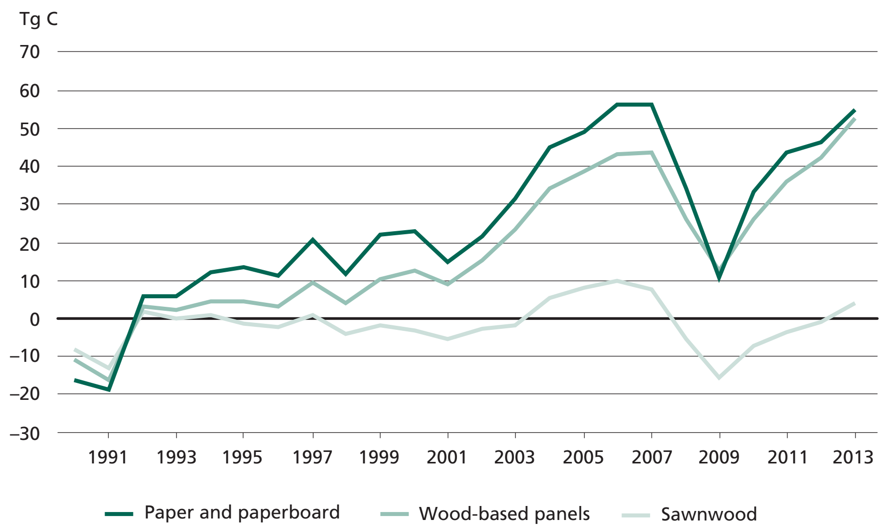


Note: Calculations are based on the inflow (calculated consumption) of HWP commodities of 179 countries using Equations 12.1 and 12.2 of IPCC (2006) as modified by IPCC (2014a). Calculations exclude landfills, which are part of the IPCC (2006) calculations.

Source: Palma, Rüter and Federici, 2016, based on data from FAO, 2015a

FIGURE 13

Annual global carbon stock changes in harvested wood products in use



Note: Calculations are based on the inflow (calculated consumption) of HWP commodities of 179 countries using Equations 12.1 and 12.2 of IPCC (2006) as modified by IPCC (2014a). Calculations exclude landfills, which are part of the IPCC (2006) calculations.

Source: Palma, Rüter and Federici, 2016, based on data from FAO, 2015a

FINANCE OPTIONS FOR FOREST-SECTOR MITIGATION

The new framework for mitigation actions under UNFCCC provides for more broad proposals by developing countries, beyond the opportunities directly associated with the CDM and REDD+. Developing countries' contribution to mitigation can be pursued independently of support or negotiated multilaterally through different funds and bilaterally with specific donors. The Green Climate Fund will play an important role in the financial architecture for both adaptation and mitigation, and therefore for forests.

Frameworks and financing for forest-based mitigation options have also emerged in the voluntary sphere, outside official frameworks. Many voluntary projects, initiatives, markets and platforms are supporting a variety of forest-sector mitigation options and are funding, generating and trading carbon units from these options.

The voluntary carbon market currently supports A/R, avoided deforestation (REDD and REDD+) and improved forest management as mitigation options. Within this market, any interested party may purchase carbon credits generated by autonomous forest-sector mitigation projects and activities. Such carbon credits are usually registered under a particular accreditation mechanism or verification organization, such as the Verified Carbon Standard (VCS) (VCS, 2015) and recently the Gold Standard Foundation. Projects seek registration on the VCS to validate and certify the carbon reductions they produce, and receive Verified Carbon Units (VCUs). Organizations and citizens often voluntarily buy the carbon offsets produced by projects to achieve carbon neutrality.

One of the major differences between the VCS and the Kyoto Protocol carbon trading mechanisms, especially the CDM, is the approach for addressing non-permanence in forest-sector mitigation projects. While the CDM is based on temporary crediting, VCS methodology adopts the buffer approach, where a risk assessment tool is applied to each project.

More forest carbon offsets are transacted in the voluntary market than in compliance markets. They accounted for half of the offset demand in 2014. REDD+ projects have been particularly popular in the voluntary market in recent years. Avoiding deforestation was the top-selling offset project type in 2014, with transactions amounting to 25 megatonnes (Mt) CO_2e (Ecosystem Marketplace, 2015a).

Regional carbon markets (e.g. the Western Climate Initiative, a regional carbon trading system aiming to reduce overall carbon emissions in participating jurisdictions by 15 percent by 2020) are attracting increasing attention (Carbon Market Watch, 2015).

Key messages: forest-sector mitigation

- Progress in science and lessons learned from implementation have paved the way to improvements in emission accounting under the Kyoto Protocol, favouring forest activities. Accounting for forest management has become mandatory, and carbon storage in harvested wood products can now be considered.
- The Paris Agreement recognizes the importance of forests for both mitigation and adaptation, singling out REDD+ activities in particular, and affirms the importance of non-carbon benefits, which could pave the way for reflection of the multiple benefits from forests in future carbon prices.
- While potentials and costs differ greatly by activity, region, system boundaries and time horizon, estimates indicate that the total economic mitigation potential of afforestation, reducing deforestation and forest management could range from 1.9 to 5.5 Gt CO_2e per year in 2040 at a carbon value of less than US$20 per tonne CO_2e. By region, these combined options have the largest economic potential in the Caribbean and Central and South America, followed by Africa, South Asia and North America.
- HWPs are not really carbon sinks but carbon storage. The wood product value chain (from the forest to the end of the product's life) contributes to the removal of CO_2 from the atmosphere, because CO_2 removed by trees is stored as carbon in products in use and in well-managed landfills.
- The use of wood-based building materials avoids emissions of 483 million tonnes CO_2e annually via substitution effects. In addition, by displacing fossil fuels, the burning of used products at the end of the life cycle avoids the emission of more than 25 million tonnes CO_2e annually, which could be increased to 135 million tonnes by diverting material from landfills.
- Forest biomass-derived energy could reduce global emissions by between 400 million and 4.4 billion tonnes CO_2e per year.

3. Expanding forest and tree cover

Forests mitigate climate change by removing carbon from the atmosphere and storing it in biomass and soil. Increasing forest and tree cover through afforestation and/or reforestation (A/R) is a key mitigation activity. Attention should be given, however, to the different definitions of A/R. A/R is included under the Kyoto Protocol as long as the tree cover, height and size of the area meet the national forest definition. FAO (2010a) defines afforestation as the "act of establishing forests through planting and/or deliberate seeding on land that is not classified as forest" and reforestation as the "re-establishment of forest through planting and/or deliberate seeding on land classified as forest, for instance after a fire, storm or following clear felling". In the context of carbon accounting under the Kyoto Protocol, the definitions differ in that they include a start date for accounting: Afforestation is defined as the "direct human-induced conversion of land that has not been forested for a period of at least 50 years to forested land through planting, seeding and/or the human-induced promotion of natural seed sources"; reforestation is defined in practically the same way as afforestation, except that it takes place on land that had been forested but had been converted to non-forested land and did not contain forest on 31 December 1989 (UNFCCC, 2002).

Agroforestry also accounts for significant terrestrial carbon storage and helps mitigate global climate change. Agroforestry is the practice of growing trees and crops in interacting combinations. Agroforestry practices include, for example, alley cropping (hedgerow intercropping), home gardens, improved fallows, multipurpose trees on farms and rangelands, silvipastural systems, shaded perennial crop systems, shelterbelts, windbreaks and taungya systems (temporary intercropping while trees develop canopies during the transition from agriculture or shifting cultivation to tree plantation or forestry). Landscape-based strategies under the broader option "Reducing Emissions from All Land Uses" (REALU) might include reforestation on degraded lands such as mine sites (Larchevêque *et al.*, 2013), as well as urban forestry.

A number of national and regional initiatives have emerged to plant more trees to address climate change. Examples include the Great Green Wall for the Sahara and the Sahel Initiative (Box 6) and the Green India Mission (Box 7).

MITIGATION POTENTIAL OF AFFORESTATION AND REFORESTATION AND TREES OUTSIDE FORESTS

Many estimates of the potential of A/R to abate GHG emissions have been produced at various scales, from national and project scale to IPCC's global estimates at given carbon values (see Table 2 in Chapter 2).

The area of currently unforested land on which forests could be reestablished varies among studies depending on their different assumptions, for example regarding land-cover classes and definitions, land considered suitable for reforestation, regrowth, harvest levels,

BOX 6

Dryland restoration and Africa's Great Green Wall

Forests and agrosilvipastoral systems in drylands harbour species that are particularly well adapted to extreme ecological conditions and provide essential goods and ecosystem services. These systems could help the 2 billion people living in drylands mitigate climate change and adapt to its effects, while contributing to food security and sustainable livelihoods. However, dryland forests and their associated ecosystems face multiple threats including deforestation, degradation, fragmentation, drought, desertification and biodiversity loss.

The Great Green Wall for the Sahara and the Sahel Initiative (GGWSSI) is a comprehensive, long-term restoration initiative to address the threats and support livelihoods and food security in the drylands of North Africa, the Sahel and the Horn of Africa. GGWSSI is implemented by the African Union Commission and 13 partner countries (Algeria, Burkina Faso, Chad, Djibouti, Egypt, Ethiopia, the Gambia, Mauritania, Mali, the Niger, Nigeria, Senegal and the Sudan) with support from FAO, the European Union (EU) and the Global Mechanism of the United Nations Convention to Combat Desertification (UNCCD), alongside other partners. Financing includes US$56 million contributed by the 13 partner countries and US$1 billion mobilized by the World Bank and the Global Environment Facility (GEF).

By restoring forest landscapes and degraded lands, GGWSSI seeks to help develop the mitigation and adaptation potential of these areas. The restoration efforts use native species, which provide additional socioeconomic and cultural benefits to local communities.

wood demand and scenarios of future socioeconomic conditions and policy responses. Benítez *et al.* (2007) indicated that 2 600 to 3 500 million hectares could be reforested. Zomer *et al.* (2008) identified 749 million hectares of land as biophysically suitable and meeting CDM afforestation/reforestation eligibility criteria; 46 percent of these were in South America and 27 percent in sub-Saharan Africa. Thomson *et al.* (2008) conservatively estimated the potential reforestable area as 570 million hectares, which could sequester 120 Gt C (440 Gt CO_2) of above-ground carbon (assuming natural regeneration of forests), but land-use changes could reduce the amount stored to 80 Gt C (294 Gt CO_2) over this century. Similarly, van Vuuren *et al.* (2007) found that 725 to 940 million hectares of abandoned agricultural land could be converted to tree plantations by 2100, potentially sequestering 116 to 146 Gt C (426 to 536 Gt CO_2); for example, Keenleyside and Tucker (2010) estimated agricultural land abandonment in Europe as 12.6 to 16.8 million hectares by 2030. Sohngen and Mendelsohn (2003) estimated an additional 416 to 963 million hectares of forested land by 2100 (including boreal regions), sequestering 39 to 102 Gt C (143 to 374 Gt CO_2).

Large-scale projects connecting A/R to the use of renewable biomass for further emission reductions would offer still greater mitigation potential.

BOX 7

The Green India Mission

The Green India Mission is a core national mission adopted under the Indian National Action Plan on Climate Change (NAPCC). It is comprehensive in terms of areas covered (from urban to shifting cultivation areas) and addresses both mitigation and adaptation, with special emphasis on delivering multiple ecosystem services. The intention is to double India's existing greening efforts through scaled-up investments and convergence with related missions under NAPCC and other national programmes. It has the following objectives (MoEF, 2011):

- a 5 million hectare increase in forest and tree cover by 2022, including:
  - ecosystem restoration and afforestation on over 1.8 million hectares of forest and other lands, including scrub lands, shifting cultivation areas, abandoned mining areas, ravines and mangroves;
  - enhancement of tree cover on over 0.2 million hectares of urban and peri-urban areas;
  - creation of new agroforestry and social forestry assets on over 3 million hectares of non-forest lands;
- significant improvement in the quality of forest and tree cover over another 5 million hectares;
- increased livelihood income for 3 million households from creation of forest assets, their upkeep, harvesting and value addition and marketing of their products;
- significant enhancement of ecosystem services including carbon sequestration and storage, adaptive capacity of forests, hydrological services and biodiversity.

The total cost of the Green India Mission has been estimated at US$7 billion. In February 2014 the Government of India approved an expenditure of US$2.04 billion for the first five years, to be raised primarily from internal resources (Shrivastava, 2014).

ECONOMIC FEASIBILITY

Economic returns play a critical part in making afforestation a viable land use. The past decade has seen an upsurge in the number of publications addressing the economic feasibility of A/R for mitigation of climate change.

Feasibility assessments are sensitive to assumptions regarding establishment and maintenance costs, which vary significantly. Apart from land price, other principal variables determining the economic feasibility of A/R activities include the opportunity cost and productive capacity of land, establishment and maintenance costs, harvesting and transport costs (including road construction and maintenance), the growth performance of the species selected, wood prices over time, discount rates or risk levels, carbon price and carbon sequestration rate. These variables can be factored in the analysis of economic returns. Table 4 summarizes assessments from eight countries, demonstrating the role of

TABLE 4
Country examples of A/R cost assessments

Case study	Assessment strategy	Methodology	Costs	Conclusions
United Kingdom	Comparison of seven forest systems: short-rotation, farm woodland, permanent broadleaf, upland conifer, lowland conifer, continuous cover	Estimated based on the cost of sequestering 1 tonne CO_2 (the "physical measure") and the cost of sequestering a particular value of CO_2 (the "value measure")	Using the physical measure, upland and lowland conifers are the most cost effective (US$31–63 per tonne CO_2). Costs for A/R with permanent broadleaves managed for game and biodiversity and with continuous cover were about US$63–142 per tonne CO_2 Using the value measure, almost all woodland types were cost effective, especially conifers	Delivering significant levels of CO_2 emissions by planting more woodland is economically feasible in the country in those areas where land is available for planting and opportunity costs are not too high Of the estimated 15 000 ha that could be planted annually, about 6 500 ha could be planted annually at a cost of under US$63 per tonne CO_2
United States	Comparison of many carbon sequestration cost estimates	Differing methodologies	Normalized costs range from zero to US$899 per tonne C	Estimates of potential for carbon sequestration differ greatly owing to the scale of the sequestration programme evaluated or the type of land considered eligible for afforestation
Canada	Modelling approach applied to open woodlands	Stand location, land productivity, planted species, silvicultural practices and other variables parametrized to calculate incomes from carbon credits; costs from road construction, silvicultural operations and plantation monitoring also considered	Growth rates, establishment and management costs and opportunity cost of alternative land use gathered to assess the feasibility of afforestation with different species	Preliminary results on the net present value of afforestation scenarios indicate that the return on investment can be expected within less than 25 years Returns vary with regard to a number of parameters (e.g. choice of planted tree species)
Tunisia	REDD+ cost-benefit analysis	Estimates based on hypothesis because carbon stocks and plantation costs are not well known	Operation costs: about US$1 500 per hectare Abatement cost: between US$6.9 (for forest plantations) and US$34.5 per tonne CO_2e	Variation found underlines the dependence of the results on the availability and quality of data

the above elements, the method of calculation and the location in estimating the economic feasibility of A/R for climate change mitigation.

Winsten *et al.* (2011) observed that the costs per tonne of CO_2e vary with carbon accumulation potentials, opportunity costs and the duration of the project activity. They analysed when afforestation could be economically attractive at which carbon price and how much carbon could be economically sequestered if the price is raised, based on a fixed project life.

Summers *et al.* (2015) predicted highly varying spatially explicit costs of establishing plantations for carbon sequestration based on different methods of re-establishing vegetation. Agroforestry options were found to be cost effective in some places because they do not generate high opportunity costs. Payments in the early years of the project and lower transaction costs favour the development of agroforestry-related afforestation and reforestation projects in the voluntary market, especially with high discount rates in marginal rural areas (Torres *et al.*, 2010).

Table 4, continued

Case study	Assessment strategy	Methodology	Costs	Conclusions
Morocco	REDD+ cost-benefit analysis	Estimates based on hypothesis because carbon stocks and plantation costs are not well known	Plantation costs: US$4 285 per hectare (factoring in the 70% success rate) Abatement cost: US$26 per tonne CO_2e	Variation found underlines the dependence of the results on the availability and quality of data
Lebanon	REDD+ cost-benefit analysis	Estimates based on hypothesis because carbon stocks and plantation costs are not well known	Plantation costs: around US$5 700 per hectare Abatement cost: US$34.5 per tonne CO_2e	Variation found underlines the dependence of the results on the availability and quality of data
Turkey	Cost and benefit estimates of implementing LULUCF rules	Carbon and non-carbon costs and benefits assessed for four management scenarios (extensive versus intensive harvest and projected versus non-projected reference emission level and one A/R scenario	Operational costs for A/R and forest management (nationwide): US$3 221 million for non-projected reference emission level	If recent EU market carbon values or recent forest carbon values (Kyoto and voluntary markets) are considered, the carbon benefits are low in all scenarios compared with other forest values; however, since most operating costs would have been disbursed anyway, the carbon benefits can be considered "extra" benefits
Ukraine	Assessment of A/R costs and benefits under different policy scenarios	Econometric analysis, simulation modelling and linear programming for three policy scenarios: carbon storage in forests; carbon storage and additional wood-for-fuel substitution; carbon storage with additional sink policy for wood products	Costs of carbon sequestration are lowest (US$19.5–330 per tonne CO_2) if carbon sequestration benefits are not discounted; if they are discounted at 4%, costs are around US$75.6 per tonne CO_2	Results vary and are sensitive to discount rates and the time horizon considered At discount rates lower than 2%, establishment of new forest is economically justified in most regions of Ukraine

Source: Presented with full references in FAO, 2016c

The opportunity cost of land is highly variable, owing to land and location characteristics. Lands with no other economic use typically represent the low end of land values.

Benítez *et al.* (2007) provided a model for identifying least-cost sites for afforestation and reforestation and derived carbon sequestration cost curves at a global level. When the model takes risk (political, economic and financial) into account, operations become more expensive and carbon sequestration is reduced by about 60 percent. The authors observed that sites for low-cost afforestation could be found in the sub-Saharan region, southeastern Brazil and Southeast Asia. However, while the cost of land is lower in developing countries, risk premiums may be larger there relative to developed countries because of uncertainties in business environments, overall regulation (including environmental licensing procedures and political stability) and issues of landownership, governance, infrastructure and product markets. Land prices are low in boreal regions, but the rates of carbon uptake in non-forest areas can be small, resulting in high costs per unit sequestered in AR projects.

Forest ownership, landowner or land manager goals and the socioeconomic context are also important factors to consider in analysing the economics of expanding forest area. Private landowners, for example, can be expected to invest in tree plantations only if they perceive that doing so will provide higher net benefits than alternative land uses. Basic knowledge of all factors, including biomass production and product prices, is not always sufficient for estimating landowners' net benefits.

Some investment considerations

When tree plantations are established on agricultural lands, volatility in agricultural commodity prices as well as returns to competing uses, such as urban development, may influence the opportunity costs and attractiveness of afforestation (Lubowski, Plantinga and Stavins, 2006).

Land tenure security is often considered a requirement for A/R investments, as a way to promote permanence of emission reductions from forest activities and ensure that emission reductions can be legally delivered to buyers. Areas under insecure land tenure are regarded as less attractive for carbon finance investments.

Location and management regime are important factors in determining economic costs. Carbon sequestration costs vary negatively with yield class and timber prices; higher yield classes generate higher wood volumes and thus lower costs of carbon sequestration. At any particular location, the local climate, soil and topography affect tree growth and the costs of plantation establishment and management. Fast-growing species (e.g. hybrid poplar) can be used in some contexts to shorten harvest periods and thus improve the attractiveness of tree planting projects. However, the establishment costs of fast-growing hybrids can be high. Because of economies of scale, larger-scale A/R projects may have lower per-unit costs of managing and harvesting trees.

The unit cost of production (such as the production cost of biomass and/or CO_2 sequestered) can be used for quick assessments of afforestation projects. The projected average cost can be compared to the likely market price for fibre or biomass; the carbon values required to make plantations economically attractive can then be inferred.

BOTTLENECKS IN HARNESSING POTENTIALS

Owing to several barriers, many A/R projects have not fully achieved expected emissions abatement (Box 8).

Additionality, eligibility criteria and non-permanence are key issues affecting the potential of A/R in mitigation. Lack of economic attractiveness, considering both supply-side and demand-side restrictions, can be significant bottlenecks. Institutional and market obstacles can also make it difficult to realize the full potential of A/R for mitigation. Other constraints to the success of A/R projects, in addition to those associated with the factors of economic feasibility discussed above, include reversibility, flexibility and liquidity constraints.

Private landowners may be reluctant to convert agricultural land to forest land, at least partly because they may not have the flexibility to reverse this decision if the prices for certain agricultural commodities (including livestock) change. Tree plantations cannot easily be converted back to agriculture (or other land use) before commercial tree harvest without significant financial costs, or without government approval. The explicit inclusion of the opportunity costs of existing land use and land-use conversion in cost-benefit calculations, and the fact that afforestation prevents other uses of the land for a period of time, might actually motivate landowners to delay A/R decisions (Plantinga, Lubowski

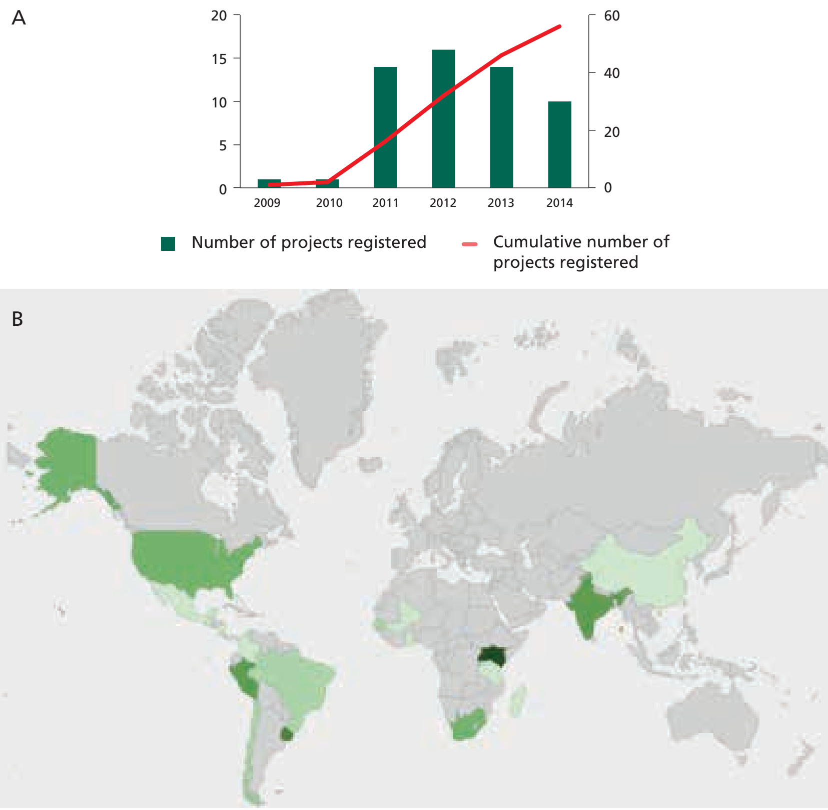
BOX 8

Progress in mitigation from A/R under voluntary markets

Voluntary markets are currently the main supporters of A/R projects (Chenost *et al.*, 2010). Of the 1 269 projects registered in the VCS online project database (VCS, 2015), 56 (4 percent) can be classified as A/R projects, representing a total annual emission reduction potential of around 4 Mt CO_2e (as of early 2015).

A/R project registration on the VCS platform from 2009 to 2014 shows a rise followed by a decline, with a peak of 16 projects in 2012 (Figure 14). The projects are located in 20 countries, in a wider range of regions than for projects under the CDM (see Box 3 in Chapter 2).

FIGURE 14
Status of A/R projects registered in VCS: (A) trends in A/R project registration; (B) geographical distribution



Note: Number of projects ranges from 1 (lightest green) to 8 (darkest green).
Source: Data from VCS, 2015

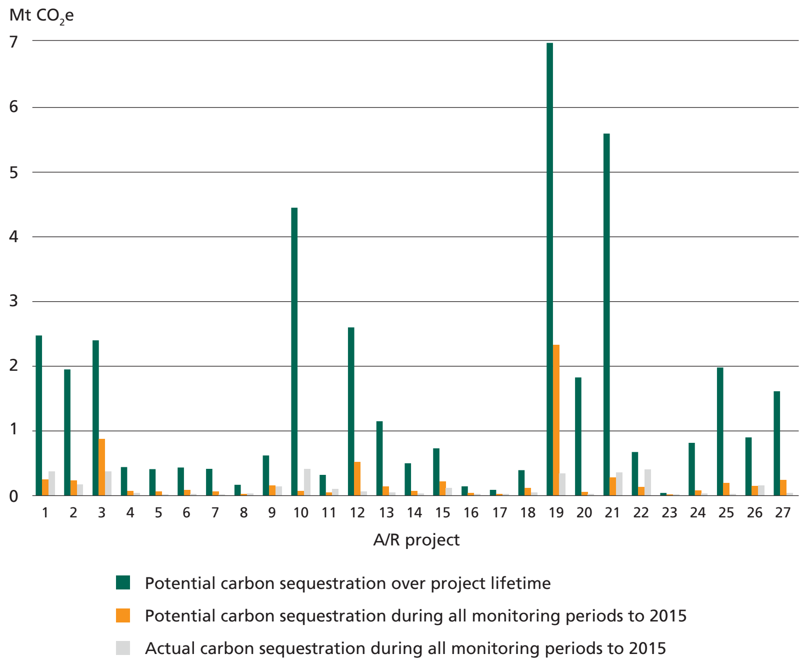
continues

Box 8, continued

As of 2015, 57 percent (32) of A/R VCS projects had achieved VCUs. The 27 projects for which monitoring reports were available (Figure 15) had achieved only around 53 percent of their expected abatement of 6.5 Mt CO_2e for all monitoring periods. However, seven of these projects actually exceeded expected carbon sequestration potential.

FIGURE 15

Projected mitigation potential and achievements of 27 VCS A/R projects



Note: The figure presents 27 projects for which monitoring reports were available. The lifetime of the project was taken as the crediting period. The carbon sequestration potentials during the lifetime and monitoring periods of the projects were calculated based on known time periods and the estimation of annual emission-reduction potential given in the VCS database.

Source: Data from VCS, 2015

and Stavins, 2002; Isik and Yang, 2004; Yemshanov *et al.*, 2015). Any real or perceived additional cost makes A/R less attractive and can induce landowners to retain shorter-rotation land-use types such as agriculture or pasture, which allow landowners to adjust more easily to changes in agricultural markets, climate and technology.

Additional potential bottlenecks include weak governance and political instability, which can discourage investment.

EMBRACING OPPORTUNITIES

Incentives, regulations and standards are essential to provide certainty and confidence in emerging carbon markets.

To identify effective incentives, policymakers may need to engage with landowners and businesses in order to learn more about their behaviour and their attitudes to planting trees (Read *et al*., 2009). Eves *et al*. (2013) showed that business-oriented farmers were more responsive than other farmers to most interventions and were the most responsive to higher timber or fuelwood prices. Engagement with landowners and businesses may also help tackle the key barrier of trust affecting the economic attractiveness of A/R ventures (see example in Box 9).

Confidence in carbon markets for the forest sector may also be furthered through the improvement of existing carbon schemes and the development of additional carbon standards or codes (see example in Box 10).

Options for incentivizing implementation of A/R projects include fiscal incentives, direct incentives and plans for A/R financed by the State or local administrations. A carbon tax may stimulate action at the national level.

Information plays a key role in developing effective carbon markets, for example, in relation to how businesses report emission savings. Demonstration sites and other public outreach and extension efforts can be effective information tools (Pannell *et al.*, 2006).

Based on an examination of challenges associated with developing A/R projects under the CDM in eight South and Southeast Asian countries, Nijnik and Halder (2013) recommended that sustainable A/R projects should develop alongside host-country institutions that safeguard local rights to land and resources, and in tandem with national legal and economic interests.

BOX 9

Reforestation, carbon sequestration and agriculture promoted through sustainable smallholder activities in Nicaragua

The CommuniTree project in Nicaragua links forest activities in smallholder agriculture to carbon sequestration. Farmers establish mixed-species forest plantations and receive a cash payment for ecosystem services. Carbon offsets generated by the project are certified by Plan Vivo. Certificates issued by 2015 totalled 346 767 (with each certificate equivalent to 1 tonne CO_2). Possible customers of the carbon credits and forest products include commercial, institutional and individual buyers in industrialized countries. As of 2015 the project included 1 170 ha and had enrolled 296 families. It is based on a locally driven approach that encourages ownership and discourages future defaults in agreed activities. Management, information and communication technologies are present at all levels, linking farmers to buyers. This successful approach is being explored for replication in Guatemala, Haiti and El Salvador (Porras, Amrein and Vorley, 2015; Taking Root, 2015).

BOX 10

Woodland Carbon Code in the United Kingdom

The United Kingdom's Woodland Carbon Code is a voluntary and independently certified carbon standard launched in 2011 to encourage businesses to invest in creating new woodlands as a way of abating CO_2 emissions (Forestry Commission, 2016a). Following rules similar to those of the major global carbon standards, it provides assurance to investors in new woodlands that carbon sequestration in trees is properly measured and verified and that standards for additionality and permanence of carbon credits are met. The code applies to the domestic forest carbon market only, not to credits that can be traded internationally. However, under the national government's environmental reporting guidelines, investors can report the carbon credits as contributing to the government's mitigation targets. More than 200 woodland creation projects have been registered under the code to date. A supporting infrastructure has been developed to enable the carbon market to operate transparently and efficiently, notably through the establishment of a carbon registry that tracks the status of all carbon credits (operated by Markit Environmental Registry). The code has played an essential role in building trust among investors that woodlands provide an effective CO_2 emission abatement option.

BOX 11

New national agroforestry policy in India

In India, many traditional mixed-species land-use systems based on woody perennials were being replaced by monospecific crop production systems because of policy constraints (Guillerme *et al.*, 2011). The Government of India, recognizing agroforestry as a provider of ecosystem services and as a strategy for carbon sequestration, launched the National Agroforestry Policy in 2014. It aims to link forestry, agriculture, environment, commerce and land management and to ensure access to planting material, knowledge, markets, credit and insurance for farmers. It is expected to set up an institutional mechanism to promote agroforestry at the national level.

Changing policy

Based on performance during the first commitment period under the Kyoto Protocol, most of the current net annual change in the forest carbon sink in the Annex I (industrialized) countries has not been the result of A/R efforts, but rather has occurred under forest management (see Figure 3 in Chapter 2). This indicates that the current policy structure is inadequate to encourage changes in behaviour to promote additional forest growth in most Annex I countries. An example of a policy approach for encouraging A/R is given in Box 11.

Some countries (e.g. China, New Zealand, the United Kingdom) and subnational governments (e.g. California in the United States of America, British Columbia and Quebec in Canada) have started to erect their own carbon trading systems that do allow trading in forest-based carbon credits (ICAP, 2015). However, not all of these are open to trading outside of their systems. Reducing the limitations to the inclusion of forests in the climate policy framework is important to move forward.

Key messages: expanding forest and tree cover

- Apart from land price, other principal variables determining the economic feasibility of A/R activities include the opportunity cost and productive capacity of land, establishment and maintenance costs, harvesting and transport costs (including road construction and maintenance), the growth performance of the species selected, wood prices over time, discount rates or risk levels, carbon price and carbon sequestration rate.
- Land tenure security is often considered a requirement for A/R investments, as a way to promote permanence of emission reductions from forest activities and ensure that emission reductions can be legally delivered to buyers. Areas under insecure land tenure are regarded as less attractive for carbon finance investments.
- Sites for low-cost afforestation were found in the sub-Saharan region, southeastern Brazil and Southeast Asia. However, while the cost of land is lower in developing countries, risk premiums may be larger there relative to developed countries because of uncertainties in business environments, overall regulation (including environmental licensing procedures and political stability) and issues of landownership, governance, infrastructure and product markets. Land prices are low in boreal regions, but the rates of carbon uptake in non-forest areas can be small, resulting in high costs per unit sequestered in A/R projects.
- Options for incentivizing implementation of A/R projects include fiscal incentives, direct incentives and plans for A/R financed by the State or local administrations. A carbon tax may stimulate action at the national level.

4. Reducing deforestation and preventing forest loss through REDD+

Since deforestation and forest degradation release large amounts of the carbon stored in forests, reducing forest loss can help to mitigate climate change. FAO (2016a) reported a net annual decrease of 3.3 million hectares of forest area between 2010 and 2015. FAO estimates indicate that deforestation was responsible for 8 percent of total anthropogenic emissions in 2010, compared with 12 percent in the 1990s. Since 2010, annual land-use emissions have remained stable, at about 4.8 Gt CO_2e in 2012 (Tubiello *et al.,* 2015). Forests at higher latitudes tend to sequester significantly less carbon than is released through tropical deforestation. Reducing deforestation and forest degradation in tropical regions is therefore one of the most efficient activities for reducing GHG emissions within the forest sector, and is a valuable component of near-term emission reduction strategies.

Forest degradation is harder to detect than deforestation but is widespread, especially in the tropics adjacent to deforested areas. When an area is deforested, as much as twice the surrounding area could be degraded because of forest fragmentation and the extension of human activities into previously undisturbed areas (Eliasch, 2008).

Finance for REDD+ is increasing, although slowly. In what is known as "fast-start finance", developed countries pledged new and additional financial resources to developing countries, including US$30 billion for the period 2010–2012, with balanced allocation between mitigation and adaptation (UNFCCC, 2014). At COP 21, developed country parties were strongly urged to scale up their financial support to achieve the goal of jointly providing US$100 billion per year by 2020 (UNFCCC, 2015), which could considerably increase financing for REDD+. The Voluntary REDD+ Database (FAO, 2016b) reports total funding from donors to recipient countries for REDD+ during 2006–2019 as US$4.5 billion. An additional US$3.1 billion is reported as the contribution to institutions.

However, information is still limited regarding how much of this finance has actually gone to support national-level initiatives, and for what purposes the organizations managing and implementing REDD+ on the ground are using the funds. Of US$1.2 billion in REDD+ commitments for seven tropical forested countries (Brazil, Colombia, Ecuador, Ghana, Liberia, United Republic of Tanzania and Viet Nam), by the end of 2012 only US$378 million was disbursed, indicating implementation-related problems or inefficiencies in financial delivery mechanisms (Canby *et al.*, 2014).

MITIGATION POTENTIAL OF REDUCING FOREST LOSS

Reversing the loss of biomass stocks in the world's natural forests would correspond to a REDD+ mitigation potential of about 4 Gt CO_2 per year from avoided deforestation and 1 Gt CO_2 per year from avoided forest degradation (Federici *et al.*, 2015). Additional mitigation potential might be achieved through enrichment and restoration of degraded forests.

Government policies and measures can influence the mitigation potential of avoided deforestation and forest degradation by determining how much deforestation can be reduced and how effectively issues of permanence and leakage are addressed. For example, private-sector entities can be incentivized to take actions to reduce their impact on forests.

ECONOMIC FEASIBILITY

Numerous economic models have been offered for assessing mitigation scenarios related to forest cover change (Lubowski and Rose, 2013; Kindermann *et al*., 2008). Many studies have explored the potential of payments for ecosystem services (PES) to provide incentives to retain forest cover as an alternative to converting forests for agricultural use (Angelsen *et al.*, 2012). The idea is that reducing deforestation should be a cost-effective measure to reduce carbon emissions in places where forests with high carbon stocks would otherwise be converted to relatively low-value subsistence agriculture. The number of years added to a rotation (if carbon values are taken into account) is positively correlated with the relative value of carbon and wood. Thus, where forests have low wood value, the carbon is more valuable and it is optimal to extend rotations further (see Chapter 5). Again, a simple incentive (or a felling tax based on the carbon value) would achieve the desired result.

The economics of climate change (Stern, 2007), also known as the Stern Review, provided an analytical framework for calculating the benefits of land-use change and converting these into an opportunity cost for the retention of forest cover, measured in terms of the agricultural profit forgone for each tonne of emissions avoided when forests are retained. Based on estimates of carbon stocks in forests and the net income from agriculture in eight, mainly tropical, forest countries, the Stern Review and its accompanying background report (Grieg-Gran, 2006) concluded that globally the cost of emission reductions from reducing deforestation could be under US$5 per tonne CO_2e in many places and possibly even less than US$1 per tonne CO_2e in some cases.

Economic analyses often consider only the realizable value of the cleared land for producing agricultural outputs and the value of any wood products obtained during land clearing. Other economic and non-monetized values are frequently missing, such as the value of climate change mitigation and other ecosystem service benefits that would be lost when forest area is cleared. Even when both carbon and non-carbon forest values are accounted for, where high-value agricultural commodities can be produced, the economic benefits of retaining forests can still appear lower than the agricultural alternatives. The costs of the impacts of deforestation can be challenging to estimate in monetary terms, particularly because much will depend on the relative price of agricultural commodities versus the price placed on carbon.

Cost-benefit analyses are highly dependent on data availability and quality. In REDD+ cost-benefit analyses for Morocco, Tunisia and Lebanon, for example (Table 5), abatement costs for the same activity varied widely because of the absence of reliable information on carbon stocks and activity costs.

TABLE 5
Abatement costs of some REDD+ activities in the Near East and North Africa

Country	Cost of REDD+ activity *(US$/tonne CO_2e)*	
	Fighting forest fire	Reducing overgrazing
Lebanon	31.8	N/A
Morocco	49.2	17–43.6
Tunisia	494 [a]	30–81

[a] Very high operational costs were confirmed by the concerned services.

Sources: Bouyer and Le Crom, 2013; Le Crom, 2014; Maurice, 2014

If the carbon price rises (which largely depends on political commitment to tackle climate change), conserving an even greater forest area on the basis of mitigation potential alone will likely make economic sense. Other trends may work against this, however; in the face of climate change impacts, rising global population and diets increasingly intensive in animal products could result in higher agricultural commodity prices, thus increasing the opportunity costs of conservation. However, the decision to conserve forests can also be determined by other considerations apart from the relative costs and benefits of factors that can be monetized.

Although political and social concerns may override economic considerations, the economic balance is likely to be tipped in favour of retaining forests where:

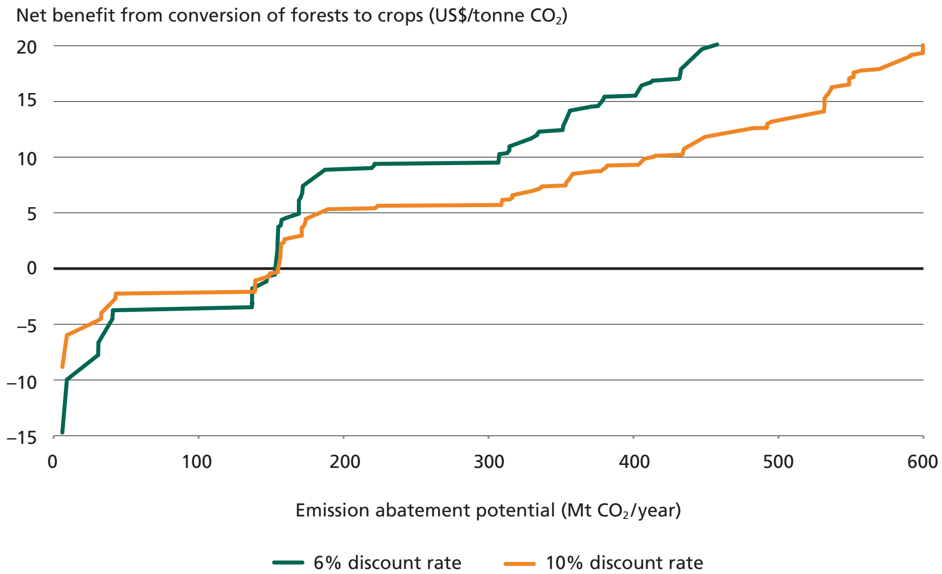
- low-value, small-scale agriculture is the alternative land use;
- soil fertility is low, topography is unsuitable or local climatic factors are limiting for agriculture;
- remote areas have poor connections to markets;
- carbon and other forest benefits are at their highest (e.g. very high carbon stocks or tourism/recreation hot spots);
- forests can be conserved effectively with minimal outlay.

Costs and benefits of reducing deforestation for mitigation in 20 tropical countries

A background study for this publication (Whiteman and Butler, 2016) examined the economics and mitigation potential of reducing agricultural expansion for various crops, using FAO datasets and a methodology similar to that of the Stern Review (Stern, 2007). For the 20 countries with the highest deforestation rates, the authors estimated the per-hectare benefits of crop expansion (measured as agricultural income or gross value added for each crop) and the costs associated with that expansion in terms of tonnes of CO_2. The results for all crops in all 20 countries were then ranked in terms of net benefit and aggregated to produce a mitigation cost curve that can be compared with specific CO_2 values (Figure 16).

The findings of the study showed that in the countries analysed, crop expansion would result in a net benefit of US$35 or less per tonne CO_2 emitted for about one-third of the emissions, US$35–65 per tonne CO_2 for another one-third, and more than US$65 per tonne CO_2 for the remainder. Net benefits from forest conversion vary widely, however,

FIGURE 16
Mitigation cost curve for the conversion of forest to permanent agriculture



Source: Whiteman and Butler, 2016

from values of over US$1 000 per tonne CO_2 for some fruits, vegetables and spices grown on a small scale to a low of US$15 for sesame seed production in Nigeria.

The latter figure is not anomalous; in a number of situations, mostly in Africa, the value added from crop production was less than the value added from forestry (i.e. the net benefit of conversion is less than zero), resulting in a negative mitigation cost. In such cases, conversion can lead to a loss in national income even before the environmental cost of carbon emissions is taken into account. Indeed, about 155 Mt CO_2 of emissions occur in situations where the land-use change from forests to crops does not result in net overall benefits to the country, as the income from these crops is on average less than the value added in the forest sector, even if only narrow, already-monetized values are measured.

About 19 to 25 percent of estimated annual global CO_2 emissions from land-use change – between 460 and 600 Mt CO_2 – is released in situations where the net benefit from crop expansion is less than the cost of the associated emissions if emissions are valued at US$20 per tonne CO_2. This suggests that there is some scope to address perverse land-use changes without any PES or incentives to reduce CO_2 emissions.

The potential for emission reductions would be even higher if shifting cultivation were taken into account, because such land-use change offers net benefits that are only about one-quarter to one-third of those from permanent agriculture for most crops. However, this potential is difficult to estimate because of weak data on shifting cultivation in many countries.

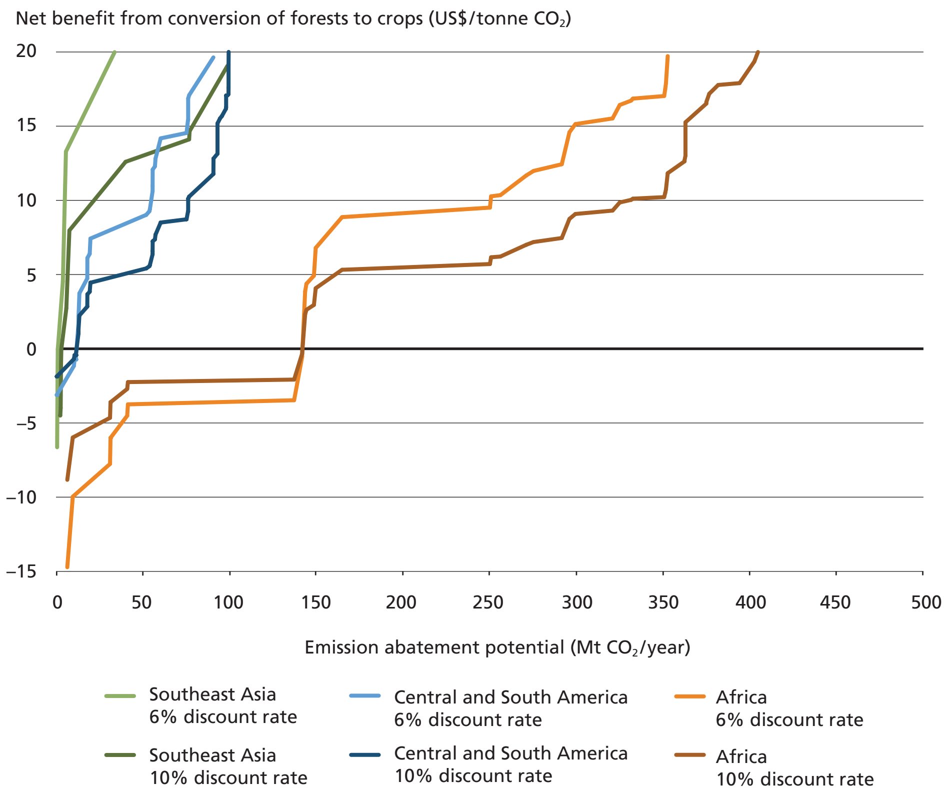
Most forest conversion for relatively low-value agricultural crops is found in Africa (Figure 17). In the other two tropical regions, significant potential to reduce emissions from land-use change only appears at relatively high carbon values.

Of nine crops evaluated (accounting for about two-thirds of crop expansion in the 20 countries over the past decade), soybean and sugar cane were seen to be very profitable; the net benefit of converting forests to these crops would be much higher than the cost of associated emissions (within the range of carbon values considered) (Figure 18). In contrast, for maize, groundnut, cocoa beans and sorghum, the net benefits of conversion are relatively low. A high share of the total expansion of these crops is in Africa, where it often results in net benefits of less than US$20 per tonne CO_2. This is the case for about 85 percent of emissions associated with forest clearing for maize production (280 Mt CO_2), for example.

In other words, 85 percent of maize expansion resulted in emissions from forest clearance that cost more (valuing the carbon at US$20 per tonne CO_2) than the net benefits gained in terms of agricultural income. If maize production had instead increased through

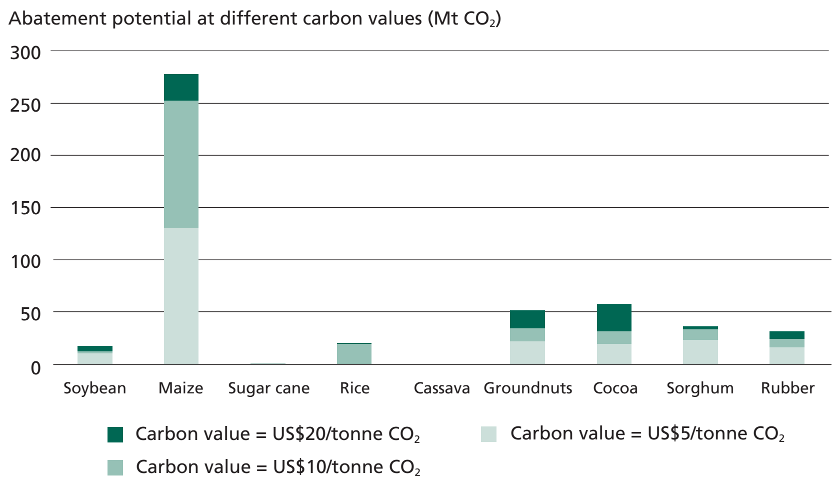
FIGURE 17

Regional mitigation cost curves for reductions in land-use change



Source: Whiteman and Butler, 2016

FIGURE 18
Emissions from crop expansion at different carbon values, by crop type



Source: Whiteman and Butler, 2016

a 70 percent increase in yields, with no expansion of crop areas, the emissions saved would have been worth US$5.6 billion per year, suggesting that a considerable amount could be invested in yield improvement to avoid the expansion of crop areas and emissions from forest conversion.

In summary, up to one-quarter of emissions from land-use change may be economically suboptimal at a carbon value of US$20 per tonne CO_2, and, of this, one-fifth may be occurring in places where the economic value of forest loss could be higher than the benefits gained from crop production. This is especially the case in Africa and for the expansion of groundnut, cocoa bean, sorghum and, in particular, maize. At the other end of the scale, large-scale conversion of forests for soybean, oil palm, sugar cane and, to a lesser extent, rice cannot be challenged as economically inefficient except at much higher carbon values. These results suggest, at least at first glance, that in a narrow economic sense, avoidance of forest clearing for maize, groundnut, cocoa bean and sorghum presents the best opportunity for mitigating emissions from land-use change at realistic carbon values, and that Africa holds great potential for targeting activities to control emissions by reducing deforestation. Investment in yield improvements, in addition to any other benefits it may bring, may be an attractive REDD+ strategy, where land conversion seems to be driven, at least partly, by declining productivity.

However, a range of other factors that go beyond the economics of land-use change must be considered, particularly the food security and livelihood needs of local people and the considerable difficulties and costs to them of implementing any measures that will reduce deforestation. Investment in yield improvements can only succeed in halting land conversion if the people who would derive their food security from expansion of those crops are the ones who benefit from the yield improvements.

REDD+ and carbon markets

According to Forest Trends' Ecosystem Marketplace (2014), the transaction of REDD+ offsets nearly tripled between 2012 and 2013 (to 24.7 Mt CO_2e in 2013), with projects in Latin America behind 70 percent of the sales.

However, Linacre *et al.* (2015) compared the potential supply of REDD+ credits from projects and jurisdictional programmes to three scenarios of demand from existing and emerging voluntary, regulatory and results-based payment programmes, and observed that the supply of REDD+ emission reductions credits far exceeds the demand for them. They concluded that prices, especially in the status quo demand scenario, will be depressed and credits produced will remain unsold unless significant policy changes are promoted or substantially stimulated demand emerges for REDD+ credits.

BOTTLENECKS IN HARNESSING POTENTIALS

While the capabilities needed to negotiate, manage and support REDD+ projects have evolved rapidly under the umbrella of REDD+ support initiatives, numerous challenges remain. Dyer and Nijnik (2014) analysed indirect land-use change, or leakage, associated with REDD+ and implications for local livelihoods. They showed that gains and losses will not be distributed evenly and that some stakeholders may draw benefits from others' losses, which could set the stage for conflict. Acknowledging trade-offs should help in the design of a politically feasible REDD+ mechanism that is effective, efficient and equitable. Projects must bring benefits to local communities and safeguard their rights and well-being.

While the underlying driver of global deforestation is increased demand for agricultural commodities and associated policies, direct drivers can vary. These may include national policy incentives for specific land uses, inadequate conservation policies, weak law enforcement, high suitability of land for conversion to agriculture and high commodity prices, which taken together can make forest conversion to agriculture appear more profitable than forest conservation. Country-level coordination and collaboration between ministries is therefore key.

EMBRACING OPPORTUNITIES

Any global mitigation regime to reduce GHG emissions from forests and other land uses must include ways to reduce deforestation and forest degradation while stimulating sustainable forest management, conservation and enhancement of forest carbon stocks. Comprehensive guidelines and tools that facilitate quantification and monitoring of environmental, social, legal and technical parameters will be important to its success (e.g. Gold Standard, 2015). Other forest-based mitigation activities and initiatives such as A/R, which helps to restore degraded areas, and sustainable agricultural land management (SALM) involving agroforestry systems are complementary to REDD+ (World Bank, 2013).

The lack of a price or value on forest carbon and other forest ecosystem services contributes significantly to continued forest loss. Establishing a price, e.g. through a carbon tax or dedicated forest carbon fund, would incentivize public and private landowners to reduce deforestation. Since carbon prices clearly affect the opportunity costs of reducing forest loss, it is important to integrate the total forest value chain into the climate policy framework, and particularly into emission and carbon trading schemes.

The supply and costs of emission reductions at the large scales necessary for global mitigation, and the suite of economic and environmental service benefits they could supply, will depend in large measure on the structure of the policies and implementation programmes that eventually emerge from UNFCCC and national or private-sector investment commitments. Modelling continually shows that reducing deforestation and forest degradation emissions and enhancing forest carbon stocks could reduce climate policy costs, if properly implemented (Kindermann *et al.*, 2008; Stern, 2007).

The effectiveness of policies for preventing deforestation depends on the national or subnational circumstances and drivers of deforestation and forest degradation. Thus far, few detailed small-scale quantitative analyses have addressed realistic implementation conditions and issues. Future analyses need to identify realistic climate policies by country, widely accepted methods for setting carbon reference levels, benefit-sharing programmes that can offer adequate financial and other incentives to change land-use behaviour, and targeting of lands for REDD+ activities.

Through country-appropriate economic and regulatory measures, breaking from a deforestation pathway, creating incentives and using reduced deforestation for mitigation are achievable goals (see example in Box 12). Politically viable measures must have the backing of key stakeholders such as indigenous communities, non-governmental organizations and the private sector.

It must be noted that most drivers of deforestation lie outside the forest sector (Hosonuma *et al.*, 2012). Reducing these drivers can include, among others, reforming agricultural subsidies, investing in forest landscape restoration, restricting credit or equity of financial institutions if these contribute to deforestation, stripping deforestation from agricultural supply chains and increasing the legal timber supply. Policies must ensure that compensation for curbing deforestation and forest degradation reaches local agents. External factors such as market prices for agricultural commodities, the level of sovereign

BOX 12

Bending the curve in Brazil: breaking the deforestation path alongside economic development

Brazil has managed to reduce its annual deforestation rate through a combination of economic and regulatory measures including a Central Bank resolution to constrain rural credit to farmers if they do not comply with environmental laws, presidential decrees and an action plan for the prevention and control of deforestation in the Brazilian Amazon. Assunção, Gandour and Rocha (2012) reported that conservation policies avoided 6.2 million hectares of forest loss that would otherwise have occurred in 2005–2009, equivalent to avoided emissions of 2.3 billion tonnes of CO_2. Equally important were falling prices for some agricultural commodities, which reduced the incentive to clear forests for agricultural land.

debt and the exchange rate between major trading partners can also incentivize or disincentivize deforestation, although countries have limited influence on these.

Lastly, actions to reduce deforestation must be tackled within the broader framework of sustainability. As noted in *State of the World's Forests 2016* (FAO, 2016d), periodic review and reform of fiscal policies and incentives across the agriculture and forest sectors for environmental compliance and other performance standards is critical to achieving climate change goals and steady progress towards sustainable development.

Key messages: REDD+

- Reversing the loss of biomass stocks in the world's natural forests would correspond to a REDD+ mitigation potential of about 4 Gt CO_2 per year from avoided deforestation and 1 Gt CO_2 per year from avoided forest degradation.
- Most forest conversion for relatively low-value agricultural crops is found in Africa. In the other two tropical regions, significant potential to reduce emissions from land-use change only appears at relatively high carbon values.
- Most drivers of deforestation and forest degradation lie outside the forest sector. Policies must ensure that compensation for curbing deforestation and forest degradation reaches local agents. External factors such as market prices for agricultural commodities, the level of sovereign debt and the exchange rate between major trading partners can also incentivize or disincentivize deforestation, although countries have limited influence on these.
- The supply and costs of emission reductions at the large scales necessary for global mitigation, and the suite of economic and environmental service benefits they could supply, will depend in large measure on the structure of the policies and implementation programmes that eventually emerge from UNFCCC and national or private-sector investment commitments.

5. Changing forest management practices

The mitigation potential of forests and trees is significantly affected by how they are managed. This chapter therefore presents some ways in which forest management can increase carbon sequestration and storage while reducing emissions.

Sound and sustainable forest management is necessary for both carbon and forest productivity, including practices intended to maintain as high an average stand volume as possible for as long as possible; to address potential risks from pests, disease, fire and extreme weather; and to maintain biodiversity.

Thus for management of an even-aged forest, rotations should be long enough to permit the average growth to culminate for the species to be harvested, unless carbon losses due to the onset of self-thinning dictate a shorter rotation. (In this sense, it would be important to check whether carbon values are closely linked with volume or whether carbon content needs to be monitored in parallel with volume growth.) For uneven-aged forest, maintaining a high average growing stock over time requires harvesting low volumes at short cutting cycles to maintain active growth and avoid senescence. Selection criteria will vary among different forest types, diameter distributions and market conditions. Rotation lengths will vary depending on the species chosen.

Forest management practices and soil carbon pool management are closely related. For example, more biodiverse stands offer better soil carbon sequestration, and long rotation periods and/or lighter thinning ensure fewer disturbances to biodiversity from harvesting. Uneven-aged forests with mixed species and/or size-classes are generally more resilient than even-aged ones.

IMPROVED HARVESTING

Timber demand is expected to increase significantly over the next few decades because of global population growth, and over 350 million hectares of natural tropical moist forests are designated by national governments for wood removals. Improving harvesting practices is not only important to meet this growing demand, but can also aid in reducing the amount of carbon entering the atmosphere (Putz *et al.*, 2008).

Reducing the impacts of harvesting, also called reduced-impact logging (RIL), involves pre-harvest inventory and planning to ensure that timber extraction is aligned with the stocking and regeneration capacity of the residual stand and sustainable harvest cycles (Killmann *et al.*, 2002). Trees are felled using directional felling techniques, i.e. in open areas and/or perpendicular to gradients, to minimize damage to the residual stand.

A critical component of RIL is periodic post-harvest estimation or mensuration of the residual stand, which helps forest managers become more aware of the trends in regeneration, recovery of canopy cover and mortality. Post-harvest mensuration increases knowledge of the spatial and temporal impacts of harvest intensity, species selection and felling and extraction techniques. With this knowledge, managers can make better-informed decisions for future harvesting activities, thereby improving harvesting practices over time.

Mitigation potential and economics of improved harvesting

Forest degradation is estimated to contribute 6 to 14 percent of annual carbon emissions from tropical forests (The Prince's Charities, 2015). Factors influencing degradation include site accessibility, which affects decisions to create forest roads, and topography, which affects the amount of damage to the residual stand from felling and extraction activities (Pinard and Putz, 1997; Hawthorne *et al*., 2011). RIL can improve carbon budget outcomes and contribute to climate change mitigation by decreasing felling damage; reducing road width and length; reducing damage through pulling or skidding of logs within the forest; and lowering losses through closer monitoring and planning (ter Steege, 1999) (Box 13).

In logged-over forest concessions designated for selective logging activities, the potential of RIL activities to prevent carbon from entering the atmosphere depends on the concession's history and intensity of conventional harvest activities, which influence the spatial and temporal forest regeneration dynamics (Kleine, 1997; West, Vidal and Putz, 2014).

Through RIL, it is estimated that 6.5 to 12 tonnes CO_2e per hectare over 7 to 70 years may be prevented from entering the atmosphere (Pinard and Cropper, 2000; Tay, 2000; Putz *et al*., 2008; Imai *et al*., 2009). Based on an average carbon price of US$3 per tonne CO_2e (estimated from the prices in the CDM and voluntary carbon market in 2013), potential financial benefits from RIL for mitigation may range from US$20 to US$36 per hectare; however, this value may fluctuate due to the variable price of carbon and the intensity of conventional harvest activities, which influences the spatial and temporal forest regeneration dynamics (Box 14).

If RIL is not employed, forest restoration can be encouraged through silviculture treatments such as vine cutting and enrichment planting. However, the estimated cost of these activities could total US$100 to US$1 000 per hectare, depending on the region, forest type, topography, accessibility and other site-specific features that influence operational costs (Laurance and Bierregaard, 1997) (Box 14).

ROTATION LENGTH AND MITIGATION

Increasing the rotation period has the potential to increase carbon sequestration and storage in forests. Old forest stands have the highest carbon density, whereas younger stands have a larger carbon sink capacity, and forest plantations have a shorter carbon residence time. However, if HWP use leads to continued carbon storage and avoided emissions because of substitution effects, continued harvests may be preferable to increasing the rotation length. Specific formulas for establishing optimal rotation length must be developed as a function of carbon sequestration, storage and residence time. Analysis of carbon stocks and flows in forest ecosystems using carbon simulation models (Alvarez *et al*., 2014) could assist in adjusting mitigation rotations.

BOX 13

Adoption of reduced-impact logging in Sabah, Malaysia

Between 1975 and 1995, the forest cover in the state of Sabah, Malaysia, decreased from 2.8 million to 300 000 ha (Kleine, 1997). In an attempt to slow the decline, the state government hosted a pilot carbon offset in 1992, which contrasted the impact of conventional harvesting with that of RIL. RIL was found to reduce damage to future harvest trees by 26 percent and to the residual stand crown and/or bark by 6 percent. After one year of RIL, areas contained 23 percent more biomass than areas harvested through conventional means (Pinard and Putz, 1997). Since then, forest harvesting operations have improved throughout Sabah, with the revision of logging codes of practice (SFD, 2009) and the continuation of research initiatives on improving harvest practices (Lincoln, 2008). In 2010, RIL was mandated in official policy, and in 2011, the Forest Enactment was revised to legislate a royalty payment on financial gains associated with carbon activities (Sario, 2013).

Malaysia, as a signatory to UNFCCC, endorses activities under Decision 1/CP.16, Paragraph 70, which includes "reduction of emissions from forest degradation". Such activities are eligible for results-based payments.

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Directional felling and the regeneration of a residual stand in Sabah, Malaysia

Mitigation potential and economics of changing rotation length

A background study for this publication (Jurgenson and Whiteman, 2016) examined the economic feasibility of changing rotation length as an option for gaining mitigation benefits. The study provided support for increasing rotation ages, corroborating a number of previous studies. The economically optimal rotation age was calculated for different

BOX 14

Financial considerations of reduced-impact logging in Pará, Brazil

As reported by M.V. Galante (personal communication), after 16 years of RIL trials in Pará, Brazil, carbon stock accumulation was found to be approximately 1 tonne CO_2e higher per hectare per year than under conventional logging (West, Vidal and Putz, 2014). At a carbon price of US$3 per tonne CO_2e, the financial benefits of using RIL for mitigation in Pará could be estimated at US$3 per hectare per year. Studies between 2007 and 2013 estimated that 376 000 ha per year were affected by logging activities in Pará (INPE, 2013), with a potential carbon value of US$1.1 million per year; this may be interpreted as the opportunity cost of RIL. In the absence of RIL, forest restoration from conventional activities may cost upwards of US$37 million per year, which could be seen as an incentive to apply RIL more widely (Berenguer *et al.*, 2014; Minang *et al.*, 2014).

species in a range of forest stands around the world with different yield classes and timber prices. The study also took into account the benefits and costs from the accumulation and release of carbon in above-ground biomass during the life cycle of the plantation (and subsequent use of wood products), including the substitution effect from the replacement of fossil fuels. The results indicate that with about 264 million hectares of managed planted forests worldwide, the potential for storing carbon through added rotation lengths is huge. Measures to encourage longer rotation lengths should use short-term market fluctuations to reduce the costs and impacts of leakage, by focusing on measures to extend rotations when market prices are low.

The economically optimal rotation age increased with a rise in the value of carbon for all tree species examined, but with variation in the timing and scale of the increase. Thus changing rotation age had little impact for teak (*Tectona grandis*) in India (a high-value crop) and a big impact for *Pinus roxburghii* (pine) in the southeastern United States of America (a low-value crop). Calculated figures for annual net carbon accumulation are useful as a general indication of the benefits that might be expected over a period of several decades if rotation periods are modified.

The scale of the increase in optimal rotation age was negatively correlated with the value of the wood product output and the growth rate of the forest stand. Where timber values and growth rates are high, carbon value has the lowest impact on optimal rotation age.

When bioenergy income and carbon benefits from fossil fuel substitution are taken into account, optimal rotation ages are shorter, because these income streams do not place a higher value on larger roundwood.

Extending rotation ages in order to sequester carbon will lock up wood from existing production forests and cause a reduction in average wood production (on the possible scale of millions of cubic metres) from forests for long periods, depending on the area of forest covered under the carbon scheme. The number of years added to a rotation, if carbon values are taken into account, is positively correlated with the relative value of carbon and wood.

The analysis demonstrates how forest management could change at the stand level if a carbon value is included in economic appraisals for a range of planted and managed forest systems worldwide, leading to the following conclusions.

- A forest management system that increases tree growth rates would reduce the extending effect of a carbon value on optimal rotation age.
- When carbon values are considered, adding in residue (bioenergy) income and carbon benefits from fossil fuel substitution makes optimal rotation ages shorter. This incentive to reduce rotation age is particularly profound in forest stands that are currently producing sawlogs of relatively low market value. The preliminary focus on extending rotation age as a carbon-related policy tool should therefore be on forests currently producing low-value wood.
- Over long timescales, an extension of rotation ages for carbon value will likely increase the production of sawlogs at the expense of small roundwood, causing more carbon to be stored in long-lived HWPs. The most profitable end-use of small roundwood produced locally would likely be for woodfuel (owing to the fossil fuel substitution effect) rather than panels and paper.
- Plantation of additional forest areas is a necessary measure when mitigation is achieved by extending rotation age.

BETTER MANAGEMENT OF PESTS AND DISEASES

Insect, pest and disease outbreaks have significant effects on forest carbon storage and sequestration rates because of their influence on growth, mortality, decomposition rates and other ecosystem processes (Ellison *et al*. 2005; Albani *et al*., 2010; Hicke *et al*., 2012; Boyd *et al*., 2013; Ghimire *et al*., 2015). Tree mortality from catastrophic outbreaks reduces forest carbon uptake and increases future emissions from the decay of killed trees (Kurz *et al*., 2008). These impacts must be accounted for in forest carbon projects and in large-scale carbon modeling (Box 15).

Insect pest attacks, like forest fires, can be regarded as natural factors in forest dynamics. However, in recent years both the number and scale of damaging forest pest and pathogen outbreaks have increased with rising world trade in trees, wood and wood used in packaging and impacts of climate change (Aukema *et al.*, 2010, Santini *et al*., 2013; Freer-Smith and Webber, 2015). Insect pest and pathogen damage may continue to increase in the future, since the most responsive pest species are those with short life spans and rapid regeneration rates, which are likely to be boosted by climate change, especially relative to their long-lived hosts (Ayres and Lombardero, 2000).

The scale of losses from some recent outbreaks underlines the potential of pest and disease damage to release CO_2 and methane into the atmosphere. Kurz *et al*. (2008) estimated that the forest in British Columbia, Canada affected by bark beetle between 2000 and 2020 will release 73.6 Mt CO_2e (9.8 g CO_2e per square metre annually over 34.7 million hectares) (Figure 19). Thus, during and immediately after an outbreak, the forest is transformed from a small net carbon sink to a large source of carbon.

Effective continuous management of insects and diseases can improve the ability of forests to fix and store carbon and thus needs to be integrated in sustainable forest management, particularly where carbon removal from the atmosphere is a major forest objective.

BOX 15

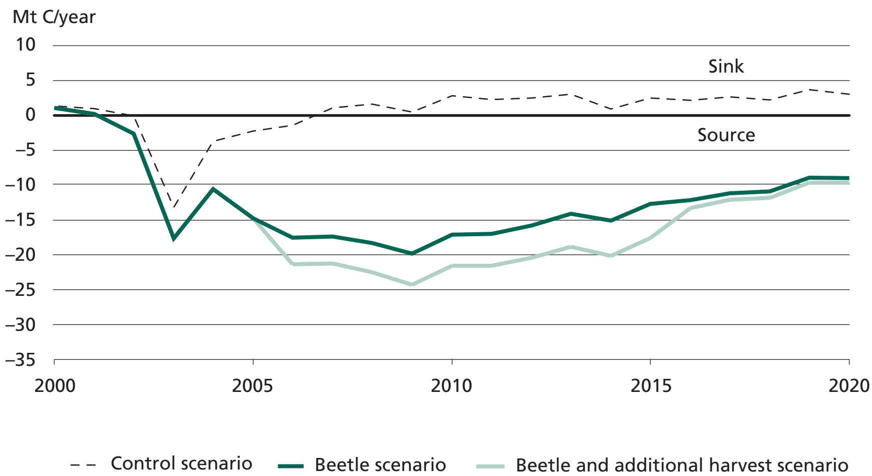
Estimating potential carbon losses from woodlands

Under a recently developed model for estimating potential carbon losses from woodlands accredited under the United Kingdom's Woodland Carbon Code (Davies, 2014), 3 to 10 percent of carbon sequestered in projects must be set aside as a buffer against future carbon losses due to pest and disease problems over 50 to 100 years. Recent verification work in the forest suggests that the actual losses at current risk levels are likely to be at the lower end of this range. Pest and disease risk varies considerably according to the tree species and regional and local factors. These relatively low carbon loss estimates apply to well-managed and certified woodlands.

The risk-based approach to carbon storage, and particularly the adoption of management practices to mitigate such risks, is important to sustainable forest management planning, forest restoration, carbon sequestration management in forest ecosystems and the design of forest carbon schemes.

FIGURE 19

Total ecosystem carbon stock change for three scenarios



Note: The control simulation was run with no beetle outbreak, and with base harvest and fires. The beetle simulation added insect impacts to the control scenario. The additional harvest simulation added the management response of increased harvest levels from 2006 to 2016 to the beetle simulation. Negative ecosystem carbon stock change values represent fluxes from the forest to the atmosphere (net source of carbon). The source in 2003 was in part the result of the large area burnt (2 440 km^2 in the study area), which was included in all three scenarios.

Source: Kurz *et al.*, 2008

BOX 16

Managing tree disease to prevent additional emissions: the case of *Phytophthora ramorum* in the United Kingdom

Phytophthora ramorum causes sudden oak death or ramorum blight and has a broad host range. In the United Kingdom, *P. ramorum* infection has resulted in dieback of Japanese larch (*Larix kaempferi*). Spread of the disease has been rapid under wet weather conditions, and by the end of October 2014, 17 485 ha had been infected, with impacts for the landscape and the wood processing sector (P. Freer-Smith, personal communication).

To limit the further spread of *P. ramorum*, 10 673 ha of infected forest have been felled, representing some 2.2 million cubic metres of roundwood, which has been processed in the normal way without significant impacts on end use. Felled areas are being replanted with productive species. In this way it has been possible to avoid the increase in carbon emissions that would have occurred if trees had been "felled to waste", that is, if the wood had remained on site to decay (King, Harris and Webber 2015; Forestry Commission, 2016b).

P. ramorum has also killed millions of oak and tanoak trees in the United States of America (California). It is likely spread through the movement of infected or contaminated plant material, growing media, nursery stock, and soil carried on vehicles, machinery and footwear (Brasier and Webber, 2010).

Outbreaks are better understood in hindsight and are difficult to forecast. Outbreaks are frequently associated with changes in host distribution or density, which are often a legacy of land-use policies or management practices. Since it remains unclear which pathogens or insect pests are most likely to benefit from climate change, diversifying plantations would be wise. Given the inherent risks associated with selecting species while the environment is in flux, monitoring needs to be increased, at a resolution that will capture changes in forest insect pest and pathogen behaviour while the damage levels are low (field experiments, modelling), so that management efforts can be adapted effectively and efficiently (Metsaranta *et al*., 2011). An adaptive management approach is needed, where forest managers are trained to expect the unexpected (Millar, Stephenson and Stephens, 2007).

In the case of outbreaks, additional carbon emissions can be avoided through sanitation felling and replanting with productive species (Box 16). A lack of intervention, with trees left to die and decay on site (more likely with pests that kill a small proportion of individual trees spread throughout a forest stand, such as the pine processionary moth in central Europe), will result in a relatively rapid return of CO_2 to the atmosphere.

IMPROVING FIRE MANAGEMENT

Over the past decade, climate change impacts (droughts and lengthening fire seasons), combined with other factors such as land management and land-use change, have altered wildland fire regimes (Flannigan *et al*., 2009) and made wildfire a major problem globally – as illustrated by a number of severe fire incidents around the globe (e.g. in Greece in 2007, Australia in 2009, the Russian Federation in 2010) which have resulted in huge losses of life, infrastructure and property. As climate changes increase, wildland fire activity is likely to become much more frequent and extensive, with potentially catastrophic results (Liu, Stanturf and Goodrick, 2010). These impacts will be most significant in boreal and temperate regions.

Wildland fires affect about 350 million hectares annually around the world, with more than 30 percent of the global land surface experiencing frequent fires (Giglio, Randerson and van der Werf, 2013). The largest increases in wildland fire activity in recent decades have been in tropical forests, where they are directly related to deforestation and land-use change (Mouillot and Field, 2005).

Increases in wildland fire activity have also been observed in Mediterranean Europe and Canada as well as in the western United States of America, where they have been attributed to a combination of climate change driven droughts, an overaccumulation of fuels due to decades of effective fire suppression and the rapid expansion of wildland-urban interface areas (Dennison *et al*., 2014).

At boreal latitudes, where climate change impacts are expected to be both early and substantial, fire statistics over the past four to five decades show extremely high interannual variability in area burnt. The total area burnt in the Russian Federation, Canada and the state of Alaska in the United States, combined, can vary by an order of magnitude, roughly ranging from 2 to 20 million hectares annually. The boreal zone contains extensive carbon-rich peatlands and permafrost, raising concerns that climate change driven increased fire activity could have severe impacts on the terrestrial/atmospheric/oceanic carbon balance.

Fire management agencies have had to adapt their activities and their resources to respond to lengthening fire seasons, increases in fire occurrence, fire intensity and area burnt, and smouldering combustion in deep organic layers. When conditions become extreme, fire activities can be overwhelming to manage, and areas burnt and losses of timber and property can be significant.

Mitigation potential of fire management

Fire management expenditures vary significantly among regions and years (see example in Box 17). The absence of data in many places prevents a global assessment of the benefits and costs of fire management as a mitigation measure. Furthermore, the unpredictability of fire incidence makes it difficult to estimate mitigation potential.

Annual global emissions from wildland fires are 7.34 Gt CO_2 (van der Werf *et al.*, 2010). If fire management could reduce the area burnt by 1 percent (a very conservative assumption), then emissions of 73.4 Mt CO_2 could be avoided. This potential implies that better fire management could be an integral part of mitigation strategies in the forest sector (see example in Box 18).

However, increasing fire suppression expenditures may lead to decreasing returns, putting the economic benefits of fire management into question. The ability of countries to mitigate projected fire impacts effectively on a large scale is severely restricted at best and could be greatly compromised in the coming decades, with fire protection capabilities

BOX 17

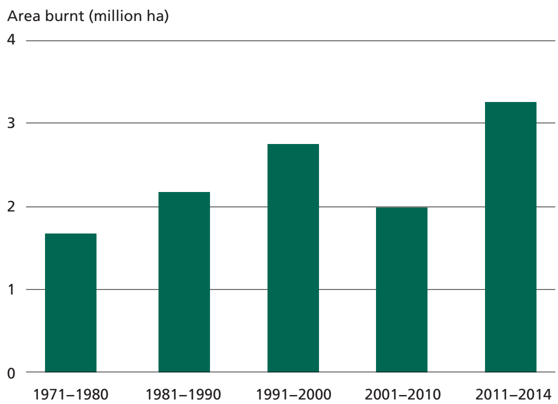
Growth of fire management expenditures in Canada

Fire protection capacity in Canada has been expanded and modernized over the past several decades, with major progress in predicting, detecting and controlling fires. Since the 1970s, the area burnt in Canada has averaged 2.2 million hectares annually, with large interannual variability (from less than 0.5 million to more than 7 million hectares) but with an upward trend over the decades (Figure 20). Fire management expenditures have increased steadily over this period, particularly in the past 20 years, although with growing interannual variability (Figure 21). The sharp rise in expenditures is mainly due to rising operational costs and an increasing number of costly fires in the expanding wildland-urban interface, where higher risk to human lives, infrastructure and property warrants proportionally higher fire management expenditures. However, Canadian fire management agencies recognize that there are physical and economic limits to further fire control, and that increasing fire suppression expenditures may lead to decreasing marginal returns in terms of escaped fires or area burnt (Canadian Council of Forest Ministers, 2005).

Source: Stocks and Martell, 2016

FIGURE 20

Decadal forest areas burnt in Canada, 1971–2014



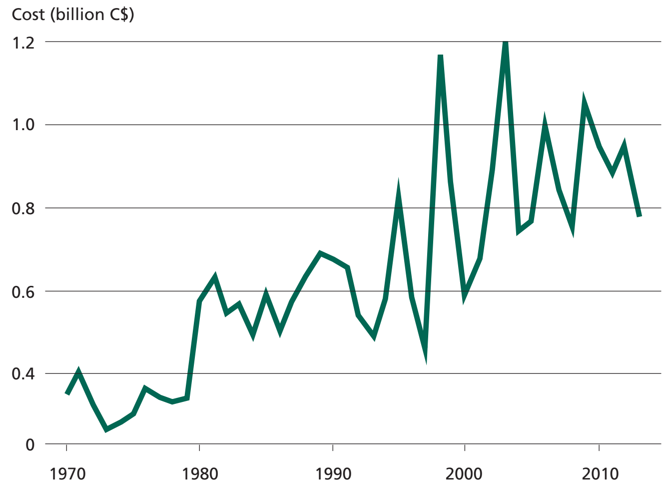
Note: The 2011–2014 period is averaged over four years.

Source: Data from the University of Alberta, Canada

continues

Box 17, continued

FIGURE 21
Total forest fire management costs in Canada, 1970–2013 (in 2013 Canadian dollars)



Note: 1 C$ = approximately US$0.93 in 2013
Source: Stocks and Martell, 2016

BOX 18
West Arnhem Land Fire Abatement Project, Australia

With the aim of reducing GHG emissions, the West Arnhem Land Fire Abatement Project has as its key objective to substantially increase the extent of early season burning using strategically prescribed fires, and to manage for and limit the extent of late season fires, thereby reducing overall area and amount burnt. The project set an annual target of 100 000 tonnes of CO_2 abatement, but in the five years to 2010 it actually abated 707 000 tonnes, greatly surpassing the target.

Source: NAILSMA, 2012

in many regions reaching their effective physical and economic limits. Increased wildfires in the future will force fire management agencies to reassess their policies, strategies and priorities. In boreal regions, for example, natural lightning-caused fire may be permitted over larger areas, while intensive protection efforts may focus more narrowly on high-value areas and resources. To protect those key areas, fire early warning systems (see FAO, 2006a) will be critical to prevent or mitigate disastrous fires, assisting in pre-suppression preparedness and supporting greater international resource sharing during periods of extreme fire activity (de Groot, Wotton and Flannigan, 2014).

MANAGEMENT OF THE SOIL CARBON POOL

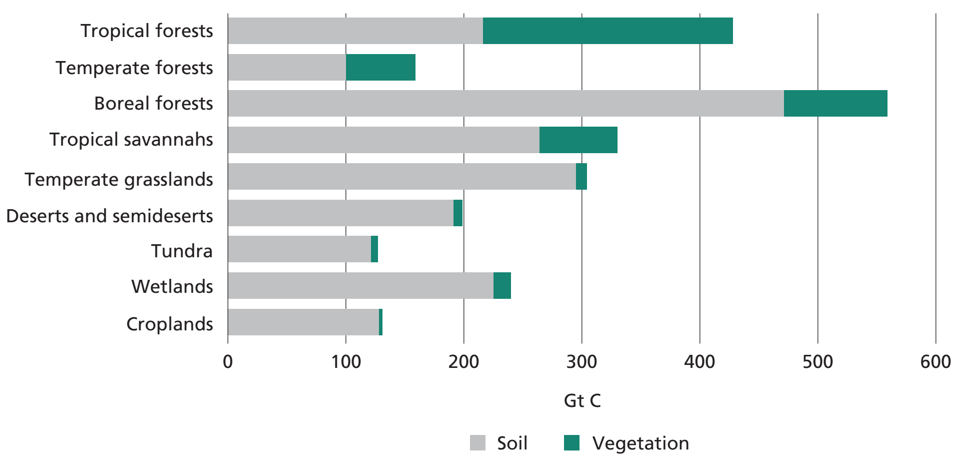
Globally, soil organic carbon (SOC) at the 0 to 30 cm surface level comprises around 66.5 Gt CO_2e (Batjes, 1996; Jobbágy and Jackson, 2000). It is the largest terrestrial carbon pool, accounting for two or three times more carbon than is held in the atmosphere (Davidson, Trumbore and Amundson, 2000).

Interest in the contribution of the soil carbon pool to mitigation strategies has been growing (Smith *et al.*, 2014). Improved land management could result in sequestering substantial SOC amounts within a few decades (Post *et al.*, 2012). Even a 5 percent increase in the size of the SOC pool with modified land management techniques could result in up to a 16 percent reduction in the amount of atmospheric carbon (Paustian *et al.*, 2000).

Forests currently contain 39 percent of all carbon stored in soils (Eliasch, 2008). The amount of carbon in forest soils varies among regions and forest types (Figures 22 and 23).

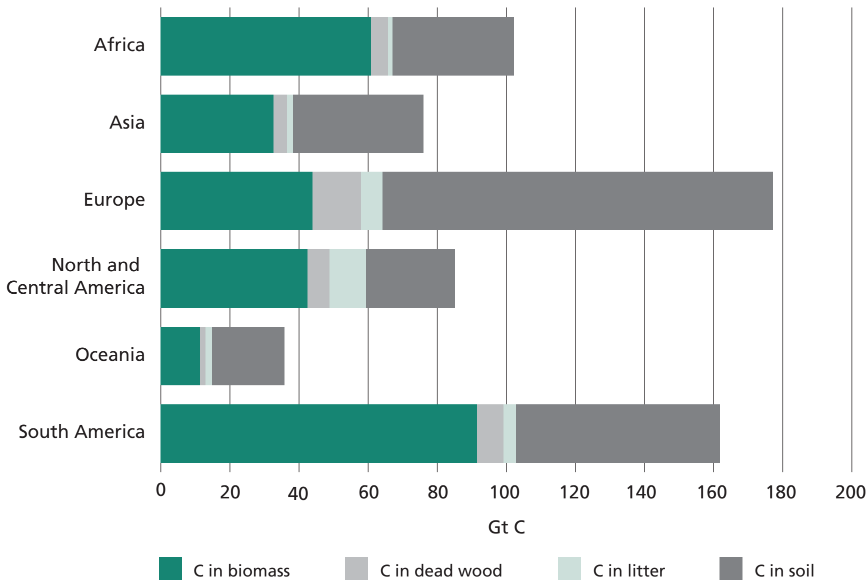
Forest management practices are intricately related to management of the soil carbon pool. Preventing deforestation and forest degradation has an important role in maintaining soil carbon stocks, as well as in strengthening the functional relationship between biodiversity and carbon sequestration (George *et al.*, 2012). This is primarily explained by the "niche-complementarity hypothesis", according to which a larger array of species in a system uses a broader spectrum of resources, causing the system to become more productive (Lehman and Tilman, 2000). More biodiverse stands offer better soil carbon sequestration, as well as greater resilience against disturbances, than even-aged

FIGURE 22
Global carbon stocks in vegetation and soil carbon pools to a depth of 1 m



Source: Data from IPCC, 2000

FIGURE 23
Total carbon stock in forests by region, 2005



Source: FAO, 2006b

monospecies plantations. Kaipainen *et al.* (2004) found that in European forests, SOC accumulated for several decades as long as the productivity of the forest (especially spruce forests) remained high, but leveled off with slowing productivity, mainly because of a decline in above-ground litter production, which controlled the SOC pool.

Afforestation of former agricultural land is generally thought to increase the carbon pool in biomass, soil and dead organic matter (dead wood and litter). A study in semi-arid Western Australia, however, documented no significant differences in soil carbon between reforested sites and adjacent agricultural fields (Box 19). How carbon stocks in different soils respond to afforestation remains unclear (Vejre *et al.*, 2003; Guo and Gifford, 2002; Paul *et al.*, 2002). A meta-analysis (Laganière, Angers & Paré, 2010) concluded that the main factors that contribute to restoration of SOC stocks following afforestation are previous land use, tree species planted, soil clay content, pre-planting disturbance and, to a lesser extent, climatic zone. Afforestation was found to have a less marked effect in pasture soils than in cultivated soils, as pasture soils already have higher carbon stocks and root densities in the upper mineral soil horizons (Guo and Gifford, 2002; Murty *et al.*, 2002). Generally, fertile and clay soils store more carbon, because of higher production of above- and below-ground litter and the associated formation of organo-mineral complexes protecting SOC from decomposition. In contrast, in poor mineral soils, slower SOC accumulation may be attributed to slower microbial decomposition (Vesterdal *et al.*, 2006).

BOX 19

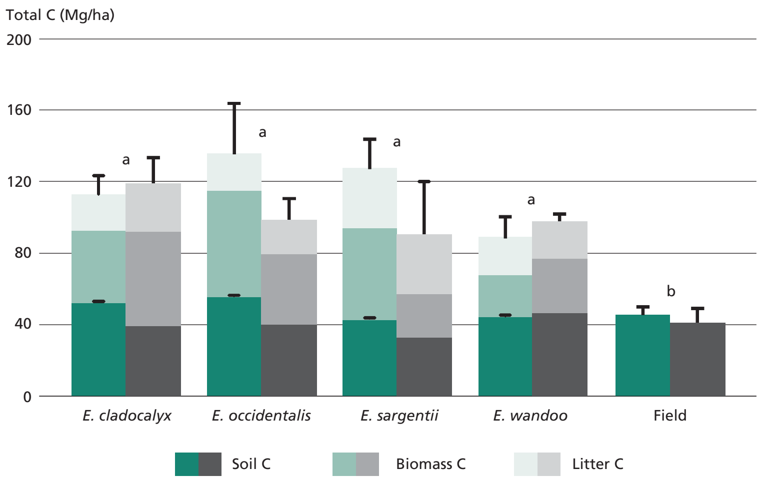
Carbon sequestration in soil and litter following reforestation of degraded agricultural landscapes

An investigation of the effects of reforestation on SOC stores compared two 26-year-old reforestation sites with farmland (conventional crop-pasture rotation) (Harper *et al.*, 2012). The reforested sites were planted with four species of *Eucalyptus* (Figure 24). SOC stores, measured to the depth of 0.3 m, ranged between 9 and 15 megagrams (Mg) CO_2e per hectare at both sites. No statistically significant differences in SOC were observed between reforested sites and adjacent farmland, but the reforested plots contained additional carbon in the tree biomass (6 to 16 Mg CO_2e per hectare) and litter (5.2 to 9.3 Mg CO_2e per hectare), with litter representing between 29 and 56 percent of the biomass carbon. The protection or use of this litter in fire-prone, semi-arid farmland will be an important component of ongoing carbon management.

These results raise questions about the conclusions of SOC sequestration studies following reforestation based on limited sampling (e.g. single paired plots) and emphasize the importance of considering litter in reforestation carbon accounts.

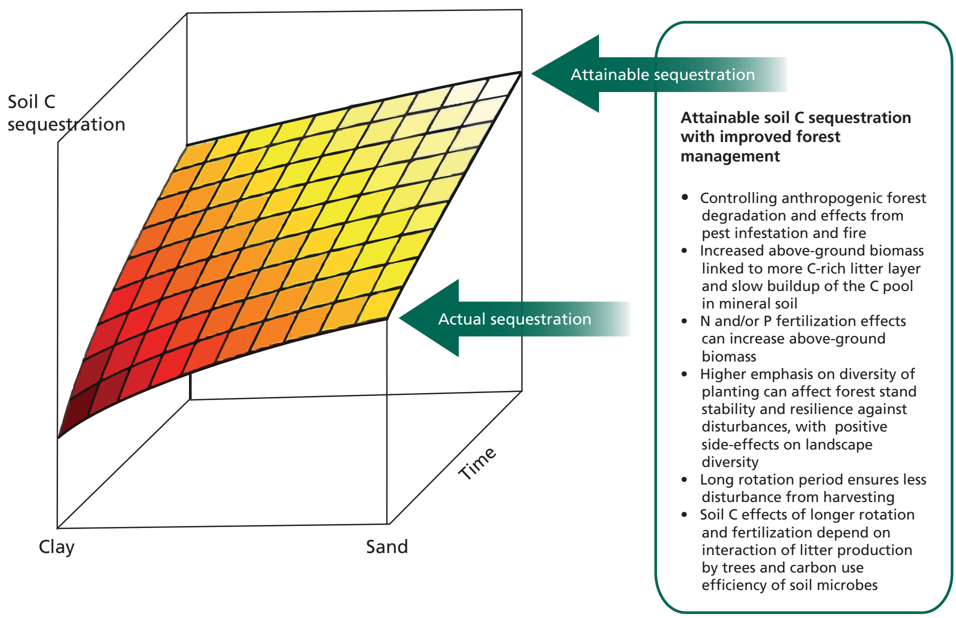
FIGURE 24

Carbon under four *Eucalyptus* species at two sites in Western Australia with Mediterranean climate having typical cool, wet winters and warm, dry summers



Note: Significant differences between treatments are denoted by lower-case letters.
Source: Modified from Harper *et al.*, 2012

FIGURE 25
Effects of different forest management strategies on soil carbon stocks



Source: Modified from Jandl *et al.*, 2007

Effect of stand management activities on soil carbon

Aside from planting, other key stand management activities – for example, harvesting, site preparation, thinning and fertilizer application – can also be manipulated to influence SOC accumulation or the release of carbon from decomposition of soil organic matter (Figure 25).

Forest stand thinning. Stand thinning is not aimed primarily at increasing carbon sequestration, but rather at increasing the radial growth of the remaining trees; it is often done at the expense of total biomass and temporarily alters the microclimate (Rambo and North, 2009; Sobachkin, Sobachkin and Buzkykin, 2005). Thinning can become a net source or sink for carbon, depending on the return of carbon to the soil through tree residues and root decomposition, against the degree of canopy opening exposing the soil to increased radiation and higher temperature, and, consequently, driving organic matter decomposition rates. The forest stand microclimate usually returns to pre-thinning conditions unless the thinning intervals are too short and intense, which results in increased soil compaction and higher slash removal with concomitant nutrient depletion (Jandl *et al.*, 2007; Paul *et al.*, 2002). In the long term, initial spacing typically has little influence on the rate of forest growth. However, further work is required to identify the interactions of the intensity of thinning, climate, soil type and species, and their influence on the change in SOC.

Site preparation. Most site preparation techniques (manual, mechanical, chemical and prescribed burning) result in some decomposition or redistribution of SOC in the profile, increase water infiltration into the soil and promote better root development (Jandl *et al*., 2007), thereby promoting rapid establishment, early growth and good survival of seedlings. Although ploughing has important short-term effects on SOC storage, long-term impacts (over more than 40 to 60 years) are difficult to detect (Compton *et al*., 1998). Furthermore, agricultural land that has previously been intensively cropped may contain carbon that is more resistant to loss after further mechanical disturbance (Paul *et al*., 2002).

Harvesting. Harvesting removes biomass, disturbs the soil and changes the microclimate more than thinning. In the years following harvesting and replanting, SOC losses may exceed carbon gains in above-ground biomass (Jandl *et al*., 2007). Rotation length and the fraction of biomass removed from the site following harvesting will substantially influence SOC changes (Jandl *et al*., 2007; Paul *et al*., 2002). Different harvesting methods also have different effects on SOC. Johnson and Curtis (2001), for example, found that for mostly coniferous species, sawlog harvesting caused an increase of 18 percent in input from slash and roots to carbon and nitrogen in soil, while whole-tree harvesting caused this input to decrease 6 percent. In general, however, different harvesting methods have a far greater effect on ecosystem carbon than on SOC, owing to the effect of harvesting on the biomass of the regenerating stand (Johnson *et al.*, 2002). Longer rotations can allow for more SOC accumulation, mainly because of less frequent disturbance from harvesting (Schulze *et al*., 1999).

Fertilization. A meta-analysis of 48 experiments spanning a wide geographical range concluded that both nitrogen-fixing vegetation and direct application of nitrogen mineral fertilizers lead to significant increases in SOC in the surface and near-surface mineral soil, especially on nutrient-limited sites (Johnson and Curtis, 2001). The likely response of tree growth to fertilizer application and the ensuing level of SOC change will also depend on plantation age and management (Jandl *et al*., 2007). Nitrogen (in relatively newly formed soil profiles) and phosphorus (in highly weathered soil) fertilizers affect above-ground biomass, but their effect on soil carbon depends on the interaction of litter production by trees and the carbon use efficiency of soil microbes. The use of nitrogen-fixing species (either as plantations or as the understorey of young, non-nitrogen-fixing plantations) offers potential to increase the total rate of SOC accumulation (Jandl *et al*., 2007; Paul *et al*., 2002).

Harnessing opportunities for SOC management

Current monitoring, reporting and verification requirements, under REDD+ for example, place little emphasis on accounting for SOC changes. Measuring these changes is difficult because SOC accumulates slowly – much more slowly than carbon in above-ground biomass in a moderately productive forest (Schlesinger and Andrews, 2000). SOC is also difficult to assess and has high spatial variability (Conen *et al*., 2004). SOC pools range along a biochemical continuum from unstable (i.e. easily broken down) carbon in fresh plant detritus to highly stabilized portions formed through interactions with soil mineral particles and aggregates (Kögel-Knabner *et al*., 2008). Unstable SOC sometimes persists

BOX 20

Soil organic carbon development over time in highly biodiverse forest

Soil organic matter increases with time as landscapes are restored. To clarify some of the uncertainties in quantifying carbon turnover rates with respect to forest restoration, George *et al.* (2010) studied SOC development along a restored forest chronosequence in Western Australia – a set of forested sites sharing similar attributes (*Eucalyptus marginata* dominated forest restored after surface mining) but of different ages. The area has a Mediterranean-type climate with hot, dry summers and mild, wet winters (with a mean of 731 mm of rainfall per year). SOC development in mineral soils was studied at four depths (0–2, 2–5, 5–10 and 10–20 cm).

The study provides several important insights into how SOC develops with age. Litter accumulation 12 years after restoration outpaced the native forest levels. Surface soils, in general, showed increases in total carbon with age, but this trend was not clearly observed at lower depths. These biodiverse forests showed a trend towards accumulating carbon in stable (recalcitrant) forms in the top 2 cm of mineral soil, while they tended to accumulate a moderately alterable SOC fraction at lower depths with increasing restoration age.

Similar trends in carbon gains in surface mineral soils have been observed in plantation forests, offsetting some of the losses of old carbon from deeper parts of the soil (Bashkin and Binkley, 1998; Giardina and Ryan, 2002; Markewitz, Sartori and Craft, 2002).

in soils if physicochemical and biological influences from the surrounding environment reduce the rate of decomposition (Schmidt *et al*., 2011). However, the usual methods of total SOC measurement do not tend to discriminate SOC quality. A more informative approach would be to partition SOC with mean residence time into pools of differing stabilities (von Lützow *et al*., 2007) (see example in Box 20). Biogeochemical process models (e.g. the CENTURY or RothC model) can predict the sensitivity of SOC inventory and turnover to climate, vegetation and parent material by subdividing fast-cycling soil carbon into readily decomposable, intermediate and resistant carbon pools. However, few field observations are available to test these predictions or to constrain model parameters (Trumbore, 1997; Smyth and Kurz, 2013).

Key messages: forest management

- Sound and sustainable forest management is necessary for both carbon and forest productivity, including practices intended to maintain as high an average stand volume as possible for as long as possible; to address potential risks from pests, disease, fire and extreme weather; and to maintain biodiversity.
- Wildland fires affect about 350 million hectares annually around the world, with more than 30 percent of the global land surface experiencing frequent fires. The largest increases in wildland fire activity in recent decades have been in tropical forests, where they are directly related to deforestation and land-use change.
- Soil organic carbon at the 0 to 30 cm surface level comprises around 66.5 Gt CO_2e. It is the largest terrestrial carbon pool, accounting for two or three times more carbon than is held in the atmosphere. Forests currently contain 39 percent of all carbon stored in soils. The amount of carbon in forest soils varies among regions and forest types. Forest management practices are intricately related to management of the soil carbon pool.
- Afforestation of former agricultural land is generally thought to increase the carbon pool in biomass, soil and dead organic matter (dead wood and litter). The main factors that contribute to restoration of SOC stocks following afforestation are previous land use, tree species planted, soil clay content, pre-planting disturbance and, to a lesser extent, climatic zone.

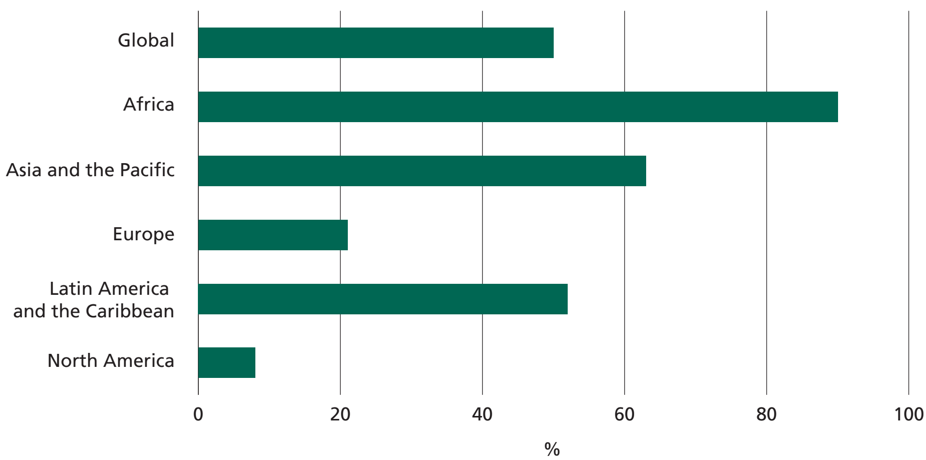
6. Improving and using wood energy

Most of the bioenergy consumed globally is from solid biomass, comprising mainly fuelwood, charcoal, agricultural and forestry wastes, renewable wastes from the paper and pulp industry and renewable municipal wastes (IRENA, 2013). It is estimated that 1.86 billion cubic metres of wood, over half of all wood produced in the world, is used for energy each year (Figure 26). Most of it (1.55 billion cubic metres) is in the form of fuelwood (Figure 27). The use of renewable wood resources for energy presents a mitigation opportunity, as they can replace the use of fossil fuels and potentially reduce net GHG emissions. Significant mitigation can also be achieved through increased efficiency in the production and use of woodfuel.

Bioenergy's share in total primary energy supply (TPES) in 1990 was estimated to be about 10 percent. Between 1990 and 2010 bioenergy supply increased from 38 to 52 exajoules (EJ). Solid biofuels, mainly wood, constitute the largest renewable energy source, accounting for 69 percent of the world's renewable energy supply (WEC, 2013). Woodfuel from forests accounts globally for about 6 percent of TPES (roughly two-thirds coming from fuelwood and charcoal and one-third from the forest processing industry) (FAO, 2014).

Wood energy accounts for 7 percent of total global carbon emissions (Table 6). However, its share in total emissions varies significantly among regions, with the highest share in Africa.

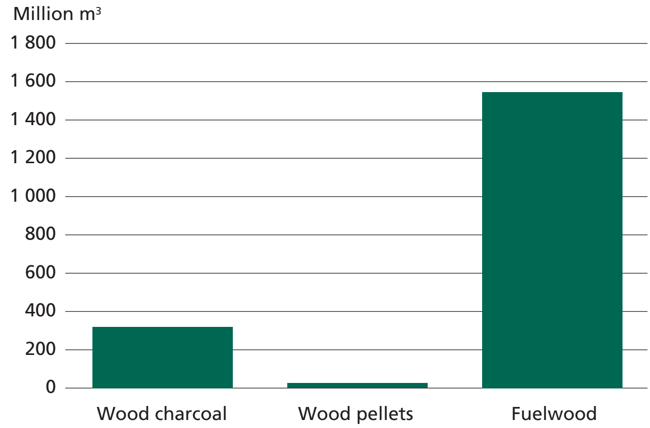
FIGURE 26
Percentage of roundwood used as woodfuel, 2014



Source: FAO, 2015b

FIGURE 27

Consumption of fuelwood in comparison with wood pellets and charcoal, 2014



Note: To convert charcoal (measured in tonnes) to cubic metres, a standard conversion factor (weight x 6) was used.

Source: FAO, 2015a

TABLE 6

CO_2 emissions from wood energy compared with total carbon emissions, 2010 (Mt CO_2)

Region	Type of activity			Emissions from wood energy			Wood energy emissions as share of total emissions (%)
	Fossil fuel energy	Land use change	Total	Fuelwood	Charcoal	Total	
Africa	1 171	1 256	2 427	590	226	817	34
Asia and Oceania	16 529	630	17 159	952	66	1 018	8
Europe	6 009	–720	5 289	195	4	199	4
North America	5 933	–116	5 817	50	7	57	1
Latin America and Caribbean	1 691	1 365	3 056	297	74	371	12
World	**31 332**	**2 415**	**33 747**	**2 084**	**378**	**2 462**	**7**

Note: Emissions from charcoal include those from its use and manufacturing (roughly one-third and two-thirds of the total, respectively).

Sources: Boden, Marland and Andres, 2013; FAO, 2015a

FROM TRADITIONAL USE TO BIOREFINERIES

In 29 countries, mostly in Africa, wood energy provides more than half of all energy consumption, and one-third of households worldwide (about 2.4 billion people) use wood as their main fuel for cooking and for boiling drinking water (FAO, 2014) (see Box 21). Domestic wood energy use is also significant in industrialized countries; 80.6 million people in Europe and 7.9 million people in North America use woodfuel as their main source of heating (FAO, 2014).

The use of wood for electricity generation began to increase significantly from the early 1990s. The most common methods of producing heat and power from biomass today are co-firing of biomass (particularly wood pellets) with another fuel (usually coal), and direct burning of biomass in dedicated biopower plants (stoker boilers or fluidized bed

BOX 21

Improved use of wood for energy for climate change mitigation in the Maasai-inhabited rangelands of Kenya

Wood is a major source of energy across the Horn of Africa and in much of sub-Saharan Africa. In the Maasai-inhabited rangelands of Kenya, wood from forests and trees outside forests accounts for over 90 percent of energy utilization. Wood energy use in the region is characterized by diversity across sectors (in terms of type and frequency), decentralized demand and supply, and a dominance of informal markets. The few forests and trees outside forests in these rangelands offer mitigation potential through carbon sequestration, if used sustainably.

A study conducted in 2014 on integrated mitigation options for this region using improved or alternative wood energy under changed-climate and business-as-usual scenarios (Mwangi, personal communication) found that the rangeland inhabitants have been improving the efficiency of their wood energy use from an emissions standpoint, for example by increasingly using charcoal in energy-efficient stoves instead of fuelwood, and by using wood from agroforestry systems for fuelwood and charcoal.

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Charcoal from Acacia *spp., traditionally widely used in the Maasai-inhabited rangelands of Kenya*

© M. MWANGI

Eucalyptus *woodlot, emerging as an improved wood-energy option for mitigation*

© M. MWANGI

Eucalyptus *teleposts store carbon, contributing to mitigation*

Plantation of *Eucalyptus* woodlots, mainly for production of teleposts (used for telecommunication and electricity poles and posts), is also contributing to climate change mitigation, as these woodlots have longer-term carbon sequestering capacity relative to production of fuelwood or charcoal from *Acacia* spp., the species traditionally extracted for these uses.

In general, fuelwood and charcoal are the main sources of wood energy used, while sawdust, agroforestry waste and such are still used only on a small scale, depending on the woody species extracted.

boilers). Retrofitting of established coal plants for co-firing with biomass requires a low incremental investment. However, co-firing generally involves coal mixed with biomass in ratios of 15 percent biomass or less, since at low ratios biomass can be used directly in existing coal plants without the need for a retrofit.

Another commercial technology applicable to wood energy is co-generation, or combined heat and power (CHP). The advantage of CHP is that it recovers waste heat from electricity production for space heating, water heating or additional electricity production. As a result, overall system efficiency is very high, ranging from 70 to 85 percent, contributing to significant GHG emission reductions (Sims *et al.*, 2007).

Many new technologies are being investigated, developed and commercialized to harness energy from wood, including processes to develop so-called second-generation biofuels. For example, biomass gasification and pyrolysis are garnering interest for heat and electricity production, given their relatively high efficiency.

Attempts to produce liquid fuels from wood date back to the early 1900s, but have gained momentum since the 1990s with increasing demand for sustainable and renewable liquid fuels in the transport sector. Biofuel from wood has not yet been produced on a large commercial scale, but biochemical and thermochemical (pyrolysis and gasification) technologies for production of diesel, gasoline and kerosene have been demonstrated at pilot level and are ready to be deployed commercially.

However, despite unprecedented incentives and investments by both private and government entities, several barriers across the entire supply chain are currently preventing profitable production of liquid cellulosic biofuels. These obstacles are mainly related to costs and availability of lignocellulosic feedstock, high pretreatment costs required to lower the recalcitrance of cellulosic biomass (mostly softwoods) and the high capital investment required.

Nevertheless, success stories have started to emerge. Since January 2015, for example, a biorefinery in Finland has been producing renewable diesel from forest residues at a commercial scale; it is ultimately expected to produce 120 million litres of renewable diesel per year (UPM Biofuels, 2015). Commercial-scale cellulosic ethanol production from wood and wood-based products can be expected in the near future.

While the various biorefinery technology opportunities are not assessed in detail in this report, they are growing in importance and are expected to play a significant role in the biobased chemical industry of the future (see Box 22).

POTENTIAL OF USING WOOD ENERGY FOR MITIGATION

The carbon neutrality of wood energy is a controversial issue (Box 23). Burning wood – or transforming it into other forms of solid, liquid or gas fuels such as charcoal, pellets, briquettes, pyrolysis bio-oil, cellulosic ethanol and combustible wood gas – releases CO_2 into the atmosphere, as well as CH_4 and N_2O. Leaving aside the emissions of CH_4 and N_2O, which cannot be fully avoided or neutralized under any scenario, a key to determining the emission reduction potential of wood energy can be considered the question of whether the carbon released is recaptured by subsequent plantations. In this view, wood energy should be closest to carbon neutral if the wood is drawn from a sustainably managed forest or system of growing forests, which would sequester an amount of CO_2 close

BOX 22

Biorefineries: higher-value, low-carbon products from forest biomass

With state-of-the-art biorefineries, biomass can be used as an input not only for food, feed, power and heat, but also in the production of fuels, chemicals, biopolymers and other chemical products of high purity such as organic acids, antibiotics and vitamins. The key is the separation of the biomass into its main fractions, for which several processes exist, depending on the biomass input as well as outputs to be generated (see IEA Bioenergy, 2015).

Advanced biorefinery processes can be categorized according to whether they use starch (from edible parts of plants such as maize, wheat and rye) or lignocellulosic feedstock from agricultural and forest residues (straw, husks, wood). Lignocellulosic feedstock is not in conflict *per se* with the food sector, as this material cannot be digested by the human metabolism. The processes used range from gasification of woody biomass into synthetic gas for the production of fuels, to hydrolysis, which does not destroy the sugar polymers and leaves broader options for sophisticated downstream biochemical processing steps.

The bioeconomy as an economic domain has attracted much attention in recent years from both the private and public sectors and civil society. Its ultimate goal is to add value to sustainable biomass use. At issue is which biomass resource inputs to use and which products to generate as outputs. Biochemicals and biomaterials are more valuable products than bioenergy produced from incineration or biogas production. Since biomass can be used as a substitute for petroleum-based feedstock, all of these products can significantly contribute to climate mitigation.

to or equivalent to the amount emitted in producing wood energy. Accordingly, many studies evaluate the carbon neutrality of wood by assessing the sustainability of the wood feedstock, the source of the wood.

Even addressing mitigation potential in this way, wood energy from sustainably managed forest would not be seen as carbon neutral everywhere. In boreal regions, for example, regrowth is too slow to offset wood energy emissions immediately (Ter-Mikaelian, Colombo and Chen, 2015). Still, in principle, sustainably managed forests in certain places and under certain conditions should be able to support a viable carbon-neutral energy system that is capable of operating indefinitely.

Taking a more complex view, the mitigation contribution of using wood for energy can only be assessed by considering the GHG emissions along the whole value chain. Whether energy use contributes to net reduction of carbon emissions, and therefore mitigation, then depends not only on the sustainability of the wood system, but also on energy consumption during production, transportation, processing (transformation and/or conversion), storage and handling; the combustion efficiency of woodfuel; the type of displaced fossil fuel; and the wood energy utilization facilities (e.g. stove, furnace, wood-fired power plant). These

BOX 23

Differing approaches to forest bioenergy emission accounting

The accounting of emissions from the use of wood for energy, and hence the calculation of forest bioenergy mitigation potential, is a subject of much debate (JRC *et al.*, 2015) National inventories under UNFCCC allocate annual forest carbon losses or sinks to the LULUCF sector. They exclude CO_2 emissions from biomass in the energy sector to avoid double counting. The life-cycle approach, in contrast, attributes the impacts of GHG emissions over the life cycle of a specific product or service to this product or service; this approach can challenge the assumption of carbon neutrality (Searchinger *et al.,* 2009; Walker *et al.,* 2013; Sedjo, Sohngen and Riddle, 2013; van Kooten, 2015).

Policies vary in this regard. The Renewable Energy Directive of the European Union (EU, 2009) considers bioenergy to be carbon neutral, assigning a value of zero to direct biogenic CO_2 emissions under the assumption that CO_2 emissions from wood burning are offset straightaway through carbon fixing via forest growth (i.e. the hypothesis of perfect carbon sequestration parity).

The United States Environmental Protection Agency, however, states that carbon neutrality cannot be assumed for all biomass energy a priori (EPA, 2014):

> *There are circumstances in which biomass is grown, harvested and combusted in a carbon neutral fashion, but carbon neutrality is not an appropriate a priori assumption; it is a conclusion that should be reached only after considering a particular feedstock's production and consumption cycle. There is considerable heterogeneity in feedstock types, sources and production methods and thus net biogenic carbon emissions will vary considerably.*

It is important to develop methods to assess carbon fluxes and sinks potentially affected by changes in bioenergy consumption in order to inform the development of sustainable bioenergy policy.

facilities may be considered "energy carriers", since their manufacturing and installation also involve consumption of energy and other materials. The mitigation potential of wood energy is also influenced by prior land use (e.g. barren land versus existing forest), above- and below-ground biomass carbon, the type of wood feedstock and the carbon intensity of the replaced fuel. The implications for soil carbon of the removal of biomass for bioenergy also deserve attention (Berhongaray and Ceulemans, 2015; Repo *et al*., 2014).

Among other factors, the temporal and spatial scale of analysis also affect estimates of net GHG emissions. Systems taking individual forest stands as the unit of analysis could accrue carbon debts that would take decades to repay (MCCS, 2010; McKechnie *et al*., 2011; Smyth *et al*., 2014), but the net impacts of increased biomass demand on sequestration may be lower when estimated at a larger geographic scale, i.e. the landscape level (Galik and Abt, 2012). The landscape – i.e. a relatively large, spatially heterogeneous geographic area composed of diverse interacting ecosystems ranging from natural terrestrial and aquatic systems such as forests, grasslands, and lakes to human-dominated environments including intensively managed agricultural and forest lands and urban areas – is generally the appropriate level for policy assessment.

Other factors influencing the analysis include the accounting period (e.g. Fritsche *et al*., 2014a) and the counterfactual scenario (capturing what would happen if the key variables in the analysis – e.g. the reference energy system or the type of forest management – were changed) (e.g. Stephenson and MacKay, 2014; Ter-Mikaelian, Colombo and Chen, 2015). In any case, the geographical scope and timescale should reflect the aim of the assessment or the scope of the (policy) instrument to be evaluated (JRC *et al.*, 2015).

Taking all these variations into account, and depending on the woodfuel technology and assumptions regarding the baseline fossil fuel displaced, biofuels and biopower derived from wood and forest residues may be able to reduce GHG emissions from 50 percent to more than 150 percent per unit of energy produced (Baral and Malins, 2014; Wihersaari, 2005; Zhang *et al*., 2009). In particular, sustainably sourced wood from forests grown on underused and marginal lands, forest residues from timber harvesting and by-products from sawnwood manufacturing offer significant potential for mitigation when used for energy.

More importantly, if multiple uses (construction materials, furniture, etc.) of the same wood biomass can be established prior to its final use as energy through a cascading biomass framework (Keegan *et al*., 2013; Dornburg and Faaij, 2015), mitigation benefits and sustainability can be greatly improved. Cascading use of biomass (Box 24) lowers GHG emissions by avoiding the use of virgin raw materials and energy intensive processes in the life cycle of biomass products and bioenergy.

BOX 24

Cascading use of wood

The aim of "cascading use" of biomass (EC, 2013) is to extend its lifetime by introducing one or more uses, for example in the construction, packaging, furniture and/or recycling sectors, before its final use as an energy source. Cascading use can be effective for meeting the growing demand for wood products and energy without disproportionately increasing pressure on natural resources.

Cascading use has some commonalities with concepts of re-use, circular economy and recycling. In cascading use, however, the final purpose of the biomaterial is energy use. Nearly all stages of biomaterial use qualify as cascading use. However, intermediate products that have no real material use for private or industrial consumers, such as process residues, and energy carriers (i.e. wood pellets, biodiesel) would not be included in a cascading use framework (Essel *et al.*, 2014).

A single cascading use already gives a great improvement in resource efficiency over direct use, but multiple uses are even more efficient. Whether to adopt a strategy of single or multiple cascading use depends on political will, associated costs and time sensitivity (Essel *et al*., 2014).

ECONOMIC FEASIBILITY

Economics of mitigation through industrial wood energy

Appropriate policy design for the generation of industrial wood energy depends on understanding the net GHG mitigation potential and costs of different ways of producing energy. The economic feasibility of wood energy for GHG mitigation varies by region and circumstances, and depends strongly on local, national and international energy and climate policy.

Substantial recent literature is devoted to the net impact of growing, harvesting and using different feedstocks. Observations include the following.

- ***Solid biomass.*** GHG savings per unit of energy produced for solid biomass pathways are in general above 60 percent both for power and heat production (Giuntoli *et al.*, 2014), although depending on the parameters of the analysis, the GHG offsets can vary strongly (Röder, Whittaker and Thornley, 2015). The parameters that have the strongest influence on the analysis are transport distances, cultivation inputs and supply of process utilities (Giuntoli *et al.*, 2014).
- ***Residual forest biomass.*** Residual forest biomass can be co-fired with fossil fuels at moderate cost (Baxter, 2005; Bauen *et al.*, 2009). For fast-decaying or burnt harvest residues, achieving carbon neutrality could take as few as five to ten years in some circumstances, depending on a number of factors such as climate and forest type (Jonker, Junginger and Faaij, 2013).
- ***Transport fuel.*** In a quantitative assessment of the environmental externalities associated with alternative transportation fuels in the United States, Birur *et al.* (2013) found that E85 fuel (85 percent ethanol derived from woody biomass, blended with gasoline) had the lowest net social costs in terms of GHG emissions and air pollution – only 25 percent of those associated with conventional gasoline. Increased use of wood for second-generation biofuels, however, implies raised prices of the wood feedstock (Sedjo and Sohngen, 2009).
- ***Wood pellets.*** Wood pellets can be used in the industrial, community and retail sectors and are suitable for all types of combustion systems without modification needed. Wood pellets can replace coal, lignite and furnace oil at the industrial level, and liquid petroleum gas (LPG), diesel and kerosene at the community and retail level and thus have the potential for important emission reductions. Tests carried out by Abellon CleanEnergy in India, which produces pellets from sawmill and log-processing waste for the Indian and European markets, showed that pellets generated 80 percent less ash and emitted less sulphur and sulphur oxides than lignite and Indian coal, as well as having higher gross calorific value (Table 7).
- ***Charcoal.*** Charcoal represents one of the cheapest fuels per unit of energy (Foster, 2000). Improving kiln technologies and harvesting wood from sustainable sources can greatly reduce the life-cycle GHG emissions of charcoal (Box 25). In the United Republic of Tanzania, Sjølie (2012) found that replacing charcoal produced in traditional kilns with charcoal briquettes made from sawmill residues could reduce net GHG emissions by 42 to 84 percent, depending on whether the substituted charcoal is considered carbon neutral or not.

TABLE 7
Comparison of wood pellets with fossil fuels in India

Fuel	Gross calorific value *(kcal/kg)*	Amount displaced by 1 kg pellets *(kg)*	CO_2 emissions per tonne of fuel *(tonnes CO_2)*
Lignite	2 500–3 000	1.36–1.64	1.64
Indian coal	3 500–3 800	1.07–1.17	1.52
Imported coal	5 000–5 500	0.75–0.82	1.53
Wood pellets	>4 200	1	Carbon neutrality assumed

Source: Abellon CleanEnergy, unpublished test results

BOX 25
Addressing environmental and human-health issues of using charcoal for energy

In principle, relatively simple innovations or modifications to conventional charcoal kiln designs can markedly increase kiln efficiency and address issues associated with their emissions, while also reducing smoke and soot and protecting human health. Metal kilns equipped with vapour incinerators, for example, are more efficient than conventional kilns. However, emissions associated with producing modern kilns can be larger than those of producing conventional kilns, and the required financial investment tends to be unaffordable in developing countries (Girard, 2002).

Alongside sustainable strategies for the use of forest resources, carbon offsets from the use of pyrolytic domestic stoves for small-scale charcoal production could provide income that could stimulate investment in clean and efficient kilns for charcoal production in small communities.

Traditional charcoal production in Mexico

Metal kilns equipped with vapour incinerator for charcoal production in France

The costs of modern wood energy are at present generally higher than those of traditional fossil fuels, with hauling costs a large influence. The proximity of forest biomass resources to generation facilities is thus an important consideration. Where waste wood is used for energy in wood-processing operations, these costs are negligible and in some cases negative, as the costs of otherwise eliminating the wood waste are avoided.

The net costs of substituting traditional fossil fuel with biomass, and the equivalent costs of GHG emissions offset from that substitution, can be estimated as the difference (in net thermal energy equivalent) between the costs of residual biomass supply and the cost of fossil fuel. Yemshanov *et al.* (2016) carried out such an analysis to assess the economic feasibility of GHG offsetting projects based on the use of forest residues for energy in Canada. They estimated an annual nationwide supply of annual GHG emission offsets ranging between 17.3 and 42.8 Mt CO_2e. Substitution possibilities for natural gas were seen to be less than those for coal, primarily because of differences in their prices and emission reductions.

Use of modern wood energy could be expected to become economically viable first in regions with large quantities of forest resources and existing coal-fired power plants where woody biomass could be co-fired. Areas with abundant forest resources located relatively close to population centres may also offer opportunities for development of new stand-alone biomass electricity generation or ethanol production facilities with reasonable transportation costs.

In the United States, a small share of public lands has excess biomass that poses fire risks, whose removal is consistent with national policy. Some of this biomass is not suitable for use in wood products and could be used for co-firing, which could also help pay for its removal as a fire treatment (Beach, 2008).

For advanced biofuels such as cellulosic ethanol, Fischer-Tropsch diesel or gasoline derived from woody biomass, the cost is largely determined by the delivered price of feedstocks. Turley, Evans and Nattrass (2013) showed that at a delivered feedstock price of less than US$55 per tonne for forest residues, biofuels can be competitive with conventional fuels. However, as the feedstock price increases above US$66 per tonne, biorefineries require financial incentives to be cost competitive.

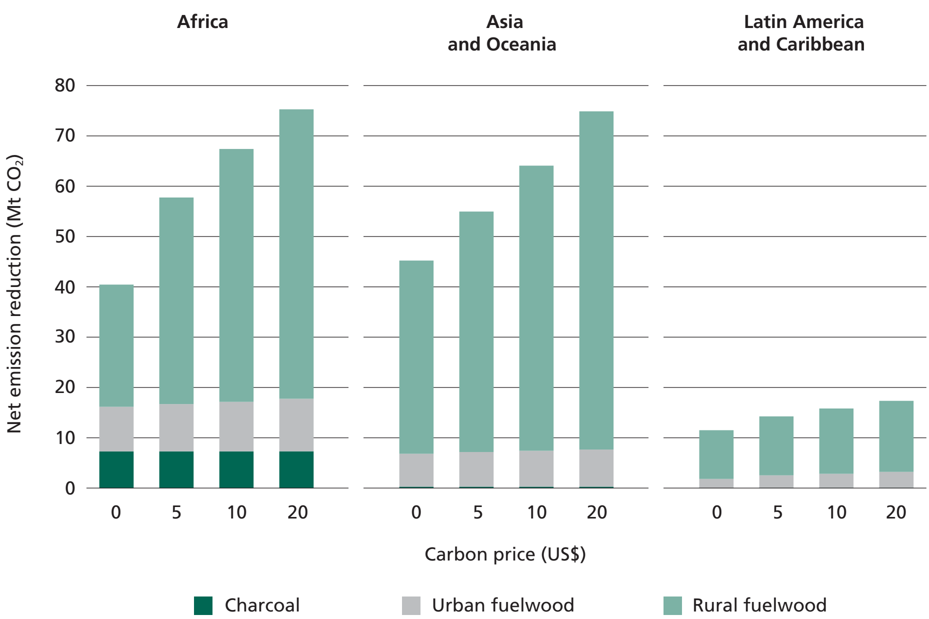
Clearly, wood energy will become more competitive with fossil fuels when there is a carbon price applied. Studies on the use of residual biomass for energy production support this idea (Cuellar, 2012; Maung and McCarl, 2013). The extent to which the use of wood energy will expand will thus depend on the carbon price, the net GHG reduction assigned and the price of residual wood fibre. The engineered wood (e.g. oriented strandboard, medium-density fibreboard) and pulp and paper industries compete with and tend to outbid the energy sector for residual wood fibre, reducing the attractiveness of woody biomass as an energy source (Stennes, Niquidet and van Kooten, 2010; Johnston and van Kooten, 2016).

Economics of using improved cookstoves for mitigation benefits in developing countries

Current woodfuel consumption for cooking is about 1.35 billion cubic metres annually and is expected to remain about the same for at least the next 20 years (Cushion, Whiteman and Dieterle, 2010). About three-quarters of the 2.4 billion tonnes of annual global CO_2 emissions from woodfuel come from the use of woodfuel for cooking. Thus, encouraging households to use cookstoves that burn less wood is one way to reduce emissions. However, more efficient cookstoves must be affordable if users are to adopt them, and cookstove projects must be a cost-competitive source of emission reductions if they are to obtain funding from carbon markets.

A background study for this publication (Whiteman and Fornari, 2016) analysed the potential emission reductions of switching to improved cookstoves in 73 countries. For each country, the analysis assessed the reduction in annual CO_2 emissions that could be achieved from the introduction of improved cookstoves across a range of carbon prices. The net global mitigation potential from the introduction of improved cookstoves was found to be about 95 Mt CO_2 per year at a carbon price of zero. If financial incentives could be provided for emission reductions, the mitigation potential could be increased to 165 Mt CO_2 at a carbon price of US$20 per tonne CO_2. This amount is relatively small – just under 0.5 percent of global emissions in 2010. However, in Africa the potential emission reductions, 40 to 75 Mt CO_2 (Figure 28), are more significant, i.e. about 1.5 to 3.0 percent of current CO_2 emissions. The introduction of improved cookstoves could thus make a meaningful contribution to emission reductions in Africa. However, the calculation and implementation of financial incentives would add more complexity to cookstove projects.

FIGURE 28
Net potential for annual emission reductions from the use of improved cookstoves



Source: Whiteman and Fornari, 2016

With improved cookstoves also having other benefits such as reduced air pollution and improved respiratory health, the analysis showed that in many countries their introduction may have a relatively high benefit-cost ratio and may be highly desirable from an economic perspective.

The main uncertainty in this analysis is the extent to which reductions in woodfuel use will lead to increased accumulation of carbon stocks in forests. The implicit assumption was that woodfuel is harvested from living trees and that these would accumulate more carbon if fewer of them were harvested for energy use. However, if woodfuel is produced from land that is being cleared for agriculture or is collected as dead wood, as harvesting or processing waste or from dead or dying trees, then reduced woodfuel demand is likely to have little or no impact on emissions.

BOTTLENECKS IN HARNESSING POTENTIALS

Meeting the increasing demand for wood sustainably

Possible difficulties in meeting the increased demand for wood biomass, and the externalities involved in supplying the increased demand, are areas of concern.

In developing countries, the heavy reliance on wood energy for subsistence has in many cases led to unsustainable and often illegal production which leads to deforestation, forest degradation and even woodfuel scarcity in some areas. Increased use of wood energy for mitigation therefore depends on an increased and sustainable supply of wood resources.

Wood deficits might also occur in developed countries. Mantau *et al*. (2010), for example, cautioned that proposed renewable energy targets in the European Union could result in a wood deficit of 200 to 260 million cubic metres by 2020, which could grow to 752 million cubic metres by 2030. Other studies, however (e.g. Fritsche *et al.*, 2014b) have suggested that structural changes and adaptations to markets will clear this gap between demand and supply. Solberg *et al.* (2014) stressed that sustainable forest biomass potentials in the EU will still suffice to meet the demand if resource-efficient cascades are implemented, more paper is recycled and post-consumer wood is reused.

Where sustainable forest management practices are not yet well entrenched, they must be developed. Equally importantly, adequate forest regeneration and restoration practices must be developed, adopted and monitored to ensure that the forest resource is available into the future.

Wood deficit can also be prevented to some extent by increasing the efficiency of wood use and multiplying the uses of wood across its lifetime, for example by promoting resource-efficient cascading use of wood (IINAS, EFI and JR, 2014) (see Box 24 above).

Higher costs of industrial wood energy compared to alternatives

A major barrier to harnessing the potential of modern wood energy is its relatively high cost compared with alternative sources of energy, given current market and policy conditions. At present, biomass electricity is not cost competitive with fossil fuel electricity or, in certain instances, with energy from other renewable sources such as solar and wind energy.

The International Renewable Energy Agency (IRENA, 2012) estimates that the levelized cost of biomass-fired electricity generation ranges from US$0.06 to US$0.29 per kilowatt-hour, primarily depending on the costs of capital and feedstocks.

Albani *et al*. (2014) found that even at a carbon price of US$22 per tonne CO_2, electricity from biomass was not competitive with electricity from coal in Europe, with the exception of electricity generated from co-firing. Policy interventions that directly encourage the use of wood energy (e.g. subsidies for biomass) or raise the price of competing energy sources with higher GHG emissions (e.g. a penalty on fossil fuels) may, however, help increase the competitiveness of wood in the energy market.

Environmental concerns and disagreements

The market for wood energy is hampered by differing opinions on its sustainability, as discussed above in the section on the potential of using wood energy for mitigation. The treatment of biomass as carbon neutral by the EU's Emissions Trading System (EU ETS) has drawn considerable criticism within the EU and elsewhere. Biomass cultivation, harvest and transport undeniably involve anthropogenic GHG emissions which must also be taken into consideration.

The manner in which forest resources are managed for energy production has implications for carbon footprint, land use, ecosystems, soil and water. The prospect of an increased scale of woody biomass production raises questions of land availability and productivity in the short and long term, environmental and ecological sustainability, social and economic feasibility and ancillary effects. The management of forests for bioenergy could have a negative impact on forest biodiversity and a range of forest ecosystem services (e.g. through habitat fragmentation and loss of microhabitats when trees are felled and bunched). However, short-rotation forestry on former marginal or bare land may lead to the improvement of biodiversity status and an increase in the value of ecosystem services (Nijnik *et al*., 2014).

In recent years, concerns have arisen about the carbon footprint of wood pellets and the sustainability of their production in light of their large-scale use for heat and power generation in industrialized countries, cross-continental trade and long-distance transportation. It is important to consider the sustainability of the supply chain as a whole – including the fossil fuels used in extracting and transporting woody biomass – and to encourage those biomass energy systems with a small footprint.

Leakage-related issues

In the context of wood energy, leakage refers to any change in GHG emissions outside the activity of energy production (and its GHG accounting according UNFCCC and IPCC guidelines) that can be attributed to the energy production activities. An example might be emissions from crops, livestock or forests owing to a change in land use.

Existing policies and programmes incentivizing the use of renewable energy, including woody biomass, typically have limited scope, and disparities across time and space can lead to indirect consequences that could be considered leakage. If the scope of assessment under the policy or programme were global, there would be no leakage, because all emissions would be inherently captured within the scope of the assessment. As Plantinga and Richards (2008) and others have argued, the development of all-encompassing national forest inventories represents perhaps the single best strategy for reducing the potential for leakage across different segments of the forest and agricultural sectors, especially for non-Annex I countries under UNFCCC, where rapid industrialization and agricultural, economic and population growth create significant land-use pressures.

Market issues

Market-related bottlenecks include the following.

- ***Competitiveness.*** Taxation, incentives and subsidies intended to favour wood over other more energy-intensive materials can lead to imbalances in competitiveness among the stakeholders involved. There is therefore a need to analyse competitiveness carefully, taking into account consumer preferences, industry traditions and material functionality (Gustavsson *et al.*, 2006).
- ***Market failures and externalities.*** Market failures and externalities mean that where private forest practice is pursued, unpriced benefits will tend to be undersupplied, and unpriced disbenefits will arise at levels above the social optimum. Monetary valuation may not be necessary or feasible for estimating all the positive and negative externalities of woody biomass production. The local social, economic and biophysical contexts should be well understood, and the non-market goods and services need to be effectively factored into decision-making through creative and effective policy design.
- ***Lack of established value chains for wood energy.*** The value chains of common feedstocks (e.g. wood pellets and wood chips) are not well established, and feedstock contracts are made on a bilateral basis. Lack of a biomass market prevents price transparency and liquidity for buyers and sellers (Albani *et al.*, 2014).
- ***Market bias against small-diameter trees.*** Becker *et al.* (2009) noted that in the United States of America, biomass for energy production (small-diameter wood and harvest residues) has too low a value to cover the cost of its removal from the forest. Extracting this material together with higher-value sawlogs is necessary to offset the cost of biomass removal and subsequent utilization.

EMBRACING OPPORTUNITIES

Enhancing mitigation potential

The contribution of wood energy to mitigation could be enhanced through a variety of measures, including the following:

- expanding sustainable woodlot plantations (such as short-rotation plantations specifically for woodfuel production, or replacement plantations) to pursue carbon neutrality in current woodfuel systems;
- evolving efficient and effective uses of wood residues (e.g. logging residues, tree-prunings, wood bark, sawdust, woodchips, black liquor from papermaking mills) as fuel;
- improving the transformation and conversion efficiency of woodfuel to marketable energy products (e.g. charcoal and wood pellets);
- reducing fossil fuel consumption in woodfuel production, transportation, processing and handling;

- improving the combustion and heating efficiency of end-use devices and/or facilities (e.g. developing efficient and clean cookstoves to reduce emissions and black carbon particles) and simplifying the operations of bioenergy facilities;
- enhancing cascading wood use in which fuel is the end stage.

Reducing technical barriers and the cost of technology

With policy support and more investment in research and development, it may be possible to overcome technical barriers to make bioenergy more efficient and cost competitive. The use of existing coal power plants may provide a capital-efficient transition to renewable energy, since they can be used for co-firing without retrofitting or modified for conversion to dedicated biomass power plants (Albani *et al*., 2014).

Pretreatment is a means of commoditizing biomass and enhancing its marketability. By assisting in biomass storage, delivery and use, improved biomass treatment technologies such as pyrolysis, torrefaction and pelletization could help to make the supply chain more efficient. Long-term purchase contracts with biomass suppliers could then minimize biomass supply risk and encourage investment in bioenergy.

Policy measures to encourage wood use for energy

The energy consumed in extracting wood for energy is far less than the energy contained in the wood (Handler *et al*., 2014). However, wood for energy competes with other wood and energy markets. Hence, for wood energy to thrive, subsidies or financial assistance may be required. Although such interventions are unsustainable from an economic standpoint, accounting for the environmental benefits can help make wood energy more cost effective (McKenney *et al.,* 2014).

A number of policies are already in place to encourage the use of biomass for energy production, including carbon taxes, cap-and-trade approaches, low carbon fuel standards, renewable energy targets and renewable portfolio standards. Further expansion of these incentives and more comprehensive GHG mitigation policy could accelerate the adoption of wood energy. Wood energy is more attractive in Europe than in many other regions, partly because of higher energy prices but also because of policy drivers in the European Union, including the Renewable Energy Directive and Fuel Quality Directive. EU Directive 2015/1513 (relating to the quality of petrol and diesel fuels) calls upon EU Member States to promote advanced biofuels with a view to reaching a significantly higher level of consumption by 2020.

Taxes, subsidies, carbon pricing and other incentives. Many governments around the globe have begun to institute policies imposing a penalty for fossil fuel emissions (e.g. a tax) or a subsidy for sustainable biomass use. In much of Europe, for example, biomass is favoured by a tax on fossil fuel emissions. In the United States of America there is no direct penalty for fossil fuel use nor any national-level climate policy providing incentives for GHG mitigation; however, many states have implemented tax credits, grants, loan guarantees and other price incentives to favour investment in specific renewable sources (Aguilar *et al*., 2012).

Incentives such as production tax credits and investment tax credits can go a long way towards overcoming market barriers for investment. Incentives for the use of waste and residues (e.g. wood dust and forest residues, mainly slash) promote bioenergy from sustainable sources. The Government of the United Kingdom provides double credits for biofuels from waste under the Renewable Transport Fuel Obligation. EU Directive 2015/1513 states that to ensure the long-term competitiveness of bio-based industrial sectors, enhanced incentives should be set in such a way as to give preference to the use of biomass feedstocks that do not have a high economic value for uses other than biofuel production.

Policies that put a price on carbon, such as carbon taxes and cap-and-trade programmes, also encourage investments in research and development for emerging bioenergy technologies.

Renewable energy targets and standards. Policies that set targets for renewable energy in general and bioenergy in particular provide some degree of market certainty for bioenergy. Mandatory targets for renewable energy are a major reason for the worldwide growth in bioenergy witnessed in recent years. For example, the EU's Renewable Energy Directive requires that 20 percent of overall energy use come from renewable energy including biomass. The United Kingdom's Renewables Obligation places an obligation on licensed electricity suppliers to source an increasing proportion of electricity from renewable sources. The United Kingdom has also set a target to achieve 15 percent of its energy consumption from renewable sources by 2020 under its 2009 Renewable Energy Directive.

Similarly, in the United States of America, many states have implemented renewable electricity standards, also known as renewable portfolio standards, whereby a certain rising percentage of electrical power production must be generated by renewables, to which biomass and wood energy can contribute; the optimal generation mix is determined by the market. To help reach these renewable energy goals, preliminary planning has been carried out for the creation of a large number of 50 MW biomass power stations, particularly in southern states where wood is plentiful. However, with the recent advent of hydraulic fracturing ("fracking") and a drop in market prices for natural gas, which has substantially lower carbon emissions per unit of energy than petroleum and coal, large investments in wood power plants have not yet been forthcoming.

The national-level Renewable Fuel Standard in the United States of America requires the annual consumption of 36 billion gallons (136 billion litres) of renewable fuels within the transportation sector by 2022. Many countries in Africa, Asia and South America have volumetric mandates for biofuels. Although most biofuel requirements are currently met by crop-based biofuels, with technological progress and cost reductions it is expected that biofuels from sustainably sourced wood biomass will play a larger part in meeting volumetric targets in the future.

Resource sustainability standards. The many existing voluntary sustainability standards and forest certification and verification schemes (e.g. Forest Stewardship Council [FSC], Programme for the Endorsement of Forest Certification [PEFC]) can be used as benchmarks to ensure that wood used for bioenergy is produced and harvested in a sustainable way.

Key messages: wood energy

- An estimated 1.86 billion cubic metres of wood, over half of all wood produced in the world, is used for energy each year. Most of it (1.55 billion cubic metres) is in the form of fuelwood.
- Wood energy accounts for 7 percent of total global carbon emissions. However, its share in total emissions varies significantly among regions, with the highest share in Africa.
- The use of renewable wood resources for energy presents a mitigation opportunity, as they can replace the use of fossil fuels and potentially reduce net GHG emissions. Significant mitigation can also be achieved through increased efficiency in the production and use of woodfuel.
- The mitigation contribution of using wood for energy can only be assessed by considering the GHG emissions along the whole value chain. Whether energy use contributes to net reduction of carbon emissions depends not only on sustainable wood sourcing, but also on energy consumption during production, transportation, processing, storage and handling; the combustion efficiency of woodfuel; the type of displaced fossil fuel; and the wood energy utilization facility.
- About three-quarters of the 2.4 billion tonnes of annual global CO_2 emissions from woodfuel come from the use of woodfuel for cooking. More efficient and affordable cookstoves can have an important mitigation effect, but their economic feasibility might depend on incentives, including from carbon markets.
- A key to determining the carbon neutrality of wood energy is carbon recapturing by subsequent plantations. Wood energy should be closest to carbon neutral if the wood is drawn from a sustainably managed forest or system of growing forests, which would sequester an amount of CO_2 close to or equivalent to the amount emitted in producing wood energy.
- The costs of modern wood energy are at present generally higher than those of traditional fossil fuels, with hauling costs a large influence. The proximity of forest biomass resources to generation facilities is thus an important consideration.
- Wood energy is more attractive in Europe than in many other regions, partly because of higher energy prices but also because of policy drivers in the European Union, including the Renewable Energy Directive and Fuel Quality Directive. Other countries, mainly developed, have also set up renewable energy goals and incentives, increasing the competitiveness of wood energy.

7. Promoting the use of wood for greener building and furnishing

Increasing the use of wood or wood-based materials in construction and in products such as furniture, cabinets, flooring, doors and window frames could present a significant opportunity for emission reductions, particularly when wood is used to substitute non-renewable materials such as concrete, metal, bricks and plastic.

Wood has been an important construction material since humans began building shelters, buildings and boats (see photos). Although it has been displaced by other materials in many parts of the world, today wood is receiving renewed and increased attention as a construction material, in part because of the carbon benefits of harvested wood products.

The global construction sector is projected to see 4 to 6 percent annual growth over the next decade (Garcia, 2011). In 2010, the building sector accounted for approximately 117 EJ or 32 percent of global energy consumption, 19 percent of energy-related CO_2 emissions and 51 percent of global electricity consumption (Lucon *et al*., 2014). Green or resource-efficient wood-based buildings with low life-cycle environmental impacts, developed with sustainably produced renewable resources to the extent possible,

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Hōryū-ji in Ikaruga, Japan, completed around the year 700, is one of the world's oldest remaining wooden buildings will play an important role in the transition to a sustainable built environment, while also providing economic benefits (Lucon *et al.*, 2014; Leskovar and Premrov, 2013; Lippke *et al.*, 2011; Ritter, Skog and Bergman, 2011).

Wood substitution – i.e. the use of wood to replace other inputs of production, providing equivalent service or function – affects energy and GHG balances in the following ways.

- ***Carbon storage.*** Wood materials physically store carbon, extending the duration of carbon storage outside the forest.
- ***Relatively low carbon emissions.*** Emissions in the industrial processing of wood are lower than emissions from manufacturing other materials such as cement and steel. For example, the carbon balance of a timber-frame building was estimated to be 114 to 151 kg CO_2 per square metre while that of a concrete-frame reference was 292 kg CO_2 per square metre (Dodoo, Gustavsson and Sathre, 2009).
- ***Increased availability of biofuels and other products from wood residues.*** Only about 20 to 25 percent of harvested biomass is actually built into construction, and in developing countries as little as 10 to 15 percent (Julin *et al.*, 2010). Residues from harvest, wood processing and building construction are often used for other purposes such as wood-based paper and paperboard, composite panels, energy, fuel and other bioproducts – thus maximizing the use of and value from woody fibre throughout the supply chain, providing economic and environmental synergies between sectors and alleviating disposal issues.

The 67 m high, nine-storey wooden pagoda of Yingxian County in Shanxi Province, China, completed in 1056, is one of the world's oldest standing multi-storey wooden structures

The capacity for mitigating climate change through increased wood use, particularly as a substitute for other materials, can only be realized with an adequate supply of sustainably sourced wood to meet increased demand. As increased wood production may be necessary, it is essential that it not be associated with land-use changes having negative environmental impacts.

TRENDS IN WOOD USE

Wood use in building construction

The current level of wood use in building construction, and the production of sustainably sourced wood to supply this use, varies significantly across regions and countries.

In tropical regions, hot, humid weather conditions present challenges to the use of wood building materials (Lauber, 2005). Special treatment of wood, insect-resistant species and appropriate building construction practices are necessary to protect wood-based construction materials from insect pests and fungal attacks and from degradation due to increased changes in temperature and moisture. Generally, wooden materials in tropical buildings are mostly used in short-span roofing systems and other non-structural building applications such as flooring and door and window components (Amoah and Dadzie, 2013).

In some tropical communities the use of wood in the structural framework of buildings is gradually increasing (Gaugris and van Rooyen, 2009), and the growing demand for affordable housing in developing countries might provide an opportunity to increase the use of wood in building construction. Wood also offers opportunities for emergency housing after natural disasters, and the seismic performance of wood frames makes such buildings advantageous in seismic zones.

In many countries with temperate and cold climates, wood is already widely used as a structural and architectural material in diverse applications (Table 8). In Japan, the Russian Federation and the Nordic countries, wood is commonly used as a structural material in detached houses but is used less frequently in multi-storey buildings. In Sweden and Finland, for example, over 90 percent of detached houses are built of wood, but probably less than 10 percent of multi-family buildings higher than two stories. In contrast, wood is commonly used for construction of both single-family and multi-family houses in Canada and the United States of America. Many European countries show signs of increased market penetration of wood.

A high proportion of wood harvested from rapidly growing plantations is juvenile wood, which may not provide solid wood stability. Recent technological advances have led to high-performance engineered wood products for structural use, including cross-laminated timber (CLT), glue-laminated timber (glulam), parallel-strand lumber (PSL), laminated-strand lumber (LSL), laminated-veneer lumber (LVL) and wood I-joists. Such composite products, also known as mass timber, make it possible to develop multipurpose buildings and to build far taller multi-storey wooden buildings than before (Lehmann, 2012; Holts and Warde, 2014). The higher load-bearing capacity of CLT, for example, makes it technically suitable and economically competitive for buildings up to eight to ten storeys tall (Miles, 2014; Ritter, Skog and Bergman, 2011) (see photos, following page). Future mass timber materials may entail lower risk as they become more resistant to fire and pests and less vulnerable to energy price fluctuation and carbon emission penalties (Green, 2012).

TABLE 8
Share of wood-based construction of one- and two-family houses in selected countries

Country/region	Share of wood construction *(%)*
United States of America	90–94
Canada	76–85
Nordic countries	80–85
Scotland	60
United Kingdom	20
Germany	14
Netherlands	6–7
France	4

Source: Based on data from Gustavsson *et al.*, 2006


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Eight-storey wood-frame low-energy apartment building constructed in 2009 using CLT structural system, Växjö, Sweden

Wood furniture production

Wooden furniture (solid wood and wood-based panel furniture) accounted for about 50 percent of total furniture production and almost 40 percent of international furniture trade in 2013 (which valued US$456 billion) (CSIL, 2014). Wood-based panels are a key input for furniture manufacturing. However, official global data on the volume of wooden furniture production are not collected.

The geography of furniture production in general has changed considerably since the turn of the millennium. In 2003, seven high-income industrialized countries – the United States of America, Germany, Italy, France, the United Kingdom, Japan and Canada – accounted for about 70 percent of the world's furniture production. A decade later, only about 40 percent of global production was in high-income countries, with the share of middle- and low-income countries having grown to 60 percent (CSIL, 2014) (Figure 29); China alone accounts for 40 percent of global production.


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The nine-storey Murray Grove Building, London, United Kingdom – the tallest timber residential building when it was completed in 2009 – will store 186 tonnes of carbon in its structure over its lifetime

The global furniture sector has recently experienced market openings and an increase in trade.

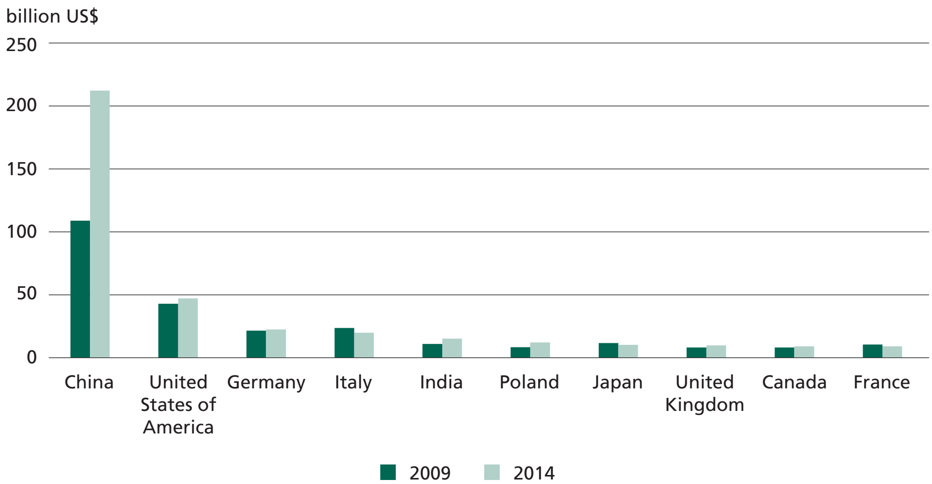
MITIGATION POTENTIAL OF WOOD USE IN BUILDING AND FURNISHING

Climate benefits of wood-based products can be demonstrated through life-cycle assessment (LCA), including carbon footprint analysis. Comprehensive LCA for wood-based systems is more complex than for many non-wood alternatives (Gustavsson and Sathre, 2011; Perez-Garcia *et al.*, 2005), in particular because of the following factors:

- the long time frame involved, which includes the time for forest growth and the life span of buildings;
- the range of useful by-products that are obtained at different points in time, including forest thinning products during forest growth, primary products and co-products at forest harvest, and combustible residues at the end of the building life span;
- the broad array of products that can be obtained from a tree (e.g. sawlogs, veneer logs and pulp logs) and a stand, as different species in a mixed forest stand have different uses;
- the complex relationship between forest management and environmental services, including carbon sequestration;
- the complexity of the life cycle, encompassing reuse and recycling;
- the lack of data on the lifetime of various wood products.

Few life-cycle studies provide comprehensive analysis of the implications of wood substitution systems. Analyses that consider only a part of the building life cycle and ignore material and energy flows in different economic sectors cannot establish the full climate implications of using wood products (Gustavsson and Sathre, 2011).

FIGURE 29
Top ten furniture producers, 2009 and 2014



Source: CSIL, 2015

An analysis of 21 studies on the displacement factors of wood product substitution (Gustavsson, Sathre and Dodoo, 2016) pointed out the following.

- Most studies show that wood products have lower GHG emissions than alternatives over the complete life cycle of the product (including use and disposal).
- The production stage of wood-based materials and products results in lower GHG emissions than the production stage of functionally comparable non-wood materials and products.
- Responsible management of end-of-life wood products, as well as of biomass residues generated along the wood-product value chain, is critical for high GHG displacement from wood products.
- The GHG impacts of the use phase of a building life cycle are generally greater than those of the construction and disposal phases, which suggests that minimizing the GHG impacts of products and buildings requires consideration of the entire life cycle, including production, use and disposal (see Box 26).
- Estimated GHG substitution impacts can depend on the baseline, methods and assumptions used to account for changes in the forest attributable to increased harvesting (Gustavsson and Sathre, 2006; Upton *et al*., 2008).

BOX 26

GHG impacts of timber-maximized residential construction in Sydney, Australia

The average use of wood products per unit of floor area in Australia has decreased significantly over time (Ximenes, Kapambwe and Keenan, 2008). Potential therefore exists for increased mitigation benefits through increased use of wood products in buildings.

After the manufacturing sector, the residential sector is the second largest contributor to GHG emissions in the state of New South Wales; residential emissions in 2009–2010 were 34 Mt CO_2e (20 Mt from electricity use, 12 Mt from private transport and 2 Mt of other emissions, primarily from the use of gas for cooking and heating) (NSW EPA, 2012). Increased wood use could offset some of these emissions.

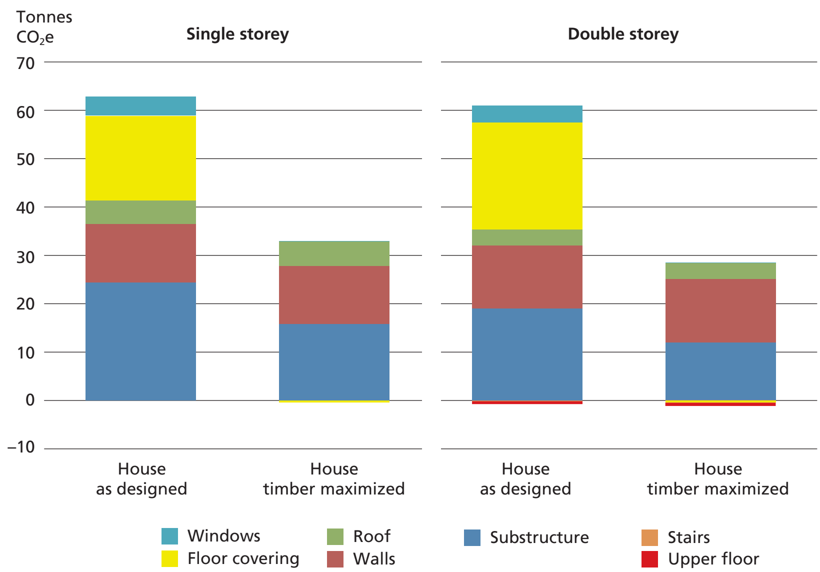
Ximenes and Grant (2013) quantified the GHG impacts of substituting current typical materials used for residential house construction with wood products in Sydney, Australia. They determined the GHG outcomes of the extraction, manufacture, transport, use in construction, maintenance and use over 50 years, and disposal of wood products and other building materials for two popular house designs in Sydney (single and double storey). Two construction variations were assessed: the original intended construction and a "timber-maximized" alternative.

Wood substitution in the substructure of the building would have the largest GHG impact because of the original design's concrete components, followed by the walls because of the substitution of bricks (Figure 30). The timber-maximized design would result in approximately half the GHG emissions associated with the base designs. These savings could offset between 23 and 25 percent of the total operational energy of the houses.

Box 26, continued

The most beneficial options for disposal from a GHG perspective were incineration with energy recovery (substituting for electricity generated from black coal) and landfill. Carbon storage in landfill made a highly significant difference to GHG outcomes, equivalent to 40 to 60 percent of total house GHG emissions.

FIGURE 30
Impact of maximized timber use on greenhouse gas emissions for two house designs in Sydney, Australia



Source: Ximenes and Grant, 2013

- Many carbon footprint studies involve, or assume, the use of wood from sustainably managed forests where harvesting and regrowth are in balance and the net flow of carbon from the forest is zero (an approach used in several widely accepted standards [Greenhouse Gas Protocol, 2011; ISO, 2013]).
- Much recent interest has focused on wood use in high-rise buildings. However, mid-rise buildings (four to ten storeys) may have greater mitigation potential overall because they are more prevalent and thus represent a larger material volume.

Further research on how to maximize the overall climate benefits from forest systems could involve the comparison of various wood building methods, such as light frame construction and massive frames using CLT. While mass timber construction can provide energy performance benefits in the use phase, it uses a significantly greater quantity of materials in construction than light framing systems.

Mitigation potential of lower energy use by green buildings

End-use energy for space heating, space cooling, ventilation and lighting can be reduced considerably when state-of-the-art green building designs and technologies are implemented in moderate and cold climates (Harvey, 2013). For example, Dodoo and Gustavsson (2013) showed that a wood-frame residential building built to "passive house" standards (rigorous voluntary standards for ultra-low-energy buildings) could use 22 percent less final energy for space heating and ventilation than a wooden house built to Sweden's 2012 building code. The wood-frame passive house, in tandem with biomass-based co-generated heat, would reduce primary energy use and the climate impact of the built environment.

To achieve greater overall benefit, the low operational energy use of buildings must be optimized within a complete life cycle perspective, including production, operation and end-of-life stages. While low-energy buildings using other materials may achieve performance levels similar to those with wood, wood buildings have lower embodied energy (the energy used to produce the material or product, taking into account the energy used at the manufacturing facility, the energy used in producing the materials used in the manufacturing facility, and so on).

Mitigation potential of wood-based furnishings and wood furniture

In non-construction applications such as furniture, doors, window frames, cabinets and packaging, materials for which wood and wood products might be substituted often include steel, plastics and aluminum, which entail relatively high GHG emissions compared to wood products on an equivalent-weight basis. Given that the amount of material substituted by wood products varies with the application, it is difficult to generalize the potential substitution benefits of wood-based materials in non-construction applications, and they vary among countries and regions.

Furthermore, estimating the quantity of wood and wood-based products consumed by the sector is problematic, mainly for the following reasons.

- The furniture industry is basically an assembling industry, employing a mixture of raw materials, including wood, metals, plastics, textiles, leather, glass and many others (González-García *et al.,* 2011). Furniture pieces are generally classified according to their most prominent material component. A table classified as wooden furniture may have a wooden top but legs and other less prominent furniture parts made of metal.
- Reporting methods are not harmonized. Current statistical databases report trade statistics (import and export) in terms of value and quantities (kilograms or pieces), while production statistics are generally in terms of value. Production volume, if available, can be reported in tonnes, kilograms, cubic metres or number of units/pieces.

BOTTLENECKS IN HARNESSING POTENTIALS

Efforts to increase the use of wood for mitigation are hampered by issues related to carbon estimation and accounting, building codes and perceptual and knowledge gaps that need to be bridged for full incorporation of wood as a structural material in large commercial structures. Concerns related to the sustainability of wood production and possible negative environmental impacts perhaps influence the buy-in for these products.

Low acceptance of wood as a building material

Generally, acceptance of wood as a green building material has been low despite growing documentation regarding the benefits and competitiveness of wood-based products and buildings compared with alternative building systems. The building construction industry is known for a tendency to be risk averse. In some countries, consumers and construction professionals perceive wood as being of poorer quality and durability than more established construction materials and may associate wood with lower market value and social housing. Construction firms are frequently satisfied to meet only the minimum requirements of environmental legislation and building codes, and few consumers pay attention to the building's structural frame or environmental impacts when they make housing decisions.

As professions, neither architecture nor engineering has clear requirements for a comprehensive study of all structural materials; university-level educational curricula in these fields frequently give little or no attention to modern wood construction techniques and systems and, in particular, to the use of wood in large construction projects.

In several European countries, the growth of wood-based multi-storey construction has been affected by safety concerns. For example, in response to large city fires during the late nineteenth century, several European countries introduced regulations prohibiting the use of wood frames in multi-storey buildings. These regulations were reversed at the EU level in 1989, but by then other construction materials such as brick and concrete had become well established; systems, standards and routines for their use had had time to develop and had become cost efficient. More than two decades after the change in policy, the use of wood frames in multi-storey construction in Europe is still relatively low.

Use of wood in multi-storey buildings, in particular, is perceived as a new phenomenon associated with many risks and uncertainties involving costs, stability, durability, fire safety, moisture and mould, sound insulation and acoustics (Hemström, 2015). Similar perceptions among insurance companies result in relatively high insurance premiums for wood buildings, raising the costs of wood construction relative to concrete and steel construction.

Disincentives

Most national building codes and standards intended to stimulate resource-efficient and low-carbon buildings do not address the climate and environmental benefits of wood-based materials; they generally focus on the operational phase of buildings, ignoring the full life cycle, including the implications of material choice. Despite improvements in their performance requirements, building codes and industry standards around the world still commonly include regulations that suppress innovative use of wood as structural material in multi-storey buildings. In Europe, fire and acoustic requirements are the main regulatory limitations to wood multi-storey buildings (Östman and

Källsner, 2011). Several European countries also have specific requirements regarding the origins and production of wood, but not other construction materials.

EMBRACING OPPORTUNITIES

Improving knowledge and awareness to drive increased use of wood for greener buildings

Governments, corporations, organizations and trade associations are beginning to recognize the environmental as well as the economic value of using wood in construction (Bumgardner *et al*., 2014). However, effective strategies are crucial to overcome bias against wood among construction industry professionals and the general public and to reverse persisting misconceptions concerning fire safety, structural stability and vulnerability to pests – challenges that have now been largely overcome through new technologies. Awareness and capacity-building programmes need to target specific groups, including architects, engineers, code officials, regulators, building inspectors, contractors/builders and educators, as well as forest product representatives and researchers (UNECE and FAO, 2012). To grow its market share and contribute to the diffusion of wood-based buildings, the wood sector will need to engage with government and relevant actors involved in all aspects of construction –

BOX 27

Wood *WORKS!*

The Canadian Wood Council created the Wood *WORKS!* project in 1998 to create a design culture that recognizes the performance capabilities of wood products, particularly in non-residential construction. The first efforts were to create awareness of wood in exceptional design (inspiration), but the programme quickly moved to providing greater technical support for design teams considering wood. Eventually, the council developed a North America Wood Awards programme for each region that implemented the programme.

Since the inception of the technical support programme, wood use has grown significantly. The programme has:

- initiated research followed by technical support and advocacy in supporting the code change allowing the use of wood in mid-rise construction;
- played a key role in advancing wood use in tall buildings;
- been instrumental in the establishment and growth of wood design curricula in post-secondary engineering and architecture programmes;
- provided technical workshops to design professionals and building and fire code officials;
- established strong relationships with various levels of government to ensure that wood is fairly recognized as a building material in the regulatory environment.

More information is available at http://wood-works.ca those who design, specify, order, regulate, build and use wood products (see example in Box 27). Growing awareness among architects and developers of the potential contribution of the construction sector to mitigation could be a driving force behind an eventual shift towards wood use.

Research and development (R&D) on large-scale wood-based and green building systems should be enhanced, as R&D for wood generally lags behind that for other major building materials (Ritter, Skog and Bergman, 2011). There is also a need to disseminate new advances, such as the technology permitting construction of tall buildings with wood (e.g. CLT panels), and to publicize successful existing wood-based buildings. Their performance should be monitored to reduce uncertainties and perceived risks.

Improvement of training curricula for engineers and architects on the design and construction of modern green buildings might facilitate increased use of wood for construction. Universities with design programmes (architecture and structural engineering) will play a role in ensuring that future design professionals receive comprehensive instruction in the potential and appropriate use of wood products. Further training for practising professionals is equally important.

The public's ability to embrace an increase in wood construction also depends on an understanding of its impact on the world's forests. Public campaigns to disseminate the GHG benefits of the use of sustainably harvested wood products can help address the concerns that may still be prevalent in some sections of society. Different traditions, regulations and characteristics of the construction and housing sectors in different countries may call for different strategies adapted to local conditions.

Policy and regulatory mechanisms

Especially where other construction materials such as brick and concrete are deeply entrenched, strong policy instruments may be needed for greater diffusion of wood buildings. Some governments, mainly in developed countries (e.g. Canada, France, Japan, New Zealand, Sweden, the United Kingdom), have begun to endorse the use of wood in buildings and to implement green building policies at different levels (Julin *et al.*, 2010). The Japanese government, for example, implemented the Law Concerning Promotion of Use of Wood Materials for Public Buildings in 2010 (Umeda, 2010). This law requires that national and local governments use wood materials for public buildings that have three storeys or fewer. In Australia, one of the early wood encouragement policies was established by the Latrobe City Council in Victoria, which held many industry workshops. In Sweden, a number of local governments engaged in wood-promotion initiatives have developed strategies to introduce the use of wood in large constructions, although their effectiveness has not yet been fully evaluated.

Policies that support the use of wood instead of more energy-intensive alternatives are likely to be aligned with green building rating schemes (see below) and with renewable energy policies (e.g. promoting the use of wood residues from forest harvest and wood-processing facilities and end-of-life wood for bioenergy generation).

Existing energy regulations may be improved to take into account the full life-cycle implications of buildings, as well as the impacts of building material production.

In Sweden, for example, following a report on the CO_2 emissions of building construction (IVA, 2014), a government enquiry has been commissioned to review whether building regulations need to incorporate requirements for the sustainable use of natural resources.

Implementing carbon taxes that consider the real impacts of materials could drive the market for the best substitute, i.e. wood.

Better estimation of the mitigation potential of increased wood use in buildings

Comprehensive and inclusive cost-benefit analyses of green buildings are scarce in the literature, and case studies are often location specific, making it difficult to draw general conclusions. More comprehensive system analyses, integrating the links among building construction, forest management, energy systems and waste management, are needed to establish the overall environmental implications of wood use in green buildings. Research leading to a greater understanding of the life-cycle implications of buildings may help optimize natural resource use in wood buildings.

LCA can thus be a starting point for promoting the use of less energy-intensive materials. A comprehensive accounting of relevant GHG flows is needed to establish the climate benefits of wood use and to account for marginal changes in analysing wood substitution systems. The analysis should include biogenic carbon flows and fossil fuel emissions from forest establishment and management; flows related to production, use and post-use management of wood-based products and buildings; and the use of associated residues for other purposes. System boundaries of LCA and carbon footprint analysis must be broad enough to include all significant climatic impacts to provide robust output for making informed decisions. Such analyses will necessarily involve interdisciplinary collaboration among the fields of forestry, construction, energy, manufacturing and waste management.

Certification and rating schemes

Green building rating or certification schemes have begun to gain more credibility as consumer preferences change to reflect environment-friendly attitudes. Schemes such as the Building Research Establishment Environmental Assessment Method (BREEAM) and the Leadership in Energy and Environmental Design (LEED) rating system developed by the United States Green Building Council (USGBC) emphasize the use of materials with low climate impact (Vierra, 2014). They may encourage designers to gravitate towards the use of wood to achieve greater levels of environmental performance.

A USGBC study found that in addition to reducing energy, carbon, water use and waste by 30 to 97 percent, LEED-certified green buildings can reduce operating costs by 8 to 9 percent while increasing their market value by up to 7.5 percent (Vierra, 2014). Many of these buildings have seen increases of up to 6.6 percent in returns on investment, 3.5 percent in occupancy and 3 percent in rent.

In assessing the GHG implications of buildings, rating schemes typically focus mainly on the operational energy requirements of the buildings; consideration of the

GHG implications of extraction, transport, manufacture and disposal of different products is limited. It would therefore be important to incorporate fuller knowledge of the environmental impacts of wood, as well as alternative building materials, in green building rating schemes.

At a product level, the recently developed global Environmental Product Declaration (EPD) system – created in accordance with the International Organization for Standardization (ISO) standard ISO 14025 (Environmental labels and declarations) and the European engineering standard EN 15804 (Sustainability of construction works) – provides independently verified and registered documentation about the life-cycle environmental impact of products. EPD has the potential to simplify LCA, allowing more companies to quantify the impact of their products. EPD could be a major driver for wider implementation of life-cycle data in existing green building rating schemes. However, further awareness of the utility of EPDs is required to realize this potential. Some green building standards, including the LEED standard, only provide credit for using products that have lower impact indicators than the industry average.

In addition to certification and rating schemes for green buildings, wider certification of sustainable forest management practices may also be necessary to the increased use of wood in construction. Moreover, efforts to increase awareness of the life-cycle environmental impacts of producing alternative materials may be needed. It may be worthwhile to advocate for transparent certification of all building materials, and not simply those derived from wood.

Pilot wood construction projects

Pilot projects involving wood construction will give businesses confidence to capitalize on its potential benefits. In Canada and the United States of America, projects in tall wood design have been supported through the collaboration of government and industry (Bowyer *et al.*, 2016). While demonstration or pilot programmes or projects may vary in the funding formula, they provide the proponent with some funds to offset, in whole or in part, the incremental difference between conventional construction and wood design, including costs for additional engineering or design, product testing or regulatory requirements. The knowledge resulting from these collaborative efforts is made available to the design community at large and helps build confidence and expertise in finding solutions that incorporate wood into real-world projects.

Innovations in wood-based furnishings and wood furniture

Conventional furniture production, whether by craft-based firms or large-volume producers, is a labour-intensive industry. However, with innovations such as flat-pack or ready-to-assemble and do-it-yourself designed furniture, mass production has become a viable market strategy. With such innovations, furniture companies, including those using wood, are able to design, manufacture and deliver products in large quantities for low- to medium-price markets, both local and international. At the same time, the more traditional solid wood furniture manufacturers are targeting market niches such as the market for high-end, expensive and design-led products (Kaplinsky *et al.*, 2003). New innovations and product designs could also help motivate increased adoption of wood furnishings (Box 28).

BOX 28

Walking the talk: innovative use of wood and bamboo in FAO conference rooms

The use of wood and bamboo in recently renovated meeting rooms at FAO headquarters demonstrates innovative solutions for addressing sustainability considerations and carbon impacts.

Red-hearted beech for flooring, wall panelling and furniture in the German Room. Red-hearted beech is usually discarded by the furniture industry, as the colour variation is considered a characteristic of inferior quality. However, in the German Room, this characteristic is used as a design feature. Using all tree parts and maximizing the wood used from each tree reduces waste in the production process and thus boosts carbon storage.

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German Room

Certified natural curved-length boards for wall panelling and furniture in the Ethiopia Room. Following the tree's natural curves in the cutting of boards saves natural resources and reduces waste in production. This process provides up to 20 percent more material for each sawed plank than is obtained in traditional milling processes, and optimizes the number of boards that can be produced from one tree. The price is not considerably higher than for traditionally milled boards.

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Ethiopia Room

CO_2 neutral bamboo for flooring and furniture in the Philippines Room. To reduce the environmental impact of the Philippines Room, bamboo planks from sustainably managed forests in China were chosen for the furniture and part of the flooring. An extremely rapidly renewable temperate species of giant bamboo was used, which has the characteristics of hardwood but has a lower cost and a

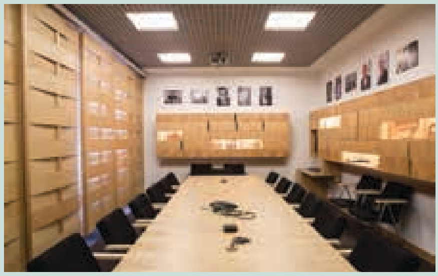
© FAO/GIUSEPPE CAROTENUTO

Philippines Room

Box 28, continued

lower carbon footprint over its life cost and a lower carbon footprint over its life cycle than many other materials (–613 kg CO_2e per cubic metre) (Vogtländer, 2014). The calculation includes the environmental cost of eventual plantation, extraction/ collection of material, processing and shipment.

Innovative wood craftsmanship in the Finnish Forestry Room. The room is entirely furnished with northern birch in different forms: sliced, turned, veneer and curly, combining traditional materials with high technology. The extra-large table is made of aircraft plywood. Window treatments made of plywood strips less than 1 mm thick form an additional wall, providing an acoustic surface.



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Finnish Forestry Room

Key messages: wood in green building and furnishing

- Climate benefits of wood-based products can be demonstrated through life-cycle assessment, including carbon footprint analysis. However, comprehensive LCA for wood-based systems is more complex than for many non-wood alternatives.
- Wood and wood products used in construction and in applications such as furniture, doors, window frames and cabinets might substitute for relatively high-emission, non-renewable materials such as concrete, metal, bricks and plastic.
- For full incorporation of wood as a structural material in large commercial structures, it is necessary to address issues related to carbon estimation and accounting, building codes and perceptual and knowledge gaps. Concerns related to the sustainability of wood production and possible negative environmental impacts may influence buy-in for these products.mitigation in this sector.
- A lack of harmonized reporting, especially on production and trade, presents challenges for accounting the carbon storage and carbon footprint of wood products used in the construction sector.

continues

- In assessing the GHG implications of buildings, rating schemes typically focus mainly on the buildings' operational energy requirements, with limited consideration of the GHG implications of extraction, transport, manufacture and disposal of different products. Environmental impacts of wood and alternative building materials should be included in green building rating schemes for more accurate estimation of emission impact.

- Technology lock-in might prevent wider use of wood and wood-based products in construction. Policies, incentives and revision of architecture and engineering curricula are needed to enhance benefits from forest-based mitigation in this sector.

8. How to make it happen

Climate change mitigation strategies have complex implications, so deciding when and how to adopt which mitigation actions is a long and complex process. Climate change decisions need to take into consideration economic and social costs and benefits, and appropriate discount rates must be applied for the most cost- and time-effective options. Ideally, climate change strategies will be supported by models that reveal the trade-offs and impacts of different options.

DECIDING AMONG MITIGATION OPTIONS

The potential of different mitigation options varies considerably among countries and regions, and their prioritization depends on local considerations. In general, preventing forest loss seems to be a quick and cost-effective choice in those areas with significant rates of deforestation, provided it does not merely shift deforestation to other areas. The success of this approach could be determined by the strategies used to address opportunity costs and other socio-political and economic issues. Options pertaining to the post-harvest use of wood seem promising in countries where an appropriate processing sector is present, industrial forestry operates under sustainability guidelines (e.g. sustainable forest management practices) and chain-of-custody is certified. However, when wood products are considered, assessment of the net emission results is more complex. No single strategy will be suitable overall, even within one country.

Decisions on whether to leave trees standing or to harvest their biomass depend on social objectives and the forest cycle. For example, the rotation period that maximizes biomass production or economic benefits, including carbon benefits, may be longer or shorter than the traditional rotation (see Chapter 5). In calculating net present value, an issue to consider is whether the rotation period is optimized for total biomass growth or stem volume growth (see van Kooten, 2015). The optimal rotation period for maximizing biomass growth for mitigation is generally shorter than that for maximizing stem volume growth for timber production because the biomass growth will culminate earlier than stem volume growth. On the other hand, optimization for mitigation also requires consideration of emissions from dead organic matter and soil, which are connected to any harvest activity and which prolong the optimal rotation period for mitigation. Measurement of the impacts of changing climatic factors on forest production and productivity is also required for decision-making (Jafari and Khorankeh, 2013).

When a forest reaches maturity, the public or private landowner must decide what to do with the trees. In some cases, it may be better not to harvest a mature forest site because harvesting may release more CO_2 than is desirable, with subsequent regeneration unable, in the short to medium term, to sequester the CO_2 released. It may be beneficial to harvest trees rather than preserve the forest if carbon can subsequently be stored in products that substitute for other products that are more emission intensive on a life-cycle basis, or if wood biomass can substitute for the burning of fossil fuels, thereby reducing the overall release of CO_2 (Box 29).

A focus on trade-offs between mitigation options can divert attention away from the potential of using a range of options. Forest and wood-based mitigation options need not be mutually exclusive – it need not be necessary to choose among options that preserve and enhance forest carbon stocks in all carbon pools and those that prolong the life of carbon stocks post-harvest through the use of HWPs. Indeed, in mitigation portfolios at different levels (landscape, regional, national) it is often preferable to integrate these options.

All the forest mitigation interventions addressed in this book have boundaries of feasibility which will be determined by factors such as economic viability, ecological resilience and social responsibility. For example, the feasibility of improving forest management through control of natural disturbances (e.g. fire) may depend on the extent to which large-scale disturbances can be managed in the long run, and the feasibility of using wood for energy may be limited by the extent to which transporting wood for energy production may result in higher carbon emissions and thus reduce the economic viability of this option. Similarly, the feasibility of increasing forest area may be limited by alternate

BOX 29

Forest management and harvested wood products in France: mitigation potential in the continuum

In France, different wood products are poduced via different types of forest management. Even-aged or uneven-aged high forests (a type of forest originating from seed or planted seedlings) provide most of the construction wood, while short- or very-short-rotation coppices provide fuelwood and part of the industrial wood. Since the different products have different lifetimes (Table 9), high forests indirectly lead to longer-term carbon storage than coppices. A switch in the type of management can thus affect the length of carbon storage in the sector. For instance, Martel (2010) showed that by extending a Douglas fir (coniferous) high forest rotation by ten years (and therefore increasing the ratio of construction wood to industrial wood, i.e. wood used to make pulp and panels), the average carbon sequestered *in situ* would be increased by 24.7 tonnes per hectare (calculated as the total carbon accumulated at the end of the rotation period).

TABLE 9

Apparent lifetime[a] for wood products in the French forest sector

Product	Lifetime *(years)*
Fuelwood	1.7
Paper/cardboard	2.2
Wood packaging	3.9
Furniture	8.5
Construction wood[b]	9.1

[a] The apparent lifetime is the expected lifetime of a product taking into account all harvesting, processing and recycling residues' lifetimes. For instance, to make a beam that has an expected lifetime of 15 years, 60 percent of the raw timber is lost in the sawmill. These sawmill residues are used as woodfuel, which has an expected lifetime of 2 years. The apparent lifetime of the beam is thus 40% of 15 + 60% of 2 = 7.2 years.

[b] Includes all wood used in construction (structure, wooden framework), as France has very few wooden houses.

Source: Vallet, 2005

land uses and the needs and value systems of local people. Thus, in the selection of effective and efficient mitigation options, it is important for forest managers and policymakers to identify and integrate optimal bundles of mitigation options for different geographical regions and different time periods, and to identify the boundaries of feasibility and their spatial and temporal variations for each option.

Forestry practices that maintain optimal carbon stocks in forests could maximize CO_2 removal and avoided CO_2 emissions. The stock of HWPs in households could increase with constant input until the stock reaches a steady state. These outcomes are interrelated. Improvements in productivity – for example, through fully stocked regeneration using productive species or through fertilization or genetic improvements – could decrease the optimal rotation period. The failure to use dead wood and trees that are biologically mature (beyond their maximum growth period) for substitution could be a missed opportunity for carbon benefits (except in special circumstances), as both are sources of emissions to the atmosphere.

Not all wood uses help to build long-lived carbon stores, and in some cases high emissions in processing and transport may undermine gains achieved from long-term storage of carbon in wood products. What matters for mitigation is how increased use of long-lived wood products compares to the alternative, which often would be continued use of other, more emission-intensive products.

CAPITALIZING ON CO-BENEFITS FOR SUSTAINABLE DEVELOPMENT

An important factor to consider, for decision-makers wishing to use forest mitigation options in their national mitigation portfolio, is their contribution to sustainable development, often discussed in terms of co-benefits. Forest mitigation projects that provide co-benefits have additional value, and the nature of the co-benefits presented by different forest mitigation options may help the decision-maker decide which options may be most suitable.

Forests can contribute to important policy objectives such as livelihood provision, climate change adaptation, biodiversity, outdoor recreation and water regulation (Table 10). However, the value of these co-benefits has not generally been included in estimates of the cost-effectiveness of mitigation options, in part because of uncertainty over their magnitude and the complexity of estimating values for benefits that are highly site specific. Consideration of co-benefits could lead to stronger alignment of forestry with other sectors and encourage implementation bio-based procurement strategies.

Income and livelihoods

Most mitigation options could contribute to income and livelihoods, as mentioned in Chapters 3 and 4 for A/R and REDD+ options, for example. In bioenergy options, higher demand for woody biomass will tend to increase forest landowner revenue, while greater reliance on small-diameter biomass from faster-growing species may help provide a more continuous source of revenue than traditional timber production. Use of wood and wood-derived materials in biorefineries is expected to contribute to the local economy by creating direct and indirect jobs in the supply chain (from harvesting, storage and transport) and in the construction and operation of refineries as well as downstream product development (biochemicals, biopolymers) and distribution networks. Harrison *et al.* (2014) showed

TABLE 10
Some key co-benefits of the mitigation options presented in this publication

Co-benefit	Expanding forest area	Reducing forest loss	Changing management practices	Using and improving wood energy	Promoting the use of wood for greener buildings and furnishing
Income, jobs, livelihoods	•	•	•	•	•
Energy (home use)			•	•	
Climate adaptation	•	•	•		
Improving water quality	•	•	•		
Alleviating flooding		•	•		
Increasing seismic resistance					•
Thermal benefits					•
Biodiversity	•	•	•		
Air quality and health benefits			•	•	

that in Europe, full use of forest and other cellulosic wastes and residues for biofuel could generate up to US$20 billion of additional revenues annually and up to 300 000 additional jobs by 2030.

As a source of employment and income in rural and urban areas of developing countries, projects for wood energy production and use can contribute to socioeconomic development not only in terms of livelihoods, but also in promoting gender equity, food security and health.

Energy benefits

Improvement in wood energy production and utilization helps improve access to clean, efficient, reliable, affordable cooking fuels for poorer populations in developing countries, particularly in sub-Saharan African and South Asian countries, where a high percentage of households rely on woodfuel for cooking.

Charcoal is a versatile material, and communities can diversify their economies by engaging in clean charcoal production. In Brazil, approximately 30 percent of the iron and steel industry has historically used charcoal as a heat-reducing agent, substituting coal coke (Nogueira, Coelho and Uhlig, 2009). In addition to having high energy density, pyrolysed woody materials are used in production of activated carbon or biochar to improve soil. These products extend the value chain and have a high carbon storage potential owing to their longevity (Box 30).

Air quality and health benefits

Improvements in wood energy production alleviate air pollution and health problems caused by inefficient combustion of woodfuel. These problems particularly affect women and children (who also bear a disproportionate burden of labour in collecting fuelwood for household use). Avoidance of forest fires through improved forest management also avoids health costs arising from smoke haze when forests are burnt.

BOX 30
Emerging non-fuel uses of charcoal

Charcoal is inherently resistant to microbial degradation, even in soil where it can be used as biochar. Converting degradable carbon into charcoal (the process of pyrolysis) therefore also has potential to deliver carbon abatement when the charcoal is not used for bioenergy. Since the effectiveness of storage exceeds the efficiency of energy use, clean production of biochar from sustainable wood reportedly has a higher life-cycle benefit than using charcoal as fuel. The overall life-cycle analysis is even more positive if energy released by pyrolysis is captured and avoids fossil fuel use. Using biochar to improve the fertility of certain soils also offers positive potential feedback into biomass production (Biederman and Harpole, 2012). The potential applications of biochar in forestry and agriculture need further investigation, but the low transaction costs associated with monitoring and verification of the carbon stored in soil as biochar, combined with defined permanency, offer clear potential for income from future carbon markets as well as improved land productivity. The challenge is to find a suitable way to fit pyrolysis technologies and biochar into local energy systems and areas where soil constraints can be beneficially addressed (Sohi, 2012).

Adaptation

Forestry measures to mitigate climate change can be linked to adaptation and can have important impacts on other policy objectives. Forests have the potential to reduce the vulnerability of communities to climate change impacts and food insecurity. They also have an important role in helping land-use-based economic sectors, such as agriculture, adapt to climate change (Pramova *et al.*, 2012).

Water benefits

Forests have an important role in the hydrological cycle. They influence the amount of water available and regulate surface and groundwater flows while maintaining high water quality. They contribute to the reduction of water-related risks such as landslides, local floods and droughts and help prevent desertification and salinization. The supply of a high proportion of the world's accessible freshwater for domestic, agricultural, industrial and ecological needs is from forested watersheds. Maximizing the wide range of forest benefits without impairing water resources and ecosystem function is a challenge and is particularly relevant in the context of adaptation to climate change (FAO, 2013).

Some emerging PES schemes rely on downstream users (including water utilities, hydroelectric dams or local administrations) to help finance upstream reforestation initiatives. Water impacts need to be considered in evaluating the cost effectiveness of forest conservation as a mitigation strategy. Forests can take up carbon only if they take up water. Part of the price of carbon sequestration is paid in water. It is therefore important to consider the trade-offs between the water consumption of forests and the ecosystem services they provide (including mitigation) (FAO, 2013).

Achieving synergies among co-benefits

Depending on the context, projects in the forest sector can produce either positive synergies (livelihood enhancement, improved local environmental services) or adverse effects (loss of forest access, negative impacts on livelihoods) (Chhatre and Agrawal, 2009; Kerr *et al.*, 2006). Because project impacts are highly contextual, it is imperative to assess the local contribution of any mitigation project to sustainable development. Such an assessment should include distinguishing who among the local community can participate in the project; expected changes in household incomes for participants and non-participants; and likely positive and negative impacts of new forest management practices on local forest users such as collectors of non-wood forest products (Pagiola, Arcenas and Platais, 2005).

Many factors can influence whether or not local communities actually derive co-benefits from a mitigation project. One factor is integration of local preferences into project design. Forest conservation may not equate with poverty reduction if projects fail to integrate local value chains and societal needs and/or if they introduce new restrictions on forest users (Pokorny, Scholz and de Jong, 2013). Another recommendation is the design of equitable benefit distribution mechanisms that adequately compensate local people for the cost of investing in new conservation activities that may not provide them with as much direct benefit as their usual forest-based activities. Promoting food and wood security for people could provide them with incentives to contribute to mitigation projects.

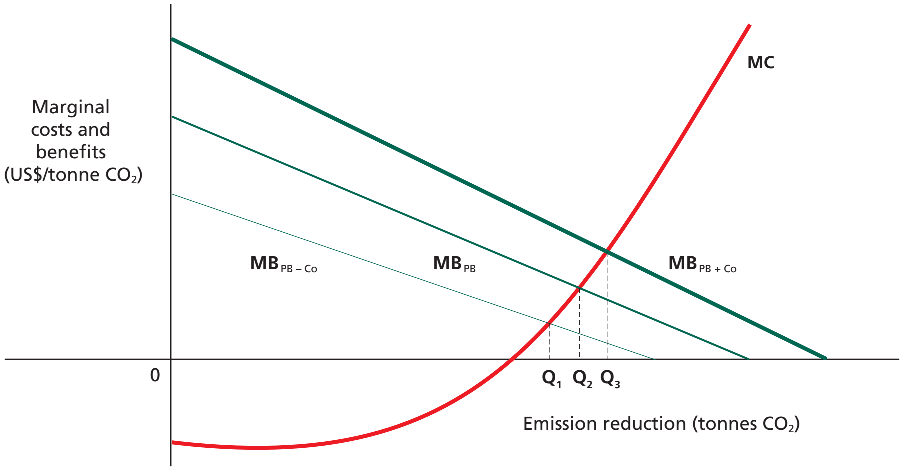
Tenure rights are another factor. Forest-based communities often have insecure rights to forest areas that they have used historically (Tacconi, Mahanty and Suich, 2010). While land rights can encourage communities to invest in long-term conservation activities, other possible options include disaggregation of carbon rights from land rights or awarding land rights to local farmers in return for more effective management of forest stocks, as has been done in community forestry in Indonesia (USAID, 2007).

In general, larger forest size correlates with more effective carbon storage and higher livelihood benefits (Chhatre and Agrawal, 2009). Thus, instead of limiting conservation activities to small forest areas, project proponents should try to expand activities to larger areas, which would also help in addressing concerns related to leakage and permanence of carbon stocks. Enlarging project areas is not easy, as it requires integration of preferences across various spatial scales and stakeholder groups.

The realization of sustainable development benefits from mitigation projects also depends on how well the recipient country is able to cover transaction costs related to project design and implementation (Tacconi, Mahanty and Suich, 2010). Actions that may assist in this regard include simplification of guidelines pertaining to various project components, combining carbon sequestration with other environmental services and working with groups of farmers to aggregate smaller plots (USAID, 2007).

In evaluating the sustainable development benefits of mitigation projects, the key is to consider the three interlinked dimensions of sustainable development (social, economic and environmental) at different spatial levels (local, national and global). A correct economic analysis of the societal benefits of a mitigation action also has to take into consideration the avoided costs of adaptation. As shown in Figure 31, the socially optimal level of emission reduction is when the marginal cost of one additional unit of emission

FIGURE 31
Socially optimal level of emission reduction when local level co-impacts are considered



MC is the marginal cost of carbon emissions. MB_{PB+Co} represents marginal benefits of emission reduction when primary benefits to the global society (PB) and positive co-impacts (Co) to the local community are added together. Q_3 is the resultant optimal level of emission reduction. MB_{PB} represents the marginal benefits curve when only primary benefits to the society are considered, with Q_2 being the optimal level of emissions reduction. MB_{PB-Co} is the marginal benefit curve showing primary benefits to the global society minus negative co-impacts for the local society. In this case, the optimal level of emission reduction is Q_1.

Sources: Adapted from Ürge-Vorsatz *et al.*, 2014; Pearce, 2000; Turner, 1993

reduction is equal to the marginal benefit from that reduction (which can also be thought of as the avoided marginal cost of adapting to climate change). When policymakers consider both the primary benefits to the global society and the positive co-benefits for the local society, the optimal level of emission reduction can be much higher (Q_3) than when only the primary benefits are considered (Q_2). When an emission-reduction project produces adverse or negative co-impacts at the local level, the optimal level of emission reduction is much lower (Q_1). Mitigation projects that enhance local incomes can therefore be hugely effective, even from a purely economic efficiency viewpoint (Ürge-Vorsatz *et al.*, 2014). Indeed, national policymakers have often drawn attention to the potential for local sustainable development to gain support for emission-reduction activities (Held, Roger and Nag, 2013; Dolšak, 2009; Teng and Gu, 2007), while negative co-impacts at the local level are sometimes a reason for resistance to mitigation efforts despite potential for overall societal gains at the global level.

The CDM (2015a) has developed a sustainable development co-benefits tool which includes an exhaustive list of indicators to measure the extent to which a project generates social, economic and environmental co-benefits. This tool has been used to evaluate the local impacts of several emission-reduction projects in developing countries, including one

A/R project (Box 31). However, while many studies have projected potential benefits of forest-based mitigation projects, relatively few have looked at local project impacts in the field. In order to advance sustainable development, it is necessary to collect evidence from the field and to build on relevant lessons in designing future projects.

SUSTAINABLE WOOD BUDGET: SECURING SUSTAINABLE WOOD SOURCES FOR THE ADVANCING BIOECONOMY

For the forest industry, engaging wholeheartedly in the bioeconomy has the potential to generate enormous revenues. The global market revenue potential for wood-based products in 2030 has been estimated to be US$1 854 billion, including US$1 309 billion from bioenergy, biochemicals and fibre composites (Mangin, 2013) (Table 11). The global

BOX 31

Sustainable development under the CDM: reforestation of grazing lands in Argentina

An A/R project in Santo Domingo, Argentina, implemented by Novartis Pharma and registered by the CDM in 2011, includes large-scale reforestation activities (a mix of 75 percent native and 25 percent fast-growing tree species) on an area of 2 292 ha. The primary benefit is generation of emission reductions in the form of CERs. Throughout the project's crediting period, 2007–2027, it is expected to generate emission reductions of 66 038 tonnes CO_2 per year. Other ancillary benefits include production of wood and timber products that can be processed by the local furniture and pulp and paper industry.

A sustainable development assessment completed in 2014 estimated that the following benefits will flow into the local area:

- Environmental
  - Reduction of dust from cattle farming
  - Improved soil quality and reduction of soil erosion
  - Water conservation through planting of native tree species
  - Increased plant diversity
- Social
  - Creation of short- and long-term employment opportunities in the wood processing industry
  - Training in forest management and wood processing
  - Income for the local community
- Economic
  - Creation of a successful business case for forest management and wood processing
  - Technology transfer to the area in the form of carbon management through planting of mixed tree species

Sources: CDM, 2015a, 2015b

TABLE 11
Global market potentials for different bio-products from forest biomass (billion US$)

Product	2015	2020	2030
Bioenergy, biochemicals, fibre composites	**505**	**776**	**1 309**
Heat and power	220	325	430
Biofuel and biogas	69	122	152
Green chemical products	132	177	381
Fibre composites	62	97	241
Building with wood	20	50	95
Living with wood	2	5	10
Conventional forest industry products	**495**	**512**	**545**
Wood industry	245	262	295
Pulp and paper industry	250	250	250

Source: Mangin, 2013

demand for bioplastics totalled 1.1 million tonnes in 2013 and is expected to reach about 6 million tonnes in 2019, at an assumed compound annual growth rate of 32.7 percent between 2014 and 2019 (*Bioplastic News,* 2014). Demand for wood and timber products is projected to increase as much as three times by 2050 (The Prince's Charities, 2015).

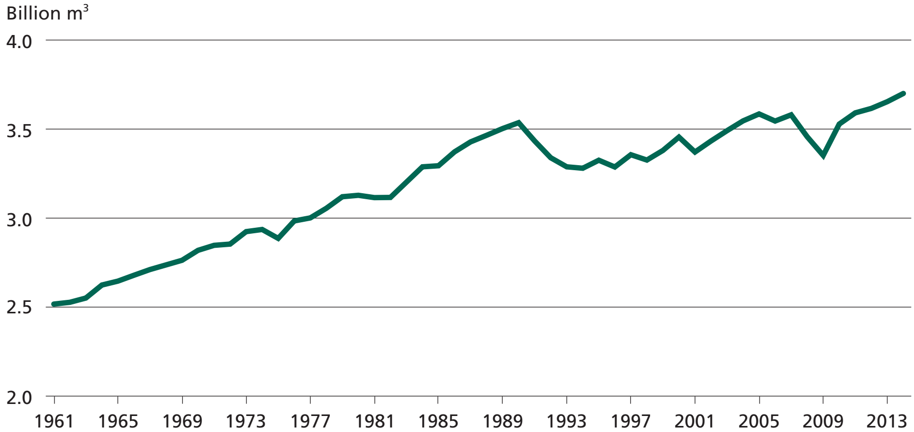
To realize the potentials, significant additional wood resources will be required. For instance, a 2009 outlook for bioenergy use to 2030 (under the then-current bioenergy policies) foresaw an increase in wood demand from roughly 1.2 billion cubic metres in 2010 to 2 billion cubic metres in 2020 and 2.16 billion cubic metres in 2030 for modern commercial heat and power production alone (Whiteman and Cushion, 2009). Brack (2015) argued that between 2015 and 2025 the demand for wood for use in biofuel will exceed the supply. In the absence of additional limits and conservation, the increased extraction would be at considerable cost to the supplies of other forest-based industries.

Increased demand for wood supplies for various mitigation options should be looked at carefully in the context of the resource demands of the whole forest sector and the emerging needs of building a bioeconomy. It is also important to monitor and regulate the extraction capacity of residual biomass from the biosphere, which conventionally supplies important nutrients to the forest. The wide-scale application of the "cascading use" of biomass (see Box 24 in Chapter 6) could arguably optimize use of wood resources across wood-based mitigation options.

Can wood demand be met sustainably using the available land?

In those countries where sustainable forest management is well established and close attention is paid to developing forest stocks for the longer term – particularly developed countries and some other forest-rich countries – a sustainable wood supply is feasible. For example, in the EU-27, the net annual forest increment in 2010 was reported to be 620 million cubic metres, while annual felling was 469 million cubic metres, leaving an unharvested annual increment of about 26 percent (Forest Europe, UNECE and FAO, 2011). On United States of America timber land, the volume of growing forest stock has increased substantially over several decades, since the annual growth of forest biomass has exceeded forest harvest while the timber land area has remained relatively stable (USDA Forest Service, 2010).

FIGURE 32
Global production of roundwood, 1961–2014



Source: FAO, 2015a

Globally, the net loss in forest area has slowed considerably as a result of increased afforestation (particularly in China), natural expansion of forests and a reduced rate of deforestation (FAO, 2016a). This trend is expected to continue. Currently, about 31 percent of the world's forests are designated as production forests. Another 28 percent are designated as multiple-use forests, where wood production is but one activity (FAO, 2016a).

Annual global roundwood production in 2014 was about 3.7 billion cubic metres, compared with 2.5 billion cubic metres in 1961 (Figure 32) (FAO, 2015a). Analyses based on FAO data (Gardiner and Moore, 2014; Payn *et al.*, 2015) suggest that with sustainable management and good forest governance, the world's requirements for wood could be met without unacceptably damaging the environment. A high-priority challenge, however, will be to ensure GHG-efficient management by planning and undertaking forest operations that limit the emission of GHGs, increase terrestrial carbon stocks and use resources efficiently.

In Europe, private forest owners play a crucial part in achieving sustainable forest management, maintaining the productivity of forests and satisfying the increasing demand from wood processors and bioenergy producers (Tuomasjukka, 2010). In North America and much of Asia, State forest ownership is more pronounced, whereas in South America, China and Oceania plantations are usually owned by companies. Responsible forest management is supported by legislation, such as the EU Timber Regulation, and by forest certification.

Role of planted forests

In general, the future supply of industrial roundwood will mostly come from managed and planted forest rather than natural forest. One-third of industrial roundwood was supplied from plantation forests in 2012 (520 million cubic metres). Industrial roundwood supply from plantation forests is predicted to reach 711 million cubic metres by 2022 and could increase to 1.5 billion cubic metres in 2050 (Indufor, 2012). Natural forests in the tropics contribute to meeting only 10 percent of the global industrial roundwood demand. Natural and semi-natural forests in boreal and temperate zones still have a role in the sourcing of raw materials, but increased supply from these forests may be jeopardized in some cases by constraints related to logistics, profitability and ownership structure (Barua, Lehtonen and Pahkasalo, 2014).

Countries in tropical and subtropical regions have increased and intensified their focus on plantations and have developed codes of practice for plantation forestry. Production from plantation forests will continue to replace natural forest production, especially in these regions (Sampson, 2005). Sustainable management of industrial plantations in Africa, Asia and Latin America can be vital to the supply of global wood demand in the long term (Barua, Lehtonen and Pahkasalo, 2014). In addition, more national-level tree planting programmes, agroforestry expansion and urban forestry development, often supported by international initiatives, are likely to increase sustainable wood supply.

Establishing plantations on severely degraded and abandoned lands is recognized as a mitigation activity under UNFCCC. New timber plantations on severely degraded forest land may achieve a high volume of timber per hectare, thus increasing carbon stocks over a harvest cycle. However, plantation establishment is not without risk; some plantations have been established with poor social or environmental results. Plantations should therefore be developed in line with sustainable forest management and timber certification standards to meet environmental and social requirements, including the recognition of community and stakeholder rights and livelihood needs (FAO, 2011). In addition, timber harvesting operations must follow principles of low environmental and social impact. Fast-growing plantations (Box 32) are one model that may increase wood availability in many regions, although they are not without controversy.

BOX 32

Fast-growing plantations: a Brazilian experience

In Brazil, 7.74 million hectares of fast-growing planted trees helped to sequester 1.69 billion tonnes of CO_2 in 2014 (Ibá, 2015). Harvesting does not reduce the forest’s carbon stock, because for every tree that is harvested at least one new tree is planted. The positive balance is confirmed by GHG inventories. However, these plantations face some resistance, mainly related to perceived negative environmental impacts of homogeneous tree plantations. Proponents claim that by altering the landscape matrix from an open area (degraded pastureland) to a tree-dominated area, these plantations bring new habitat availability, despite some particularities created by short harvesting cycles. Reforestation of tropical pastures with a variety of tree species in São Paulo, Brazil is a good example (Cook, Stape and Binkley, 2014).

Globally, some 2 billion hectares offer opportunities for forest restoration: 1.5 billion hectares appropriate for combining trees with other land uses (including agroforestry) and about 0.5 billion hectares suitable for restoration of closed-crown forests (WRI, 2011). Greening programmes should target land not currently under active agriculture to avoid negative impacts on food security. Planting of trees on farms and in other areas outside current forest lands could potentially increase land availability for forestry mitigation options.

Initiatives such as the Bonn Challenge (Box 33) and the New York Declaration on Forests have emerged to take advantage of opportunities for using available land. The country-led Initiative 20x20 was launched in 2014 to restore 20 million hectares of degraded land in Latin America and the Caribbean by 2020, mostly to contribute to the Bonn Challenge (Laestadius *et al.*, 2015).

Chain of custody

Tracing of product origin has become a requirement for responsible manufacture of forest products in order to guarantee legal sourcing. Tracing systems are applied from purchased wood to pulp and are verified by third parties such as FSC and PEFC in line with standards such as ISO 14001 (the international standard for environmental management systems). Traceability of wood is beneficial for both companies and consumers.

Recycling and reuse

Improving recycling and reuse of wood could aid in meeting demand for sustainable and affordable raw material. Recycling efforts are already on a positive trend. Of the market volume of wood in Europe in 2010, 9.2 percent was recovered as material and 12.1 percent as energy (Mantau, 2012). More effective use of harvest and processing residues could help meet the demand for some energy options (e.g. combined heat and power generation or extending feedstock for biofuels). Falk and McKeever (2004) estimated that in 2002, 43 percent of waste wood in the United States of America (equivalent to 12 percent of the country's roundwood) was suitable for further recovery (for landscaping mulch and fuel, but also for structural uses and remanufacture into value-added products). However, its actual usability depends on a variety of factors including the size and condition of the material and costs associated with acquiring, transporting and processing it into a useable raw material.

FINANCING FOREST MITIGATION

Forest-based mitigation can be costly. The cost of meeting the goals of the Bonn Challenge (see Box 33), for example, has been estimated at about US$36 billion to US$49 billion per year (UNCCD and FAO, 2015). Where will this financing come from?

Financing mitigation in the forest sector and sustainable forest management requires three stages of investment: up-front investment for the readiness phase, implementation-related investment and investment in self-sustaining financing mechanisms to ensure predictable flows of funds (Simula, 2008). Each of these three phases needs one or more sources of funds, financial instruments to deliver funds and incentives for action on the ground, and specific programmatic uses of funds. Figure 33 shows the overall movement of funds from sources of finance to financial instruments to implementation of on-the-ground actions. It is important to consider at which scale – national, regional or international – financial support for mitigation actions will be sought. Box 34 presents some questions that policymakers will need to address to ensure adequate finance for mitigation. Box 35 summarizes types of costs that should be estimated in order to finance the range of programme activities, using the example of REDD+.

Forest-related climate finance can have many functions beyond those strictly related to carbon offsets. It can be instrumental to:

- provide financial viability to alternative practices, e.g. replacing carbon-intensive practices with climate-friendly ones;
- cover losses associated with temporary restrictions on current practices, e.g. excluding grazing until soils or forest densities recover;
- overcome non-financial barriers, e.g. by supporting training and capacity building to cover knowledge and information gaps;
- overcome resistance to innovation, e.g. by providing an incentive to change long-established carbon-intensive practices;
- finance external and specialized input into design of better and locally adapted practices and policies;
- finance information and monitoring systems to measure the costs and benefits of mitigation measures or policies;
- produce co-benefits to overcome poverty and maintain biodiversity, especially under REDD+.

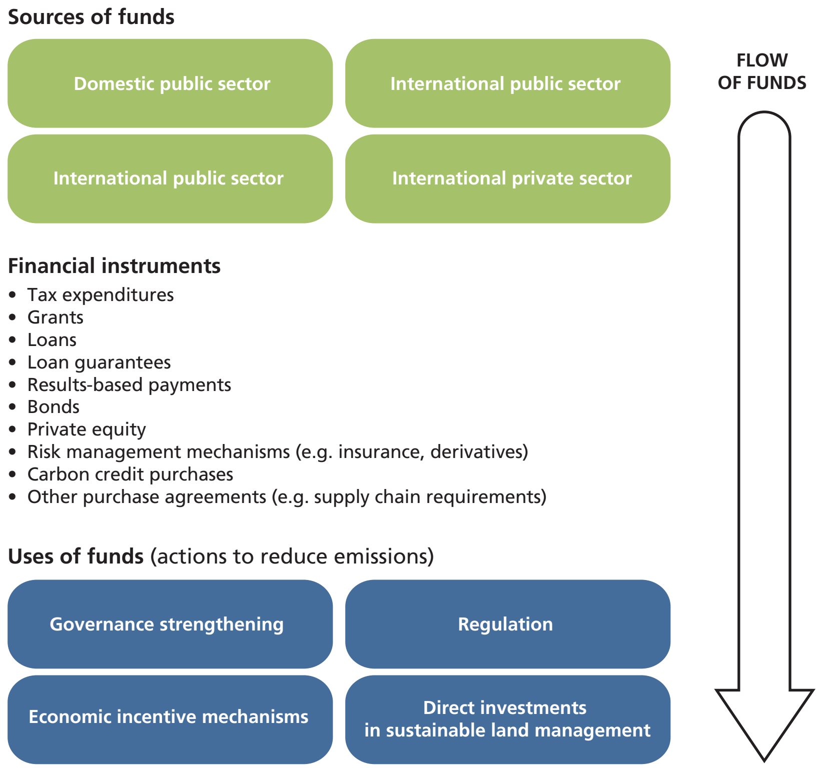
BOX 33

The Bonn Challenge

The Bonn Challenge, launched in 2011, aspires to restore 150 million hectares of the world's deforested and degraded lands by 2020 and 350 million hectares by 2030 and thus to restore ecological integrity and improve human well-being through multifunctional landscapes.

The Bonn Challenge represents a practical means of realizing many existing international commitments, such as the Convention on Biological Diversity (CBD) Aichi Target 15 (by 2020, to enhance ecosystem resilience and the contribution of biodiversity to carbon stocks through conservation and restoration, including restoration of at least 15 percent of degraded ecosystems, thereby contributing to climate change mitigation and adaptation and to combating desertification), UNFCCC's REDD+ goals and the target of land degradation neutrality set at UN Conference on Sustainable Development (Rio+20) in 2012. As of June 2016, 64 percent of the target has been committed, with a sequestration potential of 5.95 Gt CO_2 and economic activity worth US$19.9 billion (Bonn Challenge, 2016).

FIGURE 33
Conceptual diagram of the flow of funds from sources to financial instruments to policies, measures and other actions on the ground



Source: Streck *et al.*, 2015

Sources of finance

Many programmes offer support to national institutions, including forest administrations, in preparing for climate finance streams. These include UN-REDD, the FCPF Readiness Fund, the Green Climate Fund Readiness Programme of the German Agency for International Cooperation (GIZ) and the Green Climate Fund Readiness Programme of the United Nations Development Programme (UNDP), the United Nations Environment Programme (UNEP) and the World Resources Institute (WRI).

The CDM has directed roughly equal amounts of investment into A/R and forest-derived biomass energy projects, but the scope of the mechanism currently excludes REDD+ and sustainable forest management. Directly comparable investment data are not available for the voluntary carbon market, but it is clear that this market has directed substantial funds into REDD+ and sustainable forest management, in addition to the options covered by the CDM.

BOX 34

Ensuring adequate finance for mitigation, REDD+ and low-emission development goals: key questions for policymakers

- What are the priority financing needs and actions for a given province or country?
- Which financial instruments can be mobilized to provide this financing? What domestic and international sources of funds can be tapped? Do fund sources provide clear guidance on the rules and requirements for submitting proposals (i.e. will the proposed activities be eligible)?
- Are feasible instruments and financing options available for specific institutions or programmes to undertake the activities proposed? Are the institutions or programmes capable of implementing the activities successfully?
- How can previous programme failures and successes, both domestic and in other countries, inform the design, implementation and financing of the proposed activities?

Source: Streck *et al*., 2015

BOX 35

Four types of costs to be estimated for REDD+

- Opportunity costs: the foregone benefits in income, e.g. from timber harvest or crop production, that deforestation would have generated
- Implementation costs: the costs of activities, benefit-sharing programmes and monitoring protocols, etc. needed to reduce deforestation and forest degradation
- Transaction costs: the costs of designing and operating a REDD+ programme on the ground
- Institutional costs: the costs of putting in place an enabling environment in terms of policies, regulations and finance at the provincial or national level

Sources for forest carbon finance are now shifting from market mechanisms to bilateral and multilateral funds. Pledged funds have already greatly surpassed market mechanisms, but actual disbursement across all climate funds is only US$3.7 billion, or about 10 percent of pledged funds on average (Climate Funds Update, 2016). Nevertheless, the shift is likely to accelerate in the future as pledged funds are disbursed and new funds are raised – in particular, a proportion of the US$10 billion currently mobilized for the Green Climate Fund is expected to be spent on mitigation options in the forest sector.

It is important also to consider the development of self-sustaining financing mechanisms at the national and local levels to ensure long-term provision of funds for mitigation in the forest sector. National and local financing approaches that can be developed to achieve this include national forest funds (FAO, 2015c) and national climate funds. National climate funds build country ownership in developing a project pipeline and financing mitigation options.

Promoting transactions in the forest carbon market

Current status. Most of the demand for offsets or emission reduction units generated by forest carbon projects comes from major emitter countries in Europe and Oceania, while most of the offset supply comes from developing countries in Latin America, Africa and Asia (Table 12). Europe had the largest demand for forest carbon offsets in 2013. Buyers from Europe purchased nearly two-thirds of all forest emission reductions generated. The next largest demand was in Oceania (referring here to Australia and New Zealand), followed by North America.

Most offset units sold in 2014 from forest-based forest mitigation options were generated by avoided deforestation (Table 13). However, A/R generated a stable volume and value of offsets from 2007 to 2014. Demand on the voluntary carbon market for offsets from other options such as improved forest management peaked in 2012. In 2014, even though project offsets from forest management retained their price (US$8.4 per tonne CO_2e), their overall transaction volumes were lower (Ecosystem Marketplace, 2015a).

Examples of some possible national REDD finance mechanisms are shown in Box 36.

Compliance versus voluntary carbon market. Although the role of forest carbon was established under the Kyoto Protocol and its compliance market, there are now significant opportunities in the voluntary market (Meizlish and Brand, 2009), as shown in Tables 12 and 13 and Box 36. At present almost 90 percent of the forest carbon offsets transacted belong to the voluntary carbon market, with a market value that exceeds 70 percent of the total forest carbon market value.

Transaction volumes and market value of offsets for forest carbon on the voluntary carbon market in 2013 by far exceeded those of the compliance market, while the average price of forest offsets was higher on the compliance market (Ecosystem Marketplace, 2014) (Table 14). However, in 2014 the compliance market equalled the voluntary market in terms of market value, mainly as a result of the strengthening of the California market (which increased more than 240 percent in value) (Ecosystem Marketplace, 2015b).

CDM Joint Implementation forestry projects are still considered more reliable, and thus their average value per tonne CO_2e is more than double that of the average value in the voluntary carbon market. The compliance market is generally considered to have a lower price risk, and the carbon offset value is generally thought to cover the landowners' opportunity cost when they choose not to harvest timber in favour of A/R or improved forest management (Kerchner and Keeton, 2015). The volatility in the carbon values of the voluntary market is exemplified by the price range of offsets, from US$1 to US$100 per tonne CO_2e (Kerchner and Keeton, 2015). In terms of certification on the voluntary market, the Gold Standard, which began verifying forest carbon offsets in 2013, has achieved an average carbon value of around US$8.5 and US$11.1 per tonne CO_2e in 2013

TABLE 12
Forest carbon market snapshot, 2013

Region[a]	**Type of forest carbon projects transacted**			**Supply and demand in the global forest carbon market**					
	Expanding forest area *(%)*	**Reducing forest loss** *(%)*	**Changing management practices** *(%)*	**Volume supplied** *(Mt CO_2e)*	**Percentage of volume purchased** *(%)*		**Estimated volume demanded** *(Mt CO_2)*[b]	**Average price** *(US$/tonne CO_2e)*	**Estimated value of purchase** *(million US$)*[c]
EU	36		63	0.5	EU	100	18.72	14.5	97.62
OC	4	81	11	1.9	OC	95	6.90	14.5	50.63
					NA	3			
					EU	2			
NA	26	11	62	2.6	NA	98	4.59	8.6	29.61
					EU	2			
LA	4	94	3	18.2	EU	65	0.72	4.8	3.49
					OC	28			
					LA	4			
AS	67	22	11	2.8	EU	95	0.08	7.6	0.63
					AS	3			
					NA	1			
AF	4	95		5.6	EU	65	<0.1	3.4	<0.3
					NA	35			
Total				**31.6**			**31.11**	**8.9**	**182.28**

[a] EU = Europe; OC = Oceania; NA = North America; LA = Latin America; AS = Asia; AF= Africa.
[b] Calculated as the sum of a region's percentage of volume purchased from each region, multiplied by the volume supplied by that region.
[c] Calculated as the sum of a region's percentage of volume purchased from each region, multiplied by the volume supplied by that region and the average price. For example, the largest buyer, Europe, bought 100 percent of 0.5 million tonnes from Europe at an average price of US$14.50, plus 2 percent of 1.9 million tonnes from Oceania at an average price of US$14.50, plus 2 percent of 2.6 million tonnes from North America at an average price of US$8.60, plus 65 percent of 18.2 million tonnes from Latin America at an average price of US$4.80, plus 95 percent of 2.8 million tonnes from Asia at an average price of US$7.60, plus 65 percent of 5.6 million tonnes from Africa at an average price of US$3.40, for an estimated total of US$97.62 million. Note that these estimates are extrapolated from a subset of voluntary carbon market data for which buyer locations were known, and may not accurately represent the whole market.

Source: Ecosystem Marketplace, 2014

TABLE 13
Transacted volume and value of offsets for forest-based mitigation options

Mitigation option type	**Transactions in 2014**		**Cumulative transactions 2007–2014**	
	Volume *(Mt CO_2e)*	**Value** *(million US$)*	**Volume** *(Mt CO_2e)*	**Value** *(million US$)*
Afforestation/ reforestation (A/R)	1.6	14	35	270
Avoided deforestation	25	115	84.5	442
Forest management	0.6	5	14	113
Total	**27.2**	**134**	**133.5**	**825**

Source: Ecosystem Marketplace, 2015a

BOX 36

Some possible national REDD finance mechanisms

- Chile has introduced a carbon tax. The offset arrangements are not yet final, but they might incorporate REDD.
- China allows offsets from Chinese CDM projects, and REDD-type projects may be included.
- Japan is developing a bilateral crediting mechanism known as the Joint Crediting Mechanism, which includes REDD+.
- South Africa has proposed a carbon tax. Although the scope of eligible offsets has not yet been defined, REDD+ may be included in the scheme (National Treasury, Republic of South Africa, 2014).

Source: Linacre *et al.*, 2015

TABLE 14

Comparison of compliance and voluntary carbon markets in terms of forestry offsets, 2013 and 2014

Market	Volume of offsets transacted *(Mt CO_2e)*		Market value *(million US$)*		Weighted average price *(US$/tonne CO_2e)*	
	2014	2013	2014	2013	2014	2013
Voluntary	23.7 (69%)	29 (88%)	128 (50%)	140 (73%)	5.4 (27% less than average)	4.8 (8% less than average)
Compliance	10.6 (31%)	4 (12%)	129 (50%)	52 (27%)	12.7 (72% more than average)	9.7 (87% more than average)
Total	**34.4**	**32.7**	**257**	**192**	**7.4** (average price in both markets)	**5.2** (average price in both markets)

Sources: Adapted from Ecosystem Marketplace, 2014; Ecosystem Marketplace, 2015b

and 2014, respectively. The VCS has achieved half of these prices in most of its offsets owing to demand and supply dynamics, since it covers most of the market (Ecosystem Marketplace, 2014).

Flooding the voluntary carbon market with certain types of project can lead to a reduction in the average achievable carbon value. For example, REDD+ projects seem to be increasing in popularity in the voluntary market globally, with offset transactions of almost 25 Mt CO_2e (80 percent of the volume) and a market value of almost US$100 million (67 percent of the total market) in 2013 (Ecosystem Marketplace, 2014). The resulting large supply of such REDD+ offsets in the market has driven their average value down (from US$4.2 per tonne CO_2e in 2013 to US$3.7 per tonne CO_2e in 2014) while those from A/R and improved forest management projects have more than doubled in value.

Enhanced monitoring using the most updated remote-sensing technologies can allow all forestry projects to be eligible to operate on the compliance market. Regulation of the supply quantity could provide better carbon prices and more forest carbon financing, which could ease the decision of landowners to forego the opportunity costs of their business-as-usual harvest and to adopt forest carbon projects on their land.

Carbon pricing. Globally, the combined value of the regional, national and subnational carbon pricing instruments was less than US$50 billion in 2015, of which almost 70 percent was attributed to emission trading systems and the rest to carbon taxes (Kossoy *et al.*, 2015).

Carbon prices vary significantly, from less than US$1 to US$130 per tonne CO_2e. About 85 percent of emissions are priced at less than US$10 per tonne CO_2e. This is considerably lower than the price that has been estimated as needed to meet the recommended 2°C climate stabilization goal (Kossoy *et al.*, 2015).

The average price per tonne CO_2e in the voluntary carbon market is still less than half that of CDM/JI forestry projects, which are still considered more reliable. However, voluntary offset prices averaged US$5.8 per tonne CO_2e and have dropped every year since 2011, reaching US$3.8 per tonne CO_2e in 2014 (Ecosystem Marketplace, 2015a).

A carbon tax is a form of explicit carbon pricing, directly linked to the level of CO_2 emissions. The carbon taxes enforced by countries vary (Table 15).

The Kyoto Protocol rules hindered market finance for forest mitigation. Until a new instrument is created to drive the establishment of stronger compliance markets, forest mitigation cannot yet count on more significant market finance.

TABLE 15
Existing national and subnational jurisdictions with a direct carbon tax

Country/province	Tax rate *(US$ per tonne CO_2e)*	Year
British Columbia, Canada	23	2012
Chile	5	2018
Costa Rica	3.5% tax on hydrocarbon fossil fuels	
Denmark	31	2014
Finland	39	2013
France	7.85	2014
Iceland	10	2014
Ireland	25	2013
Japan	2	2014
Mexico	0.60–3 (depending on fuel type)	2014
Norway	4–69 (depending on fossil fuel type and usage)	2014
South Africa	9	2016 (proposed to increase by 10% per year until end 2019)
Sweden	168	2014
Switzerland	68	2014
United Kingdom	15.75	2014

Source: World Bank, 2016

Key messages: making it happen

- Climate change decisions need to take into consideration economic and social costs and benefits, and appropriate discount rates must be applied for the most cost- and time-effective options. By requesting countries to present Nationally Determined Contributions expressing commitment to a lower emission path than business as usual, the Paris Agreement provides the flexibility necessary for countries and regions to work on their strategies to contribute to mitigation.
- Decision-makers should consider the contributions of forest mitigation options to sustainable development, often discussed in terms of co-benefits, when deciding the appropriate policy mix.
- To realize the potentials of mitigation in the forest sector, significant additional wood resources will be required. Increased demand for wood supplies for various mitigation options should be looked at carefully in the context of the resource demands of the whole forest sector and the emerging needs of building a bioeconomy.
- Sources for forest carbon finance are now shifting from market mechanisms to bilateral and multilateral funds. Actual disbursed funds across all climate funds have only recently reached the US$1 billion mark. The shift is likely to accelerate in the future with finance mobilization for the Green Climate Fund.
- National and local financing approaches, such as national forest funds and national climate funds, can be developed to support forest-based mitigation, including in developing countries. These approaches may contribute to increased alignment of climate strategies with national developmental goals.
- The Kyoto Protocol rules hindered market finance for forest mitigation. Until a new instrument is created to drive the establishment of stronger compliance markets, forest mitigation cannot yet count on more significant market finance.

9. Conclusion

This publication has demonstrated the potential to scale up forests' contribution to climate change mitigation, not only through forest activities – reforestation, afforestation, reduction of deforestation and forest management – but also through forest products. The compilation of expert analysis and case studies presented here also reveals the complexity of accounting for forest mitigation within the UNFCCC framework. Recent agreements in UNFCCC and updated IPCC guidance to the Kyoto Protocol have provided for more precise accounting and expanded consideration of forest emission reduction. However, policymakers and climate experts will have to devote significant effort to improving data on forests and forest products and developing technologies for better estimation of forestry emissions to achieve the fullest benefits from forests' mitigation potential. As the information in this publication demonstrates, there have not yet been enough cost estimations or concrete cases of mitigation strategies that take into consideration all forest options. However, as countries advance in the elaboration of their mitigation strategies, the outstanding role of forestry is becoming clear.

Options for climate change mitigation need to be analysed at the national or regional level based on an agreed global goal. The Paris Agreement defined such a goal – to keep the global temperature increase below 2°C – as well as the aspiration to limit the increase to 1.5°C. By requesting countries to present Nationally Determined Contributions expressing commitment to a lower emission path than business as usual, the Paris Agreement provides the flexibility necessary for countries and regions to work on their strategies to contribute to mitigation.

The mitigation benefits of forest- and wood-based mitigation options can generally be assessed by evaluating data on the contribution of forests and wood products as a carbon sink or source, including carbon storage in post-harvest products, net GHG emissions from forestry operations and wood processing, and carbon flux in the forest ecosystem. In order for the assessment to be meaningful, realistic and credible baselines must be established for each of these components.

The market-mediated indirect effects of any particular use of forests or wood products may extend far beyond the boundaries of the primary activity. For example, when wood products substitute for concrete or steel in construction, or when conventional fossil-based materials such as plastics are substituted by forest-based resources, these substitutions may lead to reductions in emissions from concrete or steel production, but the reductions may be offset to some extent by changes in land use elsewhere in response to the increased demand for wood. A virtuous cycle can be enabled if at the global level reforestation, afforestation and reduced deforestation and sustainable forest management provide for increased carbon sequestration while augmenting the supply of sustainable wood products that can replace more carbon-intense products in the different supply chains.

The exercise of producing this publication through open contributions demonstrates the great number of researchers investigating forestry's contribution to low-carbon strategies, but also the need for more systematic assessments at the national or subregional level. FAO will continue to work on these assessments, engaging with countries and the research community to provide sound estimations and guidance for optimal consideration of forests and wood products in climate change strategies for a low-carbon future.

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Forestry for a low-carbon future

Integrating forests and wood products in climate change strategies

Forests are critical to mitigation, having a dual role; they function globally as a net carbon sink but are also responsible for about 10 to 12 percent of global emissions. Forests and forest products offer both developed and developing countries a wide range of options for timely and cost-effective mitigation. Afforestation/reforestation offers the best option because of its short timescale and ease of implementation. Reducing deforestation, forest management and forest restoration also offer good mitigation potential, especially because of the possibility for immediate action. Yet forest contributions to mitigation also go beyond forest activities. Wood products and wood energy can replace fossil-intense products in other sectors, creating a virtuous cycle towards low-carbon economies. The mitigation potential and costs of the various options differ greatly by activity, region, system boundaries and time horizon. Policymakers must decide on the optimal mix of options, adapted to local circumstances, for meeting national climate change and development goals. This publication assesses the options and highlights the enabling conditions, opportunities and potential bottlenecks to be considered in making apt choices. Aimed at policymakers, investors and all those committed to transition to low-carbon economies, it will support countries in using forests and wood products effectively in their climate strategies.

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