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Achieving sustainable management of boreal and temperate forests

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Contents

Introduction

Forests deliver both economic benefits and a range of key ecosystem services. This collection reviews current research on optimising their use, from understanding tree physiology and effects of disturbances to improvements in planting, stand management, sustainable logging and product diversification.

Chapter 1 sets the scene by providing an introduction to sustainable forestry. Forests have managed to sustain themselves for millennia, recovering, reorganizing or migrating in response to innumerable disruptions. The chapter focuses on current research in sustainable forestry. It discusses the concept of sustainable forestry and goes on to explore the natural resilience of forests. Further sections address the ways in which sustainability is interpreted and the challenges encountered in its implementation. In later sections, each of the subsequent chapters are referred to in turn, providing an overview of the further content of the book. The chapter concludes with a reflection on what sustainable forestry is and how it may be attained.

Part 1 Tree physiology

Chapters in Part 1 cover the physiology of trees in boreal and temperate forests. Chapter 2 reviews advances in understanding root development in forest trees, primarily focusing on root turnover and root system architecture parameters whilst also describing the plasticity of fine and coarse roots. The chapter also highlights how different environmental stressors such as drought and fire can affect the roots and cause various tree responses. It concludes by discussing how important developments in root research can be when planning landscape forest restoration of specific sites.

Moving on to Chapter 3, advances in understanding canopy development in forest trees are discussed. The chapter introduces the reader to physiological processes at the leaf, crown and canopy level. It details the importance of light and water to these processes and highlights the patterns that foliage assumes at all three levels to maximize both carbon uptake and tree performance. The chapter also provides an overview of current research in leaf orientation, leaf clumping and traits acclimation along a canopy light gradient. At the canopy level, the continuous recording of canopy phenology and the eddy covariance method of recording biosphere-atmosphere fluxes are also discussed.

Expanding on topics previously covered in Chapter 2, the final chapter of Part 1, Chapter 4, reviews the responses of forest trees to abiotic stress. The chapter introduces abiotic stress in trees and its interaction with biotic stress. It also examines the link between environmental dynamics and changes in stress. The chapter moves on to discuss the adaptive capacity of trees and forest stands to abiotic stressors, focusing heavily on Adaptive Forest Management (AFM) under conditions of climate change. It concludes by reviewing the available management options to increase tree and forest adaptation to abiotic stressors under climate change.

Part 2 Forest ecosystem services and climate change

The second part of the book discusses current understanding of the ecosystem services that forests deliver and how they can be balanced with various activities. The first chapter of Part 2, Chapter 5, focuses on advances in understanding the role of forests in the carbon cycle. The recognition that increased levels of atmospheric carbon dioxide are warming the global climate has led to forests being viewed as potential natural ways to reduce carbon dioxide concentrations in the atmosphere. Forests' complex interactions with local and global climates, however, make predicting the impacts of changes in forest cover and composition challenging. The chapter begins by discussing the importance of forest carbon content and methods of monitoring it. It also describes the mechanisms driving forest carbon storage and explores whether forests should be considered sources or sinks of carbon. The chapter concludes by discussing distinguishes between carbon and climate management.

Moving on to Chapter 6, this chapter reviews trade-offs between management and conservation for the provision of ecosystem services in the southern Patagonian forests. Forests provide critical ecosystem services for human well-being; however, some ecosystem services are more valued (e.g. provisioning services) than others (e.g. regulating or supporting services). Temperate regions contain several forests affected by humans, mainly with regard to ecosystem services and biodiversity. The chapter focuses on Nothofagus forests in southern Patagonia, analysing potential trade-offs between ecosystem services and biodiversity and how new silvicultural approaches multi-objective management at the landscape level. It also reviews forest ecosystem service characterization, the provision of forest ecosystem services in southern Patagonia and developing strategies of sustainable forest management. The chapter concludes with an overview of forest ecosystem services in a changing world and that future proposals will require fewer trade-offs and will promote positive synergies within the provision of ecosystem services.

Chapter 7 discusses advances in understanding forest ecosystem services, focusing on conserving forest biodiversity. Forest biodiversity is fundamental to ecosystem functioning, facilitating processes such as nutrient cycling, pollination and seed dispersal. A healthy forest provides a range of economic, societal and cultural values and services beyond timber production, including recreation, carbon sequestration, ecotourism, landscape aesthetics and the intrinsic value of biodiversity to society. Despite this, forest biodiversity remains under increasing pressure from agricultural conversion and intensive, large-scale, yield-driven forest management approaches. The chapter reviews the impact of forest loss and fragmentation on biodiversity, then goes on to discuss tree species diversity, composition and conservation. The chapter also highlights the impact of clearcutting on biodiversity and the importance of deadwood to forest biodiversity. It concludes by providing two case studies on managing forest biodiversity in contrasting biomes: managing forest biodiversity in landscapes of low forest cover, a case study from temperate plantation forestry in Ireland; and, managing forest biodiversity by emulating natural ecosystem dynamics, a case study from boreal mixedwood forests in Canada.

Moving on to the final chapter of Part 2, Chapter 8 focuses on the impact of climate change on forest systems in the northern United States. This area is both the most heavily forested and most densely populated quadrant of the region. Forests in the region cover 69.6 million hectares, or 42 percent of the land area. Chapter 8 characterises mid- and long-term projected climate change impacts for trees and forests of the region. It also provides ecoregional vulnerability assessments and management implications of climate change on forest systems. The chapter concludes by emphasising how important it is for natural disturbance or anthropogenic activities such as biomass harvesting to increase, because unless this changes the current middle-aged forest cohort will continue to age with time.

Part 3 Breeding and management

Part 3 of the book reviews improvements in breeding and sustainable forest management techniques. The first chapter, Chapter 9, reviews key challenges in forest management. Forest managers face many challenges, both now and in the future, driven by society's need as well as by the impacts dictated by the threat of climate change. Growing populations will also strain the forest's ability to provide traditional products sustainably while catering to the growing demands for ecosystem services not previously and explicitly managed for across forested landscapes. The chapter provides an overview of current and pending threats and challenges forest managers face around the world. It reviews current and future concerns in forest management such as climate change impacts, changing land use and ecosystem services. Key research areas of climate change impacts, urbanization/forest fragmentation and ecosystem services are also discussed. The chapter concludes by providing a case study on forest management in North America, putting the importance of forest management into perspective.

The next chapter, Chapter 10, focuses on advances in monitoring forest resource status and trends through integration of remote sensing and ground plots. Information derived from monitoring the status of and trends in forest resources is a critical tool for policymakers, managers, and other environmental decision makers. Advances in forest monitoring technology, particularly in the use of remote sensing, have helped deliver higher quality information in a timelier manner than in the past. The chapter provides background information on the practical and statistical principles behind both ground-based and remote sensing-based forest management and monitoring, provides historical context for each, identifies information gaps and practical challenges, and proposes solutions for harmonizing the two sources of information. This is emphasised through the use of a hypothetical forest management case study which is aimed at providing a conceptual framework for forest managers that seek to design forest monitoring systems.

Moving on to Chapter 11, the transitioning of monocultures to forest stands in Central Europe is discussed. The high expectations placed on forests in Europe require an integrative approach to forest management. Heterogeneous mixed-species stands are of special interest as they fulfil many ecosystem services better than monocultures, and consequently homogenous forest stands are now often transformed into more heterogeneous stands. The chapter contrasts even-aged monoculture forests and selection forests, describing the transition from monocultures to more complex forest stands. It also presents practical examples of transformation and models for scenario analysis and explains the principles of selection forest management.

Chapter 12 focuses on species choice, planting and establishment in temperate and boreal forests to meet the challenge of global change. The chapter provides a discussion of the current issues for most of the key processes of forest establishment. It also provides information on planting, direct sowing and stocking, as well as reviewing the importance of fertilization and weed control. It reviews how choosing genetic material can influence plantation forest establishment. The chapter concludes by confirming that more knowledge and accurate decision support is needed and that new resilience strategies are required for successful forest establishment.

The subject of Chapter 13 is advances in nutrient and water management in forestry, with a focus on monitoring, maintaining and restoring soil health. A number of important advances in nutrient and water management in forestry have been made since the middle of the 20th century to maintain and improve soil health. Many concerns have been expressed about the sustainability of forestry operations with intensification of management and harvesting disturbances and the occurrence of natural disturbances. The chapter begins by providing an overview of forest soils and natural disturbances that can affect forest soil development. It moves on to discuss advances in nutrient and water management and provides a section on soil quality and health monitoring. The chapter also reviews how degraded soils can be restored and how although the process is expensive, it is key to maintaining the health of forest soils.

Moving on to Chapter 14, the chapter focuses on advances in stand management and regeneration. Multiaged forests are thought to have the redundant structure to withstand changing disturbance regimes expected with future climate scenarios. The chapter describes methods for deciding how to control stand density in multiaged silviculture at both the stand level and the individual tree level, as well as providing an analysis of current density management principles. It also examines stand regeneration and the resilience and recovery of multiaged forests.

The final chapter of Part 4, Chapter 15, provides an analysis of innovations in forest harvesting technology. Forest harvesting is an essential component of sustainable forestry to ensure the maintenance of forest productivity. Increasing demand for forest product quantity and quality, shifting forest workforce composition and expectations, and rising environmental concerns are driving changes in current forest harvesting practices. New research and technologies are transforming conventional forest practices in order to improve sustainability. The chapter reviews the use of electric low-emission log trucks, cable assisted timber harvesting, lightweight teleoperated (remote controlled) felling machinery, automation, machine vision and precision technologies. These research areas hold great promise for improving forest worker safety and sustainable management of forest sites and vegetation. The chapter also acknowledges how these forest technologies require substantial development for practical applications, and concludes by discussing how research can further innovate such forest harvesting technologies.

Part 4 Pests, diseases and other hazards

The fourth part of this volume reviews ways of managing insect and fungal pests as well as natural hazards in boreal and temperate forests. The first chapter of Part 4, Chapter 16, focuses on advances in understanding and managing insect pests of forest trees. Boreal and temperate forests comprise half of all forested land globally and are a major source of timber and other ecosystem services. Disturbances caused by native and invasive insects are among the most important mediators of forest mortality. The interacting effects of climate change on insects and trees coupled with increasing arrival rates of invasive insects are creating management challenges and uncertainty. The chapter begins by reviewing information and key issues for predicting climate change effects and for managing native and invasive forest insects that are considered pests in such forests. It also covers observed and predicted responses of forest insects to climate change, genetic variability and tree resistance screening mechanisms for tree breeding programmes, integrated biological control strategies for directly reducing native and invasive forest insect population spread and growth and indirect tactics for maintaining forest stand conditions that reduce susceptibility to insect attack. It concludes by providing five case studies that highlight recent strategies being applied to mitigate forest insect-caused tree mortality.

Chapter 17 discusses advances in understanding and managing fungal and other diseases of forest trees. Forest diseases are caused by pathogens and they affect all parts of the tree, including roots, stems and leaves. Forest diseases result in volume losses and decreases in wood quality, which are considered detrimental in stands managed for timber products; however, in the context of a biodiversity reserve, diseases are important for nutrient cycling and habitat creation as agents of succession. The chapter uses a case-study approach to describe how various forest pathogens affect trees and introduces strategies to reduce damage caused by forest pathogens in managed stands. It introduces parasitic flowering plants, rust pathogens, diseases caused by *Phytophthora* spp., as well as abiotic disease. The chapter discusses the importance of exotic forest pathogens and the damage several of these pathogens have caused to ecosystems following their introduction, establishment, and spread. It concludes by discussing how climate change might change host-pathogen interactions, leading to differences in disease expression.

The final chapter of this section, Chapter 18, focuses on managing and monitoring natural hazards and forest disturbances. These are increasingly critical endeavours as proliferating pests and diseases, changing frequency and intensity of wildfires, windstorms, and invasive species and increases in ungulate herbivory are causing novel responses. The chapter begins by describing the characteristics of natural and anthropogenic disturbances and focuses more specifically on disturbances of boreal and temperate forests, with a particular emphasis on hurricanes as an example of multiple disturbance processes. It also reviews how many forest disturbances will increase in frequency and/or intensity due to climate change. The chapter concludes by highlighting how monitoring forest conditions and detecting changes are necessary to develop early warning systems for predicting disturbances and especially natural disasters.

Part 5 Developing forest products and services

The final Part of the book assesses sustainable ways of developing and diversifying forest products, including novel uses of timber and non-timber products and recreational services, as well as reviewing emerging technologies to develop new forest products. Chapter 19, the first chapter of this concluding section, reviews methods of developing timber products. Timber products can include a wide array of socially valued goods originating from diverse tree species, forest types, and ecosystems. Over the past few decades, forest product market development and timber quality have been characterized by several important factors, many of them international in scope. The chapter reviews the role of solid wood in the emerging bioeconomy and how it is an essential component of the forest product market. It goes on to discuss sustainable timber products in terms of wood product use and carbon sequestration, as well as highlighting new timber-based products and processes. The chapter also emphasises the importance of meeting global demands for wood and bio-based products, and how the customisation of timber-derived products can help to meet consumer needs in an era of globalisation. It concludes by providing a case study of Scandinavian practices in the timber industry and forest sector, as well as providing potential areas for future research.

Chapter 20 provides examples of sustainable production of temperate and boreal non-timber forest products from North America. Understorey plants and fungi are critical to healthy and resilient forest ecosystems, and many of the products they provide are essential to people for sustenance and income. However, nontimber forest products, and the plants and fungi from which they originate, are seldom included in forest management. Most are harvested from natural populations, with potential for negative impacts at multiple ecological scales. The chapter introduces sustainable use of non-timber forest resources and describes methods for assessing product inventory and recovery. It goes on to explain how traditional and local ecological knowledge is important in understanding how people steward the resources and production of non-timber products, with implications for sustainable management. The chapter also provides three detailed case studies of North American edible and medicinal forest species.

The next chapter, Chapter 21, focuses on emerging technologies to develop new forest products. It reviews new processes and applications of wood polymers, notably the use of lignins. The chapter also considers the three major biopolymers: cellulose, hemicelluloses and lignins. The chapter focuses particularly on polymers – especially lignins – as the wood constituents which are the richest carbon sources of all lignocellulosic polymers, as well as the most important aromatic polymers on earth. It also reviews how polyphenols can be obtained from bark, which are compounds with very specialized functions and structures.

The final chapter of the book, Chapter 22, reviews developing forest recreation services. A high percentage of individuals participate in outdoor recreation, and as regions around the world continue to experience population growth there correspondingly will be increased demand for recreation services. Quality in such recreation can be defined as the degree to which recreation opportunities provide the experiences for which they are designed and managed. Therefore, key to protecting the recreation experiences in certain areas is an understanding of the different aspects of the visitor experience and recognizing which of these are important to visitors. The chapter begins by providing a general introduction on recreation and is followed by a section on visitor experience. It then reviews the concept of the recreation opportunity spectrum, as well as recreation site planning and management, visitor use management and monitoring and assessment. The chapter concludes by providing a case study on the development of recreation services on privately owned forestlands in the United States.

Chapter 1

The scope and challenge of sustainable forestry

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1 Introduction

The wild and managed forests of Earth are remarkable for the many ecosystem services they generate, and on which humanity and other forms of life depend. A forest's productive and regenerative potential also makes it the paragon of a renewable natural resource. This potential, if carefully assessed and harnessed, provides the foundation for the conservation of forest values in perpetuity.

Forestry is the management of tree-dominated ecosystems to promote selected values. It is an ancient practice, an applied science and an inherently human-focussed activity. In other words, forest management is ultimately the management of human activities with respect to forests. Forests and the trees that characterize them developed long before the human species came into existence, they have fluxed and waned with changing climates and have recovered or re-organized themselves after numerous natural disturbances. Forests have persisted without us, but we often manipulate them because we have particular expectations of them. It can be argued that our interaction with forests is essentially self-centred, whether that is to harvest natural resources or to protect vistas and species that we deem valuable. In much of the world, 'forestry' is equated with wood production and harvesting, an unnecessarily narrow definition that is contextualized below and elsewhere in this volume.

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Similarly, it must be emphasized that logging is not forestry: mere resource extraction is not management if it isn't conducted within a framework of stewardship and consideration for future values.

Sustainability is the ability of a system or an attribute to persist. In the context of natural resources and environmental services, sustainability implies that resources will not be depleted and that the natural environment will not be degraded. The discipline of scientific forestry was one of the first to devise a formal approach to assure sustainable resource production. Yet the concept of sustainability can be complex and nuanced, especially when it comes to the multiple expectations we place on systems as diverse and important as forests. Some of these alternative perceptions are discussed below, while subsequent chapters more fully explore recent developments and options in support of the goal of managing forests sustainably.

2 The natural resilience of forests

All the tree species found today are the products of millions of years of evolution and adaptation. The assemblies of plants, animals, fungi and microbes associated with those trees – forest ecosystems as we know them – have taken shape over several thousand years. Neither the species nor the ecosystems can be considered permanent, but trees as a growth form and forests as ecosystems are incredibly persistent wherever the climate is suitable. The climatic envelope for temperate forests is loosely defined as being between 3°C and 20°C mean annual temperature and between 550 mm and 3400 mm of mean annual precipitation. Boreal or taiga forests are found where mean annual temperatures range from −6°C to 4°C and mean annual precipitation falls between 350 mm and 1500 mm (Whittaker, 1975, p. 167). Within those zones, as in most tropical moist climates, the land 'wants' to grow trees, as the competitive and selective advantages are so great for plants to position their photosynthetic apparatus above that of competing plants, and this typically requires leaves supported from woody branches and sturdy wooden trunks. Shade-loving plants, cavity-nesting birds and wood-decaying mushroom species tag along on the shirt tails of the dominant life form, with different combinations of species finding their optimum expression under different climates, topographic positions and soils to make up thousands of distinctively different forest types around the world.

Yet forests and the evolutionary sculpting of their component species are not just the products of climatic constraints. Depending on the location, forests can be subject to a wide range of physical disturbances, including volcanic eruptions, landslides, floods, windstorms, fires and heavy snow loads. Biotic pressures can sometimes build to outbreak proportions too, killing many trees and changing the composition and structure of forests over wide areas as a result of insect defoliators, bark beetles, fungal pathogens or high levels of vertebrate herbivores – many of which prey upon particular tree species or genera and are thus more selective than many abiotic disturbances. Collectively, the characteristic combination, frequency, event area, and severity of biotic and abiotic disturbances are described as a forest's natural disturbance regime (Runkle, 1985). Every natural forest type is thus the product of evolutionary (long-term) and ecological (recent) selection for traits jointly tolerant of the climate, the terrain and the natural disturbance regime.

Because of the pervasive role of disturbances – at one scale and frequency or another – in all forests of the world, and the long history of natural selection, forest species are generally adapted to persist after disruptions characteristic of the natural disturbance regime under which they developed. Where fire is a characteristic part of the landscape and part of the evolutionary backdrop, we often see thick-barked tree species (such as *Pinus maritima* in southern Europe, *P. ponderosa* in western North America) that are able to survive all but the most intense fires; other species protect their seeds in serotinous (such as *P. contorta*) or semi-serotinous (as in *Picea mariana*) cones, with the seeds released by high temperatures quickly regenerating a recently burnt forest stand (Johnson, 1992). Insect outbreaks and fungal epidemics typically kill a particular species or size of tree, allowing the survivors to take up the newly available resources and fill the recently vacated space (Flower and Gonzalez-Meler, 2015). Some strategies, such as the ability to resprout vegetatively after the aboveground portion of a plant is killed, constitute a generalist adaptive strategy that can allow an individual plant to recover after fire, herbivory, landslide or flood. Seed dispersal traits, often in the form of winged or plumed seeds for wind dispersal, or in the form of attractive or adhesive fruits for animal dispersal, assure species persistence elsewhere even if they cannot persist in place. The shifting combination of species that dominate a forest site after disturbance is expressed in the phenomenon we recognize as ecological succession (Prach and Walker, 2011). Even where species turnover is limited, forest recovery after natural disturbances usually goes through recognizable stages of stand initiation or regeneration, crown closure and self-thinning, maturity and the development of canopy gaps due to the scattered death of mature trees, and (if allowed sufficient time) a self-maintaining old growth stage in which most trees originate in gaps rather after stand-level disturbance (Oliver and Larson, 1996).

But forests are not infinitely tolerant of or resilient to the disruptions that nature or humankind throws at them. Climate shifts associated with continental drift, mountain building and glaciation have resulted in the displacement of boreal and temperate forests for millennia. With many species persisting in refugia or colonizing from other less-affected forest types, forests have remarkably re-occupied suitable habitat in a few thousand years wherever climate was suitable (Pielou, 2008). When fires are too frequent, forest land may revert to steppe or tundra vegetation (Jasinski and Payette, 2005). Where mammalian browsing pressure and human foraging for wood is too intense, forests can be degraded to scrub or even desert, as has happened at low elevations in much of the Middle East and around the Mediterranean basin (Vogt et al., 2007; Sands, 2013). Forests exposed to any novel disturbance – such as exotic invasive species, acid precipitation or ionizing radiation – will inevitably go through a period of reaction and adjustment in which sensitive species are lost and others gradually take their place according to their tolerance to the new stress as well as the other background environmental factors and disturbance regime.

3 The evolution of a concept

Humankind has been using wood for fuel and to construct homes and boats since time immemorial. History documents many examples of forests being depleted and lost as human populations rise, not only in response to the demand for wood, but as more and more forest land is cleared to support agricultural production (Sands, 2013). People also have depended on forests to provide non-timber forest products, ranging from edible fruits and mushrooms to bark used for tanning leather and habitat for wildlife hunted for food. As empires grew and industrial development progressed, forests have been exploited for navies and war machines, to provide timbers for mine supports, and to provide fuel for industrial processes such as ceramic production, glass making and metal smelting. When human populations have temporarily declined as a result of plagues or wars, forests have typically recovered on their own over one or two centuries. Even without logging or cultivation, however, the grazing and foraging of domestic livestock (goats, cattle, swine) and browsing by wild ungulates have often constrained forest regeneration and recovery (Sands, 2013; Innes, 2017).

Fuelwood and timber shortages often prompted local authorities to issue decrees to curtail tree felling and wood gathering; in Europe, such restrictions are documented as far back as the fourteenth century (Innes, 2017). Efforts to assure future supplies of desired wood products are expressed through a history of tree planting, thinning and coppicing that extends into antiquity. Medieval nobles and monarchs from China to England also established forest reserves that were off limits to the population at large, and were protected (often with brutal consequences) and managed for wild game, for the hunting pleasure of the aristocracy. While these early efforts at forest conservation represent the birth of forest management, they also epitomize some of the tensions in sustainable management that persist to this day. Where access to forest resources is limited, those tensions are twofold: first, that protecting forests for future use or enjoyment sacrifices desired uses or profits today (Maser, 1994) and secondly, that there are conflicts between centralized (governmental or industrial) control and the desire of local populations for customary access to harvest desired levels of wood, wild meat and other forest products (Innes, 2017).

In the face of widespread deforestation and timber shortages, the revolutionary concept of sustained yield timber management evolved in central Europe in the eighteenth century. Forest managers realized that it was not enough to simply curtail timber harvesting and forest conversion in an ad hoc manner, but that consideration of the overall forest extent and its rates of tree growth and regeneration would allow the estimation of a level of timber harvesting that could – in theory – continue in perpetuity. This principle of *Nachhaltigkeit* (as the sustainability principle was originally articulated in German) remains at the core of sustainable forest management around the world today (McDermott et al., 2010; Schmithüsen and Rojas Briales, 2012). Simply put, harvesting is limited and silviculture (the regeneration and manipulation of forest stands) is promoted so that the volume of wood harvested in a given management area over a specified period of time does not exceed the amount of wood grown in the same area over the same time period (Fig. 1). Its objectives can be met at two different scales: either by maintaining the size structure within an uneven-aged stand so that an abundance of seedlings, saplings and pole-size trees is there to replace the harvesting of mature trees; or by maintaining the age structure of even-aged stands across a forest estate

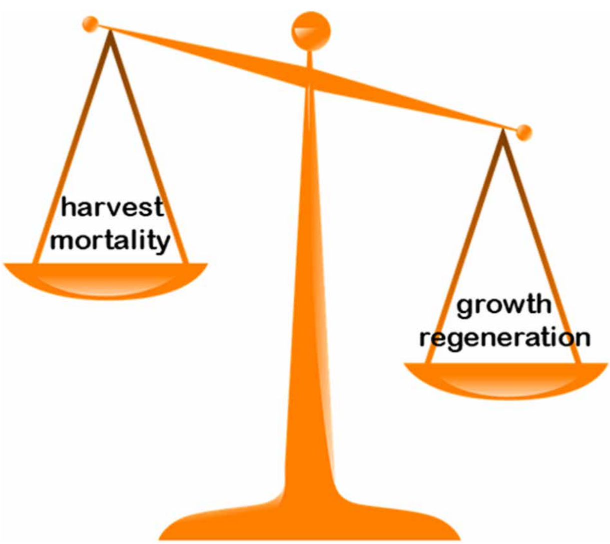

Figure 1 Under sustained yield forestry, timber losses and consumption must be balanced by equivalent (or greater) levels of timber gains through tree growth and regeneration.

as a whole so that younger stands are there to replace the harvesting of mature stands. While these different management approaches have spawned debates over the value of continuous-cover forestry and the use of clearfelling, their appropriate implementation also depends on the size of a forest holding, its management objectives and the silvics (ecophysiological properties) of desired tree species. It can be argued that both approaches merely represent ends of a continuum defined by gap size and forest edge effects, with trees under an uneven-aged management regime harvested in small canopy gaps, and those harvested by clearfelling leaving large gaps in the forest matrix (Coates and Burton, 1997).

Sustained yield forestry was widely adopted on both public and private lands in the northern hemisphere and many European colonies in the nineteenth and twentieth centuries. Often focused on rebuilding timber supplies after wars and other causes of over-cutting, this priority typically resulted in forest transformations from diverse slow-growing native broadleaf species to a few fast-growing (often exotic) conifer species. With its emphasis on fibre production and strict regulation of tree cutting and the need to assure regeneration success, control was not limited to logging, but often included the exclusion of grazing and recreational use, and a general erosion of traditional rights to the commons (Innes, 2017). Expanding acknowledgement of the multiple values of forests and the legitimate rights of various forest users led to the development of 'multiple use' policies in the United States and other temperate jurisdictions in the 1960s. Backlash from rural and Indigenous communities in tropical regions eventually led to the development of a 'community forestry' movement in the 1970s, a concept now adopted in temperate and boreal regions as well, in order to assure better local control over the timber and non-timber benefits of nearby forests (Charnley and Poe, 2007; Gilmour, 2016). The many roles of forests as embraced under the multiple-use and community forest paradigms include the protection of wildlife and fish habitat, the provision of fodder and grazing opportunities, watershed protection and accommodation of recreational activities. In many cases, however, where forest access development and other interventions are undertaken by industrial or government managers intent on commercial wood production, these other roles and values are grudgingly tolerated as constraints, rather than being actively promoted.

The next major steps in the evolution of forestry are associated with a broader societal adoption of the principles of sustainability; indeed, it can be argued that the principle of *Nachhaltigkeit* and sustained yield forestry spawned the concept of sustainability in general (Kuhlman and Farrington, 2010). Following the coining of the term 'sustainable development' by the World Commission on Environment and Development, there is now widespread expectation that interventions in the natural world and investments in human enterprises should '[meet] the needs of the present without compromising the ability of future generations to meet their own needs' (WCED, 1987). Sometimes considered an oxymoron or a politically negotiated compromise (Hauhs and Lange, 2000), the sustainable development mandate nevertheless recognizes the global limits to growth earlier highlighted by the modelling efforts of the Club of Rome (first released in 1972; Meadows and Randers, 2004), and the need for humanity to steward the planet's resources. Sustainable development is often portrayed through the metaphor of a three-legged stool supported equally by pillars of ecological integrity, social acceptability and economic viability (Kidd, 1992). More recent interpretations acknowledge that the economy is a subset of society, both of which are nested within and dependent upon a healthy and productive environment (Fig. 2; Giddings et al., 2002), and that the overriding tension is really between societal consumption and nature's capacity to generate resources (Kuhlman and Farrington, 2010). In the context of forest management, the sustainable development mandate dictates that sustainable forests are not enough, but that sustainable forest communities and sustainable forest enterprises are also necessary ingredients in any recipe for sustainable forestry.

The United Nations Conference on Environment and Development, held in Rio de Janeiro in 1992, resulted in several documents (since endorsed by most nations on Earth) that promoted and advanced concepts of sustainable forestry. Those documents included an overarching set of 27 principles for sustainability (Agenda 21), commitments to save endangered species and their habitats (Convention on Biological Diversity), recognition of the effects of anthropogenic climate change and the potential role of forests in carbon sequestration (Framework Convention on Climate Change) and commitments to combat deforestation and to sustainably manage forest resources under a set of Guiding Principles on Forests (Burton et al., 2003). The promises and aspirations articulated at Rio then spawned several efforts to operationalize sustainability principles into a series of criteria and indicators that could be used to gauge and certify sustainable forest management policies and

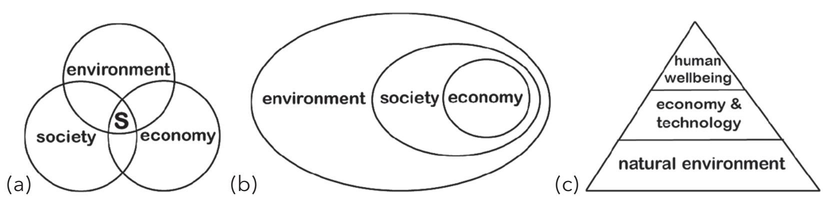

Figure 2 Alternative graphic portrayals of the required components and priorities for sustainable development: (a) the classic Venn diagram that portrays sustainable development, S, at the intersection of ecological integrity, social acceptability and economic viability; (b) an alternative portrayal of economic considerations as a subset of social priorities which in turn depend on a healthy environment; (c) the Costanza et al. (2014) pyramid in which a vigorous economy depends on resources from the natural environment and which is necessary to support social well-being and equity as ultimate goals.

practices. Prompted by consortia of environmental non-governmental organizations, forest products companies and national governments to counteract widespread public protests and boycotts, several certification processes were devised to recognize sustainably produced wood and paper products (Nelson et al., 2003). Those certification criteria, as devised under the Helsinki Process (1993–98) and the Montreal Process (1995–97), endorse the need to maintain productive forests, to protect biodiversity, to protect soil and water, to recognize the contribution of forests to global carbon cycles and to generate socio-economic benefits under appropriate legal and institutional frameworks. These guiding principles now constitute the basis for 'sustainable forest management' (SFM) in many boreal and temperate countries. The SFM paradigm has also been interpreted as extending the sustained yield concept beyond its timber production origins to include all forest values (Adamowicz and Burton, 2003; Higman et al., 2005).

Following the Rio+20 world summit held in 2012, the United Nations adopted 17 Sustainable Development Goals to be implemented from 2015 to 2030. These goals implore all humankind to live within planetary limits, share in a living economy and experience a fair distribution of those benefits (Costanza et al., 2014; see http://www.undp.org/content/undp/en/home/sustainable-development-goals.html). Sustainable Development Goal (SDG) 15, in particular, calls upon all nations to protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, halt and reverse land degradation and halt biodiversity loss (Costanza et al., 2014). Sustainable forestry policies and practices are needed to harvest timber without permanently damaging the world's forests, to guide reforestation and afforestation, and to protect forest-dependent wildlife and other forms of biodiversity. It is clear that forests also have a role to play in providing reliable supplies of clean water for human use (SDG 6) through watershed protection. Biomass production in forests also constitutes one of mechanisms for meeting SDG 7, which calls for affordable, reliable and sustainable energy.

Sustainable forestry arguably is positioned to contribute to all 17 of the UN SDGs. For example, by providing meaningful employment in forest planning, harvesting and renewal, and in processing, transporting and marketing wood products, the forest sector provides decent work and contributes to economic growth (SDG 8). With forestry activities often taking place in dispersed and rural locations which often have no other economic activities, the sector also serves an important role in poverty reduction (SDG 1). The wood harvesting and processing industries are constantly innovating, improving efficiencies and releasing new products based on renewable sources of wood fibre (SDG 9). This contributes to their role as responsible producers (SDG 12), with the use of wood in construction contributing to sustainable cities and communities (SDG 11). Forests are increasingly used as the setting for solace and recreation, contributing to good health and well-being (SDG 3). Forest protection, afforestation and prompt regeneration contribute to carbon sequestration and the slowing of climate change (SDG 13). Sustainable and progressive policies in forestry have the potential to lead the way in other SDGs as well. On the other hand, there can be trade-offs and constraints in the pursuit of all SDGs (Nilsson et al., 2016); forests and forest sector investments often must compete with other land uses (e.g. agriculture) and economic sectors (e.g. industrial development) that also contribute to achieving the SDGs.

4 Multiple interpretations of sustainability

Sustainability may be a near-universally accepted goal of modern society, but its interpretation and assumptions vary with every attempt at application. At its simplest, the problem reverts to a question of what resources or values, in what geographic arena, should be sustained? Even though the time horizon is notionally 'in perpetuity', what period of time constitutes a sufficient window for making projections and assumptions – is a decade enough, or even a century? Because we do not want to 'save 'or 'sustain' everything found in the world around us today (including current levels of degraded habitats, pollution, disease and crime), the choice of priorities and their indicators become a value-laden decision. Interpretations of an ideal sustainable world are shaped by cultural history and experience at individual and community levels (Fien and Tilbury, 2002). An underlying tension between the three legs of the three-legged sustainable development stool can be seen in most claims to sustainability, which often favour one of environmental protection, social justice or economic opportunity over the other legs on which we as a society must depend if the Brundtland vision is to be achieved (WCED, 1987).

Some of the key concepts around which sustainability theory, planning and implementation are built include intergenerational equity, perceptions of wealth or values, and the degree to which different values or resources can be considered substitutable (Adamowicz and Burton, 2003). But it may not be enough to assure a diverse, healthy and productive future for one's descendants – intergenerational equity – if those benefits and opportunities are not equally accessible around the world now and in the future. It can be considered irresponsible and elitist if insufficient attention is paid to the 'social' pillar of sustainability, and as long as poverty and deprivation exist within a community, a nation and around the world. For example, it could be argued that many high-income nations maintain high levels of protected and sustainably managed forests on the backs of timber imports from other countries where forest management is unsustainable (Busa, 2013).

In the long run, decisions implemented in the face of social disparity can foreseeably be expected to fail, for poverty, inequality, injustice and exploitation will inspire the underprivileged to disrespect those decisions and plans. At an international level, these situations lead to further disrespect for conservation initiatives and can result in unregulated migration by the desperately poor. People inevitably differ in their conceptions of what is valuable, and whether wealth is interpreted in terms of monetary returns, biological diversity or breadth of recreational and personal development opportunities. This means that the trade-offs necessary in implementing any one sustainability plan will always be unacceptable to one stakeholder or another, because they do not see their values being sustained at the levels desired. Such challenges, though ultimately global in scope, must be addressed by every forest manager with respect to the land and communities for which s/he is responsible. It remains an ongoing challenge for economies, corporations and forest management plans to fully internalize (i.e. account for and fairly pay for) all the external impacts and considerations in their supply chains.

One of the greatest discrepancies in how to implement sustainability can be interpreted as a debate over where policy should aim along the spectrum from 'weak' to 'strong' sustainability. Strong sustainability denotes an emphasis on the conservation of natural capital, with assumptions that many aspects of that wealth (e.g. rare species, primeval forests) cannot recover or be substituted for once they are lost. Weak sustainability, on the other hand, seeks to conserve the overall capital, including built or human and institutional wealth as well as natural resources, and assumes that development, technology and innovation can substitute (or are a fair trade) for the loss of some natural resources (Turner, 1993; Kuhlman and Farrington, 2010). These options are nicely illustrated in the discipline of sustainable forestry, where a strong sustainability emphasis in parks and protected areas demands that managers limit human activities to the fullest extent possible, whereas the development of an industrial or multiple-use forest perceives value in using the revenue from old-growth harvesting to develop a road network and efficient plantations, with the intent of effectively substituting intensively managed second-growth stands for the less productive but greater-volume old-growth forest. So policy makers and the managers they hire have to be quite clear on the management objectives and priorities for any given holding (Noss, 1993): is it sustainable forests (in the strong sense of all-aged ecosystems and all the biodiversity they support), or simply sustainable wood volume production, or sustainable forest management – a spectrum of values including biodiversity, non-timber products, recreation, a viable timber enterprise and community well-being?

5 Challenges in implementing sustainable forestry

Despite being an enshrined principle of responsible forestry for centuries, and even while the concept is being adopted by other sectors of society, it has been challenging to implement and demonstrate sustainable development in the context of operational forest management. Such challenges are understandable for a number of renewable resources – such as wild fish stocks that are difficult to track and annual agricultural crops that are sensitive to vagaries of a single season's weather – but why should it be difficult to manage forests sustainably, when trees and forests are long-lived, stationary and can be readily counted and measured? (Townsend, 2008, p. 190).

Even if trying to simply achieve sustainable fibre (timber) production, one dimension of the problem is that the key elements of wood supply sustainability depend on estimation. Many key parameters and coefficients inherent to wood supply projections and allowable harvest determinations are fluid: estimates of growing stocks, growth rates and regeneration delays; and losses to pests, fires and storms are all subject to error and uncertainty. Year-to-year variation in weather conditions, seed crops and small mammal populations can affect regeneration success (Savage et al., 1996; Kitajima and Fenner, 2000). Tree growth and mortality rates also vary with weather and weather events, and can depend on conditions of stand structure and inter-tree spacing that may be imperfectly characterized and understood. Timber losses to disturbance events – wildfires, windstorms, mass movements, floods, pest outbreaks – can be particularly difficult to anticipate; planning that depends on historical averages can grossly overestimate or underestimate impacts. With climate becoming more variable and disturbances more frequent under the effects of anthropogenic climate change, traditionally used forest yield models are becoming less reliable (Monserud, 2003).

As if those biophysical challenges weren't enough, socio-economic and technological aspects of wood production present even more intractable challenges to sustainability. Oak woodlands historically nurtured to support shipbuilding lost value when ships were instead made of steel (Innes, 2017). The wisdom of planting or promoting one species or group of tree species over another is subject to the whims of market demand, as well as to the vagaries of species-specific outbreaks of native and invasive insect and fungal pests. Many forests reserved or planted for timber are now seen to have more value for amenity purposes such watershed protection, wildlife habitat and recreation, and so are protected from harvesting; this then requires adjustments to the rate of cut that can be sustained elsewhere in the forest estate. Growing human populations and ballooning real estate values mean that considerable forest land and timber production potential is lost to exurban sprawl and residential development, putting further pressure on the timber lands that remain (Drummond and Loveland, 2010). Globalized trading patterns are often able to offset regional differences in fibre supply and demand, but these are sometimes disrupted by tariffs and other trade barriers reflecting the politics of the day. Forest interventions (i.e. forestry and forest restoration) require financial investments, for which there are always alternatives: capital moves worldwide; land may be more valuable for agriculture or residential development; public funds are often diverted to health, education, infrastructure and defence. As forest products enterprises become increasingly concentrated in large, international corporations, investment capital is also increasingly mobile and fickle. Businesses undertaking sustainable wood production that protects the environment, have broad social support, and are economically viable can still be abandoned when profits aren't high enough.

The greatest challenge in implementing sustainable forestry is probably in achieving agreement on precisely what should be sustained, over what area of land, and with what priority to rank the forest values that inevitably conflict (Aplet et al., 1993; Wiersum, 1995; Oliver, 2003). If diverse stand compositions and multiple canopy layers are desired to support avian biodiversity, for example, this may be compatible with non-motorized recreational activities, but at some cost to maximum conifer wood production. Conversely, productive plantations may offer the best opportunity for rapid carbon sequestration, but may have little value for old-growth-dependent vertebrates and lichens. Sometimes a representative balance of these values can be sustained over a sufficiently large landscape through zoning and explicit resource-emphasis management in different zones. This still begs the question of how much land should be allocated to each resource emphasis (each value), and every such allocation decision is subject to our uncertainty as to 'how much is enough' (Tear et al., 2005). In general, the larger a land base available under a given management plan or policy regime, the better the prospects for sustainability of individual values and for the sustainability of net value to society. But large holdings often result in an unbalanced distribution of activities, so that some sites and some local activities bear the brunt of impacts that are clearly not sustainable at a local scale. For example, a village may face damaged vistas, fuelwood shortages and compromised wildlife habitat after rapid industrial logging in easy-to-reach traditional use areas, even though all those values may be sustainable over the geographic and temporal scope of the entire area being managed.

Forestry and its tradition of sustained yield also come with some undesirable baggage that is difficult to jettison or reform. Many forest management policies call for 'maximum sustained yield' and an 'even flow' of timber to sustain mills and forest-dependent employment and rural communities. Maximized yields demand management as close as possible to the feasibility frontier of decision-making, a frontier that is frequently overstepped when disturbances strike or the investment climate changes. The even-flow requirement may inspire a more conservative level of harvesting and assumptions about production, but ignores the event-driven sensitivity of forest ecology, business decision-making and politics. Sophisticated analysis of forest management systems has sometimes pointed out these vulnerabilities, but the response is often to attempt a greater level of command and control, a philosophy of natural resource management with innumerable failures (Holling and Meffe, 1996) and which inevitably inspires protests and backlash from local citizenry. The ultimate irony is that we see examples of forest practices that are in place to make forests follow the assumptions of the models and systems we use to make management decisions, rather than doing the hard work required to make our models and decision-support systems better match the real world.

6 Boosting the sustainability agenda

6.1 Learning by doing

There are many documented examples of temperate and boreal forests being successfully managed for long periods of time, even in the face of the many challenges outlined above. These include planted European forests that have generated multiple generations of timber with limited evidence of any decline in yields over time (Evans, 1999). The plantation wood production model has been successfully exported around the temperate world, and is found, for example, in pine (*Pinus* spp.) plantations in Australia, Chile, New Zealand, South Africa and the US Southeast, as Douglas fir (*Pseudotsuga menziesii*) plantations in Europe and the US Pacific Northwest, and as Chinese fir (*Cunninghamia lanceolata*) plantations in China. Other native forests subject to extensive management (e.g. in eastern Canada) seem to have recovered naturally after being logged or even cultivated (e.g. in the New England states of the United States) a century or more ago, and are once again delivering commercial quantities of timber. Success at sustainable wood production with shorter regeneration delays and shorter rotations has depended on access to sufficient forest land, soil conservation, the planting of nursery-grown seedlings, tree breeding programmes, the control of unwanted vegetation and forest pests, making the more accelerated or intensive forms of forestry dependent on external factors such as publically funded research, the availability and cost of labour, petroleum fuels, chemicals and so on. As noted above, these dependencies on external inputs and subsidizations may not meet everyone’s criteria for sustainability.

Whether sustainably produced wood and paper products fully meet our modern definitions of sustainable forest management varies on a case-by-case basis. Even mono-specific planted forests provide habitat for some associated plant, animal and fungal species, and provide watershed protection during the bulk of a rotation (Bauhus et al., 2010). Assessments of the status of various sustainability indicators developed in the wake of the Rio Summit and the Montreal and Helsinki Processes are now being performed on individual management plans (or forest estates) and individual forest policies (at corporate, state or national levels), and are reflected in sustainability certificates and progress reports (Chandran and Innes, 2014). The desirability

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