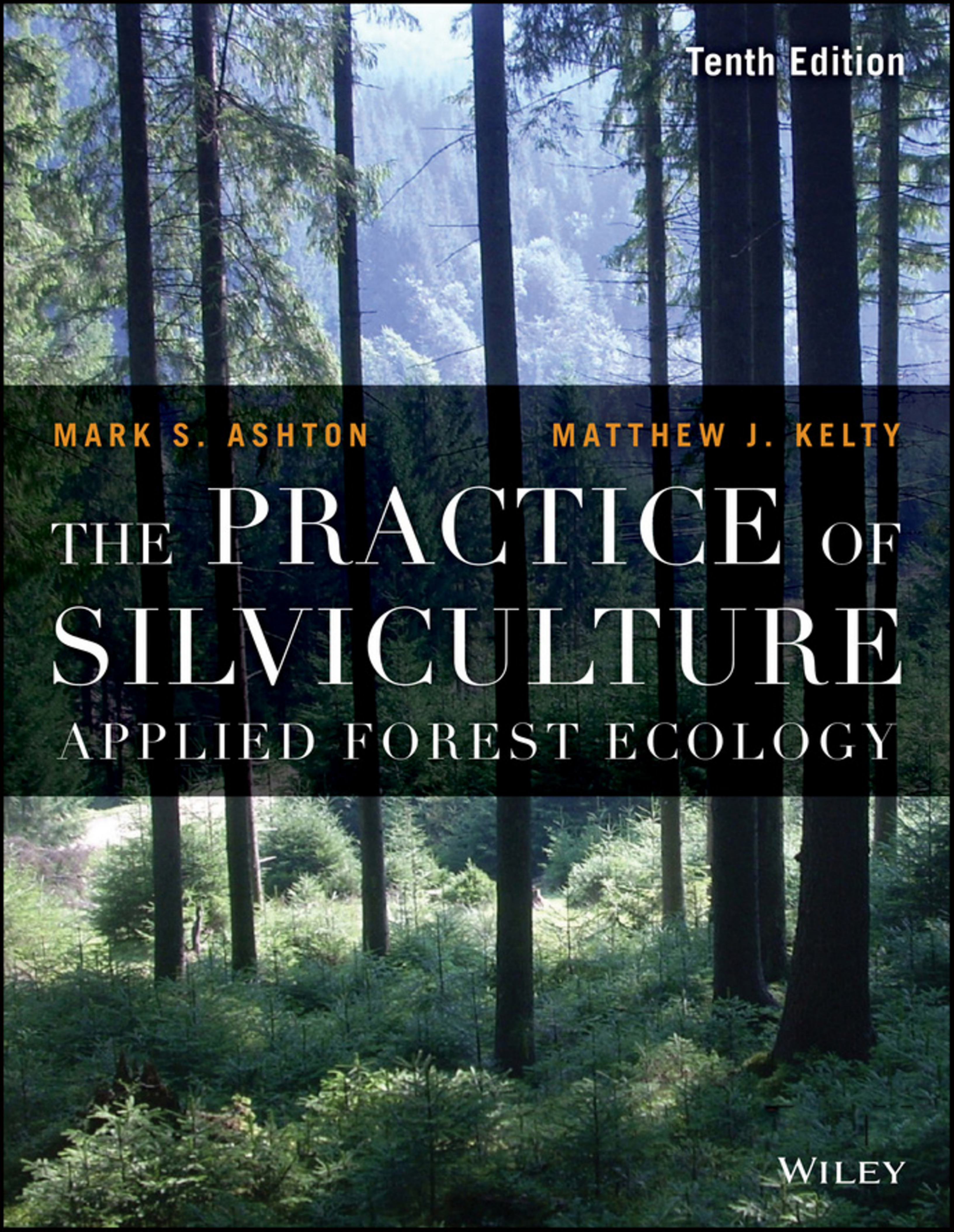


Tenth Edition

MARK S. ASHTON MATTHEW J. KELTY

THE PRACTICE OF SILVICULTURE

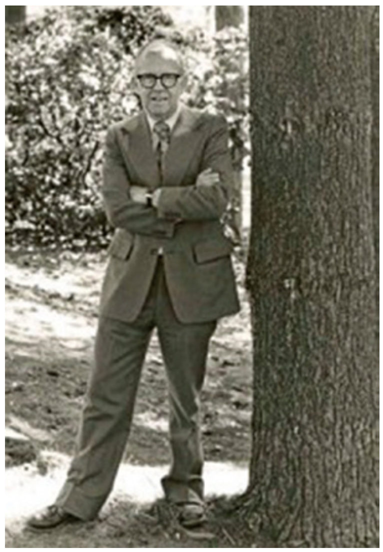
APPLIED FOREST ECOLOGY

WILEY

The Practice of Silviculture

Dedication

DAVID MARTYN SMITH
March 10, 1921–March 7, 2009



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David M. Smith, longtime Professor of Silviculture at Yale University, was our mentor and our friend. We dedicate this 10th edition of *The Practice of Silviculture* to his memory, in thanks for all he gave to us.

Dave was born in Texas and raised in Rhode Island. After graduation from the University of Rhode Island, he served as a meteorologist for the US Army Air Force during World War II. He earned his masters and doctorate degrees from Yale University under the guidance of Professor Harold Lutz. Dave quickly became a faculty member in the School of Forestry and Environmental Studies at Yale. One of his most notable contributions involved helping to found the sub-discipline of silviculture known as *forest stand dynamics*, which uses stand reconstruction to evaluate the past and to project the future of forest growth. During his years at Yale, Dave served as the Director of School Forests and as the Morris K. Jesup Professor of Silviculture. His wit and wisdom are fondly remembered, as are the many lessons taught in the classroom and in the field. Dave educated a legion of professionals who have had a lasting impact on forests throughout the world.

David Smith worked with Ralph C. Hawley as co-author of the 6th edition of this book, and then went on to author the 7th and 8th editions alone. He was lead author on the 9th edition, working with three of his former students. In his field trips and teaching, Dave showed his students how a practical knowledge of botany, ecology, and geology could allow a forester to look at a stand of trees, pick out clues, and make deductions about the forces shaping the forest. His skills in this area led some students to dub him "Sherlock Holmes of the forest." We are ever grateful for his wisdom and guidance.

Mark S. Ashton
Matthew J. Kelty

The Practice of Silviculture

Applied Forest Ecology

Tenth Edition

Mark S. Ashton
Yale University

Matthew J. Kelty
University of Massachusetts Amherst

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Contents

Preface

The late Ralph C. Hawley, one of the pioneers of American forestry, wrote the first edition of this book in 1921. He based it on knowledge imported from Europe and on what he, and a few hundred foresters, had learned by managing the limited tracts of forest on which true long-term forestry was being practiced. At the time, American society regarded forests only as a source of timber, and the book focused on timber production silviculture that would be financially sound in the long run. Professor Hawley went on to revise the book four times. David M. Smith became a co-author on the 6th edition, published in 1956. Emphasis was placed on presenting the scientific basis for silvicultural practice. Professor Smith wrote and edited two more editions as sole author. In the 9th edition, Professor Smith brought on three colleagues, all of whom were his past students: Bruce C. Larson, Matthew J. Kelty, and Mark S. Ashton. His intent was to carry on the tradition of the text in the same manner in which Professor Hawley had worked with him. In the 9th edition, published in 1997, the phrase *Applied Forest Ecology* was added to the title. The basic purpose was to call attention to the fact that foresters should design forests based on sound ecological theory. This applied ecology is concerned with managing the interactions among organisms and their environment, regardless of the degree to which the forests are managed or devoid of human influence.

This 10th edition is a significant revision of the 1997 text. The contents have been completely restructured to further emphasize the ecological basis for silviculture, as well as to expand the relevance of silviculture to a range of forest and tree-related resource management issues. In this edition there are six parts: (1) an introduction and history of silviculture, (2) a summary of the ecological foundations for silvicultural practice, (3) methods of regeneration, both natural and artificial, (4) post-establishment (intermediate) treatments, (5) silvicultural considerations for forest management, and (6) examples of applications for different land ownerships and uses. The previous edition began with intermediate treatments; this book starts with concepts and treatments for regeneration, then progresses to intermediate treatments. The text ends with a new and more elaborate section on applications of silviculture to different resource issues: industry and industrial management, public lands and ecosystem management, restoration and forest health, watershed management, wildlife habitat, agroforestry, urban environments, and climate mitigation.

The 10th edition has been expanded and largely rewritten with clearer language and explanations, updated references, and new photographs, tables, and figures. Boxed inserts have been added to provide greater detail on particular silvicultural treatments or examples of their use. Each chapter strives to provide regional examples for the southern, northeastern and western United States. The glossary contains words and phrases which are highlighted in the text using bold color font. Words in black bold font are for emphasis only.

The book still has a strong North American focus, but contains more examples from across the world to provide a more global perspective of silvicultural use for the North American forester or student. This may be the most expansive book on silviculture yet, and covers a wide range of topics and resource issues that are currently faced by the forester or resource professional. It does not lose its strength in explaining the principles for silvicultural treatments.

Work on this 10th edition began over 10 years ago. The long process has involved many people acknowledged elsewhere in these initial pages. It is hoped that this effort will be well received and appreciated by the forestry community. We thank our families for their patience and the time we have been allowed in preparing this book.

Mark S. Ashton, Morris K. Jesup Chair of Silviculture and Forest Ecology, Yale University
Matthew J. Kelty, Professor Emeritus, University of Massachusetts Amherst

Acknowledgements

There are many individuals who have helped in a variety of ways with this book. We would not have been able to do this book without the fundamental and ever present help of D'Ann Kelty. We would also like to thank our close colleague Bruce Larson at the University of British Columbia, who helped with initial writing of Chapter 24 and provided many helpful suggestions and edits throughout the text as this book was being developed. Each chapter was reviewed by students from Mark Ashton's silviculture class at Yale University, and by many of our colleagues at universities in North America. In particular we would like to acknowledge the silviculture instructors and researchers who reviewed multiple chapters of the book and provided many, many helpful comments. In alphabetical order they are: Heidi Asbjornsen (University of New Hampshire), John Bailey (Oregon State University), Graeme Berlyn (Yale University), Craig Brodersen (Yale University), Wayne Clutterbuck (University of Tennessee), Phil Comeau (University of Alberta), Kristofer Covey (Yale University), Anthony D'Amato (University of Vermont), Tom Dean (Louisiana State University), Mark Ducey (University of New Hampshire), Marlyse Duguid (Yale University), David Ellum (Warren Wilson College), Andrew Ezell (Mississippi State University), Michael Ferrucci (InterForest LLC), Alex Finkral (The Forestland Group), Thomas Fox (Virginia Polytechnic Institute and State University), Brent Frey (Mississippi State University), John Goodburn (University of Montana), John Groninger (Southern Illinois University), James Guildin (US Forest Service), Jefferson Hall (Smithsonian Tropical Research Institution), John Hodges (deceased, formerly of Mississippi State University), Jennifer Hoyle (Yale University), Steven Jack (Jones Ecological Center), Thomas James (Hama Hama Forest Resources), Eric Jokela (University of Florida), Shibu Jose (University of Missouri), Kathleen Kavanagh (Texas A & M), David Kittredge (University of Massachusetts), Karen Kuerrs (University of the South), David Larsen (University of Missouri), Xuhui Lee (Yale University), Victor Lieffers (University of Alberta), Brian Lockhart (US Forest Service), James Long (Utah State University), Doug Maguire (Oregon State University), Florencia Montagnini (Yale University), David Moorehead (University of Georgia), Colleen Murphy-Dunning (Urban Resources Initiative, Yale University), Linda Nagel (Colorado State University), Kevin O'Hara (University of California, Berkeley), Klaus Puettmann (Oregon State University), James Saiers (Yale University), Mike Saunder (Purdue), Oswald Schmitz (Yale University), Robert Seymour (University of Maine), David Skelly (Yale University), Steven Tesch (Oregon State University), Geoff Wang (Clemson University), Kristen Waring (Northern Arizona University), and Eric Zenner (Pennsylvania State University).

A core group of Yale University graduate students reviewed and provided edits on the chapters. They include: Karin Bucht, Vihn Lang, Anthony Mecum, Serena Liam, Nicholas Olson, Frances Sawyer, Kristina Solheim, and Sabrina Szeto. We would like to thank them most sincerely for their efforts. They were very important in making sure the book read well, and was understandable, for the main audience and readership it is intended for. We also thank Julius Pasay for preparing the information for several of the boxes in Chapters 1 and 2.

Finally we would like to thank Yale University and the US Forest Service and many other organizations and individuals who have been credited with photographs and figures within the book.

Part 1

Introduction to Silviculture

A history of silviculture and the philosophical approach taken in this book.

1

The History and Philosophy of Silviculture

Introduction

There are three parts to this chapter that describe silviculture as an evolving sub-discipline of applied ecology and its contribution to the well-being of society. The three parts include: (1) history, (2) philosophy, and (3) the literature and sub-disciplines of research relevant to current resource issues. The first part summarizes the origins and evolution of silviculture as a part of an ancient indigenous agricultural practice used by many peoples for production of food and shelter in combination. Silviculture was originally the forest part of swidden systems where forest patches were cleared for agricultural use for a period of years to provide food, before being left fallow and allowed to grow back to trees, and secondary forest that was harvested for timber, fiber, fruits, and medicinals. With the development of permanent agricultural and pastoral fields, silvicultural systems followed suit and forests and woodlands were managed separately from agriculture. There is then a discussion of silviculture's systematic evolution as a science in response to the degeneration and degradation of forest lands associated with the industrialization of economies in central Europe, then in North America, and subsequently elsewhere. A synopsis of silviculture's roots to reforestation and restoration in Germany, British India, and the United States follows. Finally there is a discussion of silviculture as it is practiced at present.

The second part comprises a discussion of the different philosophical approaches of silviculture. It first describes silviculture as an ecological technology. It shows that silviculture has a relationship with the social sciences and contributes to the management discipline of forests and woodlands. It describes how silviculture should be used as part of a long-term economic view for the betterment and sustainability of social values obtained from trees. It then discusses the variations in the intensity of practice in relation to circumstance. This part of the chapter concludes with a philosophical perspective of how silviculture should be applied to forests.

The third part comprises a synthesis of the silvicultural literature as a body of scientific knowledge. It uses the literature to discuss modern day developments in silvicultural research as a sub-discipline of ecology, and then relates this body of research to today's resource issues.

Silviculture, its Origin and Development as an Applied Ecology

Silviculture is the oldest application of the science of ecology and is a field that was recognized before the term *ecology* was coined (Toumey, 1928). Many of the ways of developing forest stands rest heavily on cuttings that alter or modify the stand environment in order to regulate the growth of remaining vegetation. The reliance on ecological knowledge in silviculture is therefore all the better for not simply resting on philosophical principle. The economic returns from forestry are usually not great enough to protect forests from all the shifts and changes of nature. Therefore, silviculture is usually far more the imitation of the natural processes of forest growth and development, than of completely substituting a new stand for them.

Silviculture as a Preindustrial Construct

Silviculture, as a practice of cultivating and growing vegetation within forests and woodlands, has a much longer history of development and learning over thousands of years than its more recent transformation into a science. The most ancient form of silviculture was, and still is in the more remote forests of the world, a part of what is called **swidden agriculture**. It is a temporary intensive cultivation of a patch of cleared forest for food crops, which is then either abruptly or more slowly relinquished back to forest through succession. It is widely practiced in the more remote forest regions of the world and can be a very sustainable form of agri-silviculture.

Such systems have different lengths of successional development before returning back for cultivation. They are largely dependent upon the soil's inherent capacity to become fertile again. After cultivation of arable crops is stopped, many swidden systems incorporate tree

The Practice of Silviculture: Applied Forest Ecology, Tenth Edition. Mark S. Ashton and Matthew J. Kelty.

plantings and intentional natural regeneration methods that are then followed up with the tending and harvesting of tree crops. Trees that provide fruits, medicinals, and building materials can be harvested with the growth of the new forest into the future until the next cycle of forest clearance and cultivation (Box 1.1). People who practiced swidden agriculture knew exactly where, when, and what tree species to cultivate within a swidden. Many swidden systems can be regarded as very sophisticated, much more so than the credit given them by western science and the modern day practice of agriculture and forestry.

In particular regions of the world, agriculture developed into a permanent practice of cultivation allowing people to settle. These regions can be considered the birth places of modern agriculture and of the origins of civilization (Fig. 1.1). In addition to permanent agriculture came silvicultural practice to produce the goods and services desired from these agricultural systems. Such systems resulted in complex land-use practices with a mixture of intensive to non-intensive treatments reflecting the inherent productivity gradient across a landscape (Box 1.2).

Across most of Europe and the British Isles up to the 18^{th} century, the monarchy, the church, or the nobility held the land rights to hunt and to extract large timbers for shipbuilding and construction. Peasant and tenant

Box 1.1 Examples of preindustrial silviculture.

Swidden Cultivation System of the Yanomami in Brazil

The Yanomami Native Americans are one of the largest tribes in Latin America, straddling the borderlands of northern Brazil and southern Venezuela. The combined Yanomami territories of Brazil, comprising 23.7 million acres (9.6 million ha), and Venezuela, comprising 20.3 million acres (8.2 million ha), form the largest indigenous lands in the world (Chagnon and Gross, 1973). The lands are under threat from goldminers, cattle ranchers, and poor national government enforcement. The Yanomami live in relatively large communal houses called yanos. Men hunt and fish for game, providing about 10% of the food; women farm, providing about 80%. Only about 4 hours of work per day is necessary to maintain their way of life. Villages periodically move within the territory about every 30 years to accommodate the shifting agricultural systems. Large gardens are cleared by the men from primary forest (old-growth) and crops (cassava, sweet potatoes, plantains, beans, corn, squash) are cultivated by the women for only 2–3 years because the soils are so infertile (Fig. 1). New gardens are then created in another patch of primary forest. Old gardens are used for hunting animals that like early successional habitat, harvesting insect grubs feeding upon young growth, and harvesting fruit, medicinals, and vines for cordage and basketry (Nilsson and Fearnside, 2011). It usually takes no longer than 2 hours walk to get to a garden from the village. Several gardens are worked at the same time. In other areas, the Yanomami have old groves of fruit

Box 1.1 Figure 1 An aerial view of swidden cultivation in the Amazon comprising a patchwork of current and abandoned fields. *Source:* R. Butler, 2008. Reproduced with permission from Rhett Butler/mongabay.com.

Box 1.1 (Continued)

trees planted and then protected from years ago. The total number of plant species used by the Yanomami is well over 500 and cater to every necessity of life ranging from toothpicks, to foods, to medicines, to fish poisons. Hunting for different purposes is carefully zoned across the forest for different kinds of game and for hunting at different seasons and even times of day. Other zones are restricted as game preserves. All of this means there is an extensive trail network for the different hunting and gardening practices.

Cultivation Systems of Native Americans in Eastern North American Oak Forests

Indigenous peoples of North America strongly influenced the landscape vegetation of the eastern oak forests of the United States. They did this by cultivating crops. However they also manipulated tree density and species composition to increase mast and game populations, to encourage easy woodland travel, and to reduce pests and diseases. Eastern tribes cultivated maize, beans, squash, and tobacco, often on a large scale, and sited these clearings on fertile soils most suitable for agriculture, usually in large river flood plains. Early explorers reported extensive areas of cultivation. In 1616, Smith remarked that the Massachusetts coast "shewes you all along large cornfields" and "many Iles all planted with corne" (Day, 1953). In New England, cultivation shifted after soil exhaustion and more forest had to be cleared for new fields. This kind of cultivation created a patchwork of successional ages and structures (Cronon, 1983). In addition to intensively managing agricultural fields, Native Americans managed forests to create open savannah woodlands with grassy understories and widely spaced trees. These woodlands were primarily composed of fire-adapted, masting species such as oaks, chestnuts, and hickories. In 1525, Giovanni da Verrazzano traveled 15–18 miles inland from Narragansett Bay, Rhode Island and observed open plains, completely free of trees, extending miles, as well as woodlands that "might well be traversed by an army ever so numerous." (Verrazzano, 1825 in Day, 1953 p. 334). Other early explorers echoed such reports and also noted the large and numerous fires, which were ignited annually or twice a year in the spring and fall. These fire-maintained savannahs had several purposes, chief among them being the provision of food. Frequent fires favored nut-producing hardwoods, such as oaks, particularly the sweet acorn-bearing white oaks, chestnuts, hickories, walnuts, and butternuts, and maintained them in open conditions, maximizing sun exposure and thus mast volumes. Nut collection was also facilitated by the open understory. The growth of fruit-bearing understory plants such as blueberries, raspberries, strawberries, and hazels was also encouraged. Not only did these savannahs feed humans directly but they also supported abundant game populations (Abrams and Nowacki, 2008). Denton (1670) reported "stately Oaks" with "broad-branched-tops" and "grass as high as a man's middle, that serves for no other end except to maintain the Elk and Deer, … then to be burnt every spring to make way for new" forage (Day, 1953). Just as frequent fires increased game populations, they reduced populations of pests such as rodents, ticks, and fleas (Williams, 2005). In fact, the Narragansetts listed the "destroying of vermin" as a reason for burning in their discussions with Roger Williams in 1643 (Day, 1953).

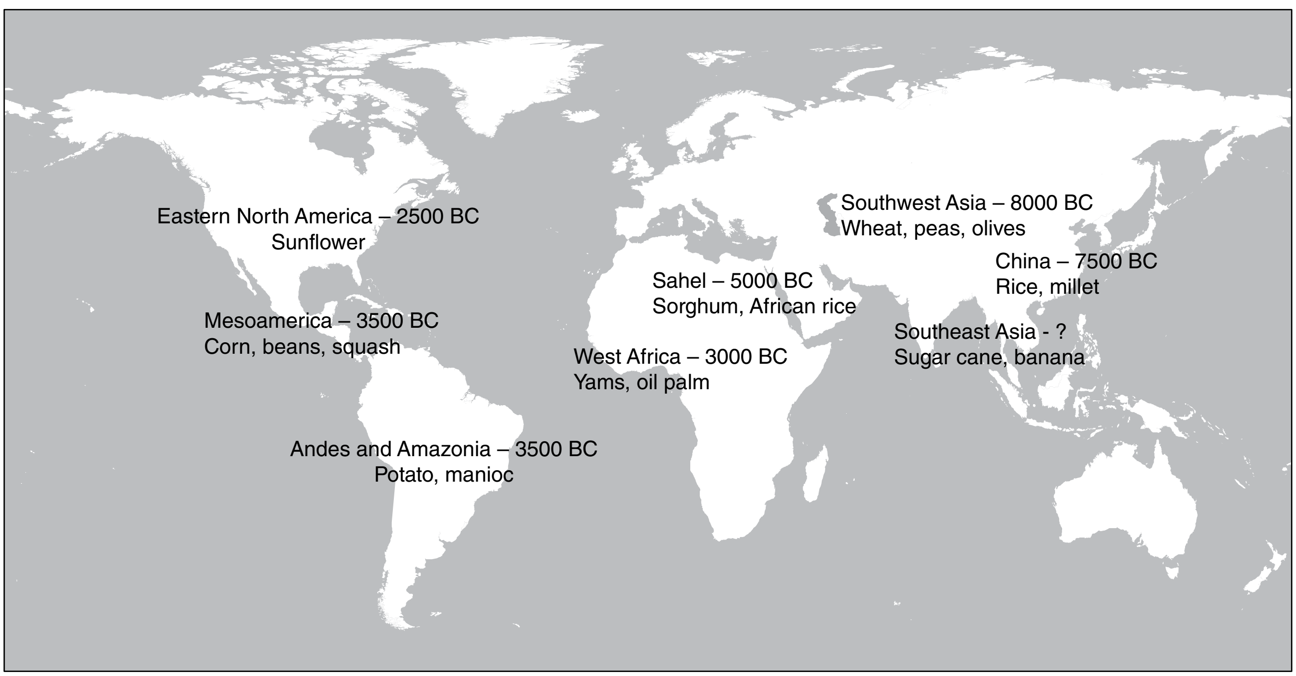


Figure 1.1 Early agricultural civilizations of the world and their main crops. *Source:* Adapted from mapsopensource.com under the terms of the Creative Commons Attribution Licence, CC-BY 3.

Box 1.2 Indigenous silvicultural systems of ancient civilizations.

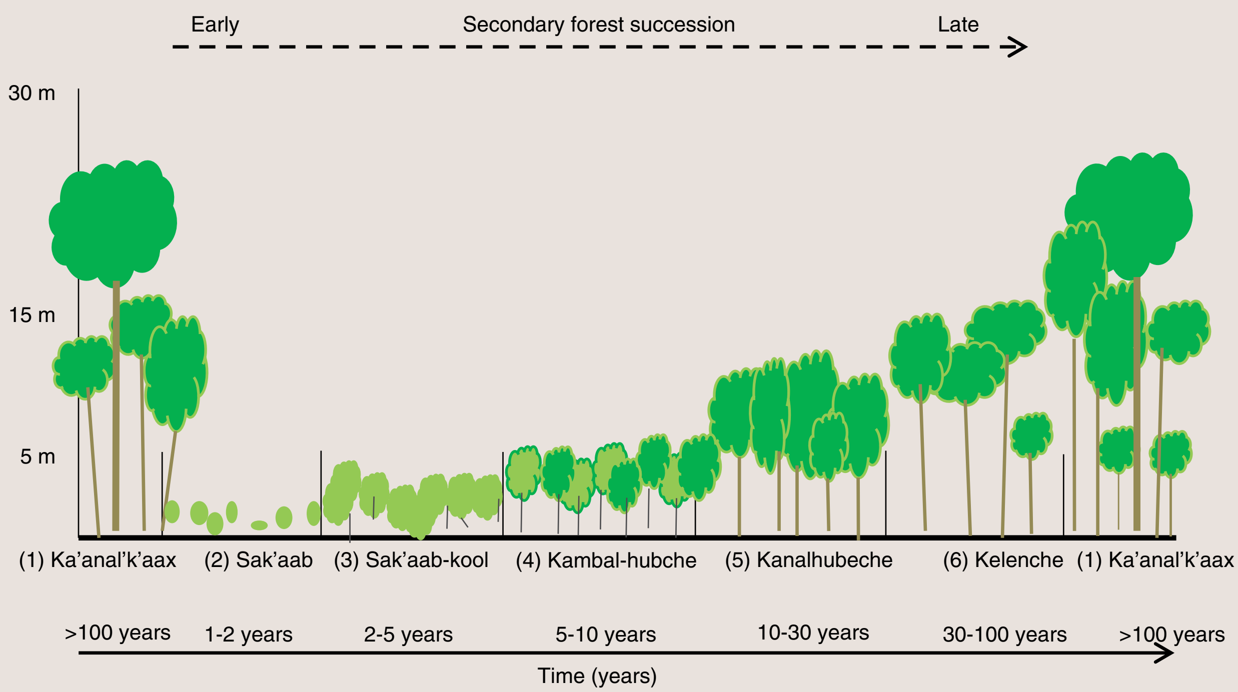
Maya of the Yucatan, Mexico

The Maya civilization of Mesoamerica can be defined by two periods: the pre-classic period (2000 BC – 250 AD) established the first complex cities and the cultivation of staple crops (maize, beans, squash, and chili peppers); and the classic period (250 AD – 1000 AD) which saw the rise of a large number of city states interconnected by trade highways. This period was the zenith of complex agricultural and silvicultural systems. Trees were incorporated into almost all components of an intensively managed landscape. Hydraulic systems were used to both drain and irrigate the staple crops of beans and maize. Swamps were drained and fields raised with trees planted along the bunds and the channels used for aquaculture. Upland slopes were terraced and irrigated for cultivation and shade trees used for stabilization and protection. Further away on poorer upland soils, the milpa swidden system (see Fig. 1) that is still used by the descendants of the Maya was widely practiced to cultivate crops (corn, beans, squash) for a short period of time. In preparation, second-growth pioneer species were slashed at about a meter high to open up the ground to sunlight. Annual crops were dibble planted for several years while the pioneers re-sprouted and were used as shade and fuelwood. Enrichment planting of cacao often follows annual crop cultivation using the shade of the second growth for establishment. Most milpas had an arboreal shelterbelt that was protected around the margin as a conservation strip. Around the households forest gardens cultivated a wide variety of fruit trees (*e.g., Brosimum alicastrum, Chrysophyllum cainto*, *Manilkara zapota*, *Spondias* spp.) and medicinal herbs and spices. These tree gardens were called Pet Kot. In addition, the Maya had sacred forests and groves around temples that were protected and where Maya harvested a variety of medical plants. Over one third of the flora have known medicinal value. The Maya civilization collapsed about 12,000 AD from unknown causes – possibly warfare, disease, or from land degradation and soil erosion or some combination. The second growth that has come back within the region is reflective of this historic land use dramatically enriched in species from purposeful Mayan silviculture.

For more information read: Gomez-Pompa, A. 1987. On Maya silviculture. *Mexican Studies*, 3(1): 1–17.

Sinhala of Northeastern Sri Lanka

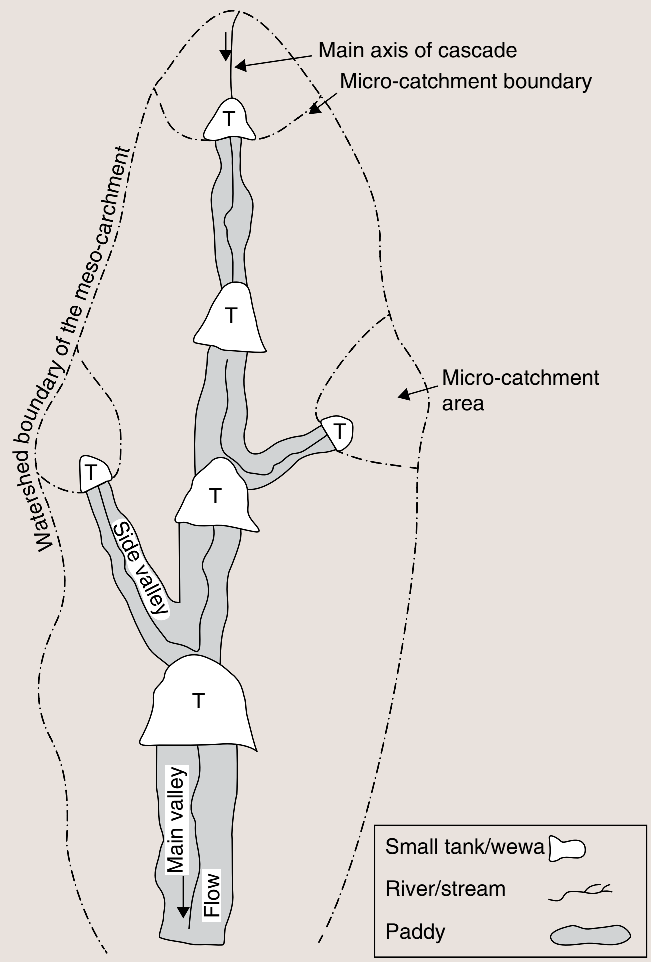
Southern India has a very sophisticated history of forest and crop cultivation dating back to 2000 BC. The start of civilization in northeastern Sri Lanka dates back to about 500 BC with the arrival of the Sinhala people and the Prince of Vijaya from North India. Northeastern Sri Lanka has a monsoonal climate that comprises a long dry season and a



Box 1.2 Figure 1 A diagram depicting Maya swidden succession. Maya succession nomenclature are (1) Ka'anal'k'aax: old tropical forest (30 or more years old); (2) Sak'aab (or Sak'ab): second year milpa; (3) Sak'aab-kool: Recently abandoned milpa; early succession; (4) Kambal-hubche': 5–10 years old succession; (5) Kanalhubche': 10–30 years old succession; (6) Kelenche': 30–100 years old succession; (3-6) Hubche': secondary vegetation. *Source:* Adapted from Gomez-Pompa, 1987.

Box 1.2 (Continued)

shorter wet season. The people learned to manage water by a complex system of reservoirs (called tanks) that were arranged as a cascade that comprised an interconnected series of tanks that reused water for irrigation within a single watershed and that gradually increased in size progressing from the upper to the lower parts of the watershed (Figs. 2, 3). These systems developed over a 2000-year period culminating in about 30,000 tanks in a dry zone area of 15,500 mi^2 (40,000 km^2). The undulating topography with its ancient impermeable metamorphic geology and relatively thin to bedrock soils that were weathered *in situ* make this landscape perfect for water capture and irrigation. The Tank Cascade System allowed two to three crops of rice to be cultivated per year in the lower lying land beneath each tank by a system of irrigation channels and fields. Some of the lower lying fields were purposely left for the birds to draw them away from those that were cultivated. The tanks themselves were lined with riparian forests and vegetation that served to protect the sides of the tank and to serve as a wind barrier. Potable drinking water was purified through a system of channels drawn from the tank separate from the irrigation systems. These channels flowed into small wetlands in which the water was cleansed of sediments and pollutants. The villages and houses were organized immediately outside but adjacent to the floodplain. Individual households had kitchen gardens and patios surrounding the house where many of the perennial light-loving shrubs (banana, plantains, citrus) and herbs (curry plant, cumin, cardamom) could be cultivated. Surrounding the kitchen garden, tree gardens of a variety of shade-loving long-lived species (mango, coconut, jak fruit, tamarind, areca palm) were grown for fruit and timber. Upstream and at higher elevations of the catchment areas beyond the tree gardens, second-growth forests were managed through swidden cultivation (called Chena) for upland dry crops, firewood, and medicinals. Beyond these second-growth forests, in the most remote and highest parts of each watershed catchment, existed relatively undisturbed forests whose main purpose was to yield subsurface water flow into the dry season through deep infiltration. These areas were carefully controlled by the community and by the temple monks. Many of these forests were regarded as sacred and completely protected from use.



Box 1.2 Figure 2 An example of a tank cascade for a single watershed in northeast Sri Lanka. *Source:* Geekiyanage, 2013. Reproduced with permission of Elsevier.

(*Continued*)

Box 1.2 (Continued)

Box 1.2 Figure 3 The ancient managed landscape of northeastern Sri Lanka. The tank cascade systems can be seen in the distance. Adjacent and downstream areas to the tanks are the cleared lands for paddy cultivation. The settlements with complex tree gardens are adjacent to the tanks on the upper ends along the margin in the middle of the picture. On higher ground is sacred forest associated with the temple that serves as watershed protection. *Source:* Mark S. Ashton.

farmers had grazing rights for livestock, rights to gather fuelwood and litter, and rights to some timber for building, but they were obliged to pay a fee for these rights. Similar land right arrangements between nobility and the peasants were present in northeast Asia (China, Korea, and Japan) during this time. Particularly innovative and forward-thinking nobles started the systematic and purposeful management of forests for timber on such lands as early as the 14th century in Germany (Nurenburg) and by the 16th century in Japan. Forests were divided into sections, with the ideas of sequentially harvesting for timber over time and purposeful regeneration. In the 17th century, the ideas of John Evelyn and Jean-Baptiste Colbert led to the first plantations in the British Isles and France respectively. Each of these men were sent by their respective governments to assess the depleted state of the forests in their countries.

Prior to the industrial revolution, one predominant form of silviculture and forest type was associated with permanent agriculture. These were coppice or sprout origin forests. Still throughout much of Africa, Asia, and Central America, forests and woodlands are all managed based on sprout growth to produce fuelwood for cooking and heating, litter and mulch for agricultural fields, timbers for buildings, artisanal wickerwork and poles and posts for farm infrastructure (Box 1.3). It is amazing that in this modern age of technology, the majority of the world's population still relies on fuelwood for energy and forest leaf litter as a source of soil fertilizer.

Silviculture as a Western Construct

It was with the birth of the industrial revolution, particularly in central Europe, that forest lands were decimated for timbers to support underground mining for coal, iron ore, and salt, and for fuelwood. This was to create charcoal to power the furnaces for the smelting of iron ore, evaporating water to extract salt, and to provide heat and cooking fuel for a burgeoning and urbanizing populace that had come for work in the cities. Whole areas of central Europe were converted from subsistence agricultural and coppice woodland systems to waste-

Box 1.3 A coppice and wood pasture system in medieval Europe.

Ancient wood pastures, often identified today by the presence of old pollarded “veteran” trees or land records, were common throughout Europe since at least the Neolithic Age. In England, documentation dates back 1200 years (Rackham, 1996). While the practice was largely abandoned several centuries ago, wood pastures do persist. While most were converted to other land uses, some have “infilled” with younger cohorts of trees and are now barely discernible, while others are preserved as living museums, and fewer still are actively managed as wood pasture.

A rich literature has accumulated, particularly in the British Isles, on the social and ecological history of these wood pastures (Fig. 1) and their role in a complex landscape of commons, forests, parks, and woodlands. The grazing of animals and growing of trees on the same land has been sustainably practiced for centuries (Rackham, 1998). The nuances of these pasture systems vary by region and make use of different species and techniques to meet location specific needs. Two broad categories of wood pastures can be distinguished: (1) coppice meadows and (2) pollard meadows (Hæggström, 1998). Coppice meadows are comprised of multi-stemmed trees that are cut at intervals of some decades to produce stakes, poles, firewood, and wood for carpentry. Hay is produced between the coppice trees. Livestock are often excluded from these meadows at least for a period of several years to give recently cut trees time to grow above the browse line. Pollard meadows are used to produce fodder from tree cuttings while livestock are allowed to graze between the trees. These trees are cut at 3–5 ft (1–1.5 m) to keep them safe from browse. Cuttings are often dried and stored as winter fodder or used directly. Shredding is an alternative pollarding technique where only the lateral branches are cut and the top of the tree left intact. Differences in pollarding technique arise from variations in species autecology and climate.

A case study by Bargioni and Sulli (1998) on the Valdagno farm on the eastern slopes of the Lessini Mountains, Italy provides an illustrative example of pollard meadow management. The local climate exhibits long, cold winters with short, hot summers and an annual precipitation of 58 in (1489 mm). The farm breeds cows and at any given time has 4–5 milking cows, 2–3 sheep, 25–30 chickens, and one pig. The 10–12 acres (4–5 ha) is 47% grassland, 29% wooded pasture, and 10% coppice woods with the remaining 14% split between high forest and farm infrastructure. The Valdagno farm faces constraints on its productivity. The 4–5-ha farm encompasses only 2 tillable hectares, which significantly constrains total productivity. To help overcome this limitation, vertical space is cunningly utilized to expand animal husbandry.

Between May and October, cows are grazed in the wooded pastures and excluded from the winter hay-producing meadows except for the time following the second mowing. The animals are sustained through the long winters with a mixture of meadow hay and tree fodder. Two kinds of fodder

Box 1.3 Figure 1 An ancient sweet chestnut (*Catanea sativa*) wood pasture in Monmouthshire, Wales. *Source:* A. Miles, 2012. Reproduced with permission from A. Miles.

(*Continued*)

Box 1.3 (Continued)

are produced on the farm. *Broco* is produced by shredding leaves directly from the tree for immediate use, while *frascari*, faggots of branches and leaves, are collected and preserved for winter nourishment. Ash (*Fraxinus* sp.) is the most important species for fodder production, while alder (*Alnus* sp.), poplar (*Populus* sp.), and hazel (*Corylus* sp.) are commonly used to produce *broco*. Beech (*Fagus* sp.) is a common spring fodder as its shoots appear before grass emerges from under the forest cover.

Pollarding commences when trees are between 7 and 12 in (18–30 cm) in diameter and are 7–8 years old. At this time, the leader is cut causing the stem to bifurcate and all branches along the stem are cut at 6–8 in (15–20 cm) from the main stem leaving stubs. These stumps will produce the *frascari* and can be used as ladder rungs for the farmer to climb the tree in the future. Each year, *broco* is produced from the top crown while every third year the stems, which are 1.5 m long at this point, are cut to produce *frascari* bundles in late August. Trees are cut and replaced when their tops stop producing leaves, usually at a diameter of 10–12 in (25–30 cm). These pollarding techniques have enabled the Valdagno farm to take advantage of vertical space and sustain itself despite a shortage of tillable land.

lands in order to supply the wood necessary for this development. As a result in the state of Hesse, Germany, George Ludwig Hartig envisioned the first school of forestry for reforestation in 1787. Later, Heinrich Cotta, who has been attributed the name "pioneer of forestry", started a forestry school in 1811, in the town of Tharandt, near Dresden, Saxony. His school and his teaching became the foundation for German forestry and its later influence around the world. The notion of teaching forestry and the idea of forestry schools spread in the late 18th century to Russia, Austria, Sweden and France. Spain opened its first Forest Engineering School in 1844 in Madrid, and the British government commissioned Sir Dietch Brandis, a student of Cotta, to start the Indian Forest Service and a School of Forestry at Dehra Dun (Box 1.4).

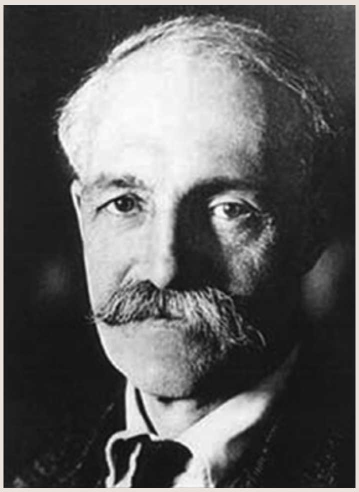
Box 1.4 The development of the Indian Forest Service and Sir Dietrich Brandis.

Sir Dietrich Brandis was born in Germany where he studied botany at Copenhagen, Göttingen, Nancy, and Bonn (Fig. 1). At the behest of Lord Dalhousie, Governor of British India, he was asked to take on supervision of the famous native teak forests of Burma in 1856 (Milward, 1947, Underwood, 2013). He developed the "taungya system" whereby villagers were allowed to cultivate vegetables in between planted trees and in return they weeded and protected the new plantings (Fisher, 1910). This has now been repeated worldwide and is an agroforestry practice that can involve communities in tree planting. In 1864 he became the first Inspector General of the Indian Forest Service. He founded the Imperial Forest School at Dehra Dun in 1878 to formally educate the local peoples in scientific forestry (Fisher, 1904). He wrote a treatise on Forestry in British India and the book "Indian Trees" and documented and described sacred groves throughout India. He was among the first to acknowledge the relationship between forest protection and involving local peoples. For his service to the British Empire he was knighted and retired back to Germany where he met future German foresters as well as Gifford Pinchot and Henry Graves. Pinchot relied on Brandis for advice in setting up the nascent US Forest Service. He died at the age of 83 in 1907. The model for modern forest management in the United States, Britain, and Australia lies in the practices of the Indian Forest Service (IFS) that Brandis started (Pyne, 1997; Oosthoek, 2007).

Box 1.4 Figure 1 Sir Dietrich Brandis. *Source:* Forest Research Institute, Dehra Dun, India.

Box 1.5 A brief biography of Gifford Pinchot.

Gifford Pinchot was born in 1865 and grew up in Simsbury, Connecticut (Fig. 1). He attended Yale College. After graduating from Yale he studied forestry at the French National School of Forestry in Nancy. Upon his return in 1892 he was hired by George Vanderbilt, a wealthy railroad tycoon, to manage the Biltmore Forest Estate outside of Asheville, North Carolina. This was under the suggestion of the renowned landscape designer, Frederick Law Olmstead (Miller, 2001). He was succeeded by Carl A. Schenk, a German forester, who set up the first School of Forestry at Biltmore in 1898, a few weeks prior to when Bernard Fernow, another German forester, started the New York State College of Forestry at Cornell University. Gifford continued on to succeed Fernow as the Chief of the Division of Forestry that same year, 1898. In 1900 he and his father, James, endowed Yale to create and start the first postgraduate program in forestry at what was then called the Yale Forest School and is now the Yale School of Forestry and Environmental Studies (Miller, 2001). He seconded two US forestry division personnel to be its first Dean, Henry Graves, and faculty member, James W. Toumey. Toumey went on to become a founding member of the Ecological Society of America and wrote the first forest ecology text for the country (Pinchot, 1998). In 1905, Pinchot became the first Chief of the newly made US Forest Service at the behest of then President Theodore Roosevelt. Pinchot is largely responsible for developing the administrative foundation of the Forest Service and the creation of the National Forest System which now comprises the majority of public lands in the US (Meyer, 1997; Miller, 2001). After leaving the Forest Service he went on to become a two-time governor for the state of Pennsylvania. He died in 1946.



Box 1.5 Figure 1 Gifford Pinchot. *Source:* US Forest Service.

By the end of the 19^{th} century the newfound profession of forestry was ripe for development in North America. Gifford Pinchot (Box 1.5) had gained his forestry training in Germany and France. Several German foresters, upon invitation, had emigrated to the USA to introduce forestry. Two such German foresters, Carl Schenck and Bernard Fernow, respectively, started the Biltmore Forest School in Asheville North Carolina, and the New York State College of Forestry at Cornell University in 1898.

Silviculture as a Current Practice

Current silviculture is a much more complex and varied practice than at any stage in its development history. In the more remote forests of tropical Africa and the Amazon, people still practice the silviculture associated with swidden systems. In many populated rural regions of the tropics, coppice systems, once widespread in Europe and northeast Asia, still predominate. Much of the developed world now has intensive plantation systems for wood production, and considerable second-growth forest on more marginal sites that have returned after agricultural abandonment. These forests are managed for multiple benefits often using complex natural regeneration methods.

Silviculture and its association with long-term investment for future products and services desired by the landowner and by society must have social stability. This means that stability and clear recognitions of land tenure, environmental laws, and strong and diverse markets must exist; only under these conditions can silviculture flourish. Without this security it is unlikely to be practiced with any surety or investment of purpose because of a reluctance to invest in the forest for the future (see Fig. 1.2). The most sophisticated silvicultural practices are at both ends of the development continuum. On the least developed end, people can practice silviculture where their land tenures and ways of life, though not necessarily officially codified, have been untouched by the process of development. On the most developed end of the continuum, silviculture can be practiced where economies have developed to create strong values for both services and products from the forest, with healthy and diverse markets, strong enforceable regulations in land use, and formal rights to land tenure. The most difficult place along the development continuum is in the middle, where countries or regions are experiencing social transition like colonization, economic development, poverty alleviation, and political democratization. In these cases, silviculture can be practiced but with a

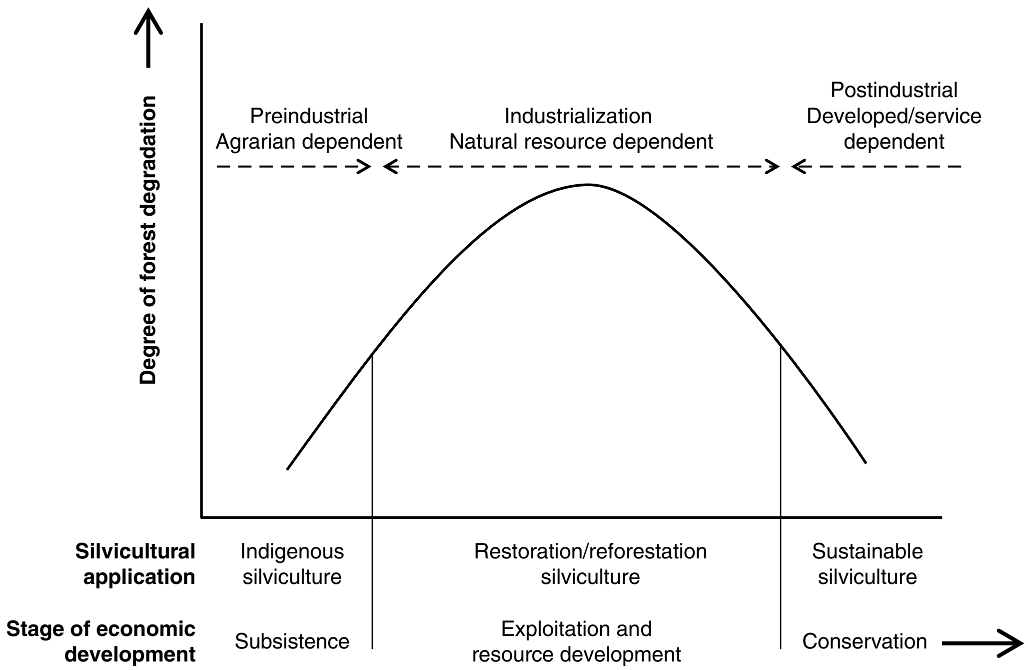


Figure 1.2 Economic and social development process leading to a developed economy and the forms of silviculture practiced. *Source:* Adapted from Panayotou and Ashton, 1992.

tendency toward risk-averse investment in time and labor and with a focus on the short term.

The Philosophies of Silviculture as a Practice

Ecological Technology

The necessity that nature should be understood and emulated does not mean that silviculture should slavishly follow either the reality of natural processes or abstract theories about them. Most forests live longer than people. It is difficult to recognize that the natural disturbances that renew forests, often after intervals of centuries, are usually big, such as fires, windstorms, and insect outbreaks (Oliver, 1981; Kimmins, 1987; Oliver and Larson, 1996). Some forests are slowly and continuously renewed by minor disturbances, but these are far from being the norm. The various patterns in the development of forest vegetation over time and after disturbance are discussed in Chapter 4 on stand dynamics.

The web of life is so complicated that it is easy to argue that humans should do nothing to the forest for fear of doing something wrong. However, because of the exploitation of so much of the world's natural resources, humans must develop solutions to counteract the destruction of these natural resources. Tightly controlled **forest research experiments** are the standard for creating new knowledge in the forestry field, but they are also very expensive. Thus, society requires practitioners of forest science to act without full knowledge. The best that can be done is to proceed by **adaptive management**, in which action can be taken on the most complete knowledge available. This approach has become quite useful. The three steps include:

1) **test assumptions:** use the current knowledge regarding the specific site; determine and collect monitoring data to determine if the assumptions are correct;
2) **adaptation:** change assumptions if new information has been found from the monitoring and project experience;
3) **documentation:** describe the planning and implementation for the specific site, and maintain records of the results.

Silviculture is conducted on the basis of ecological principles. The goods and benefits that flow from forests with proper, long-term management depend on living processes and are thus renewable to the extent that basic productive site factors are maintained and they can even be increased if these factors are permanently improved.

The wood produced by forests is the most important structural substance in human use. Unlike mineral or agricultural materials, its production requires much less energy and does little that would damage or pollute. In fact, the growing of wood increases the stock of resources even as it cleans both air and water. If forest vegetation were more efficient in yielding human food and in concentrating sources of fuel, the future of the world ecosystem would be much brighter for the human race. It is therefore ecologically ignorant to assume that "saving forests" by substituting wood with substances produced with fossil fuel from mineral resources benefits any human-dominated ecosystem.

Economic and other social factors also affect the silvicultural policy of any given area. The simple objective is to operate so that the value of benefits derived from a forest should exceed the value of efforts expended. The most profitable forest type is not necessarily the one with the greatest potential growth or the one that can be used or harvested at the lowest cost. One must also consider the silvicultural costs of growing the crop or maintaining the stand and the prospective losses to insects and disease. In fact, it is usually the insects, fungi, and atmospheric agencies that ultimately show where silvicultural choices have run afoul of the laws of nature. The majority of the best choices are imitations of those natural communities.

It is also not entirely safe to accept the success of modern agriculture as justification for highly artificial kinds of silviculture. The environment of a cultivated field is much more thoroughly modified and readily controlled than that of a forest stand. Furthermore, forest crops must survive winter and summer over a long period of years, whereas most agricultural crops need survive only through a single growing season. One disastrous year harms the production of just one annual crop, but it can destroy the accumulated production of many years in a stand of trees. Neither economic nor ecological principles permit the forester to engage in the wholesale, routine use of pesticides and fertilizer on which intensive agriculture often rests. Any silvicultural application of refinements borrowed from agriculture must be combined with all the kinds of measures appropriate to the intensity of agriculture imitated. Forestry can profitably borrow much more than it ever has from the science on which modern agriculture is based, but there is little place for uncritical imitation. In addition, silviculture, even in the most intensively managed systems, needs to balance other multiple values that a forest must provide to society (clean drinking water, biodiversity conservation, recreation). Intensive agricultural systems often over-ride or ignore these values.

Some silvicultural measures depart drastically from natural precedent. These usually involve the introduction of exotic species or the creation of communities of native species unlike anything that might come into existence naturally. Departures of this sort cannot be thoughtlessly condemned but should be viewed with reservations until they have been tested over long periods. Otherwise, most of the choices can be thought of in terms of the degree to which natural processes are accepted or arrested, pursued or reversed.

Relationship with Forest Management and the Social Sciences

The decisions made in silvicultural practice are based as much on economic constraints and social objectives as on the natural factors that govern the forest. Recognition of societal objectives and limitations in any given case reduces the silvicultural alternatives that need be considered. Even though intelligent application of silviculture can make a very positive contribution to the management of forests, it is ultimately guided by strategies for solving problems associated with the social sciences. Matters that involve social and economic considerations are more broadly dealt within the interdisciplinary field of forest management. Forest management is concerned with planning, stakeholder analysis, economic analysis, conflict mediation, harvest scheduling, and the administrative aspects of the whole forest area (Davis and Johnson, 1987; Davis *et al*., 2005; Bettinger *et al*., 2009). The field of forest policy deals more indirectly with the effects of sociological and political phenomena, as well as economics, on the uses and governance of forests.

Silviculture and forest management are therefore interdependent, and not parallel approaches to the same problem. Because of its dominant concern for efficient application of the natural sciences, silviculture is as "practical" as forest management, with its tendency toward preoccupation with economic considerations. No management plan is better than the silviculture it stipulates, nor is any silvicultural treatment better than the usefulness of the results it produces for management.

Silviculture and the Long-Term Economic Viewpoint

It is said that money does not grow on trees, but it is the bane of forestry that the popular view is that trees exist but do not grow. The short-term outlook of conventional economic theory holds, in effect, that the silviculturist cannot win in growing a forest to reap the long-term benefits while certain naturalistic ecological theories warn against trying. The economic timescale of forestry is so vast and unique that to many investors it really is not profitable.

There is scarcely any part of forestry in which this issue must be faced more squarely than in silviculture, especially when investments in establishing or treating young stands are considered. It takes a certain kind of ambivalence to keep the economics of forestry in perspective. The decision to practice forestry is usually a matter of ethics, politics, and social concern for posterity. It is usually not one of conventional economics unless the product grown is highly valued and grown like an agricultural crop, which in reality is refined to a narrow set of sites and circumstances. In general it is the failure of economics and society to properly value the multiple service values that forests provide that is the most detrimental to the sustainability and financial integrity of forest management in the long run. However, once the decision is made, it becomes logical to apply economic analysis to determine how best to execute the details. Any conflict is not between "silviculture" and "economics" but between the long-term economic viewpoint of forestry itself and customary short-term outlooks on financial matters. In the long run, short-sighted silviculture and poor environmental management become unprofitable. A forester should be extremely cautious of allowing economics to over-ride silvicultural principles that relate to the constraints of site and ecology. It will usually mean a much larger unrecognized financial disaster for the future with the depletion of the soil and forest resource and little ability to restore this resource for the benefit of society.

The holding of land for future production of wood, non-timber forest products, or other service benefits involves silviculture, even if nothing more is done than to let nature take its course and to harvest trees occasionally. Ownership incurs costs, and these constitute investments in the future even if nothing is invested in treatments to increase future production.

Foresters must ensure that money is spent very efficiently because funds are rarely sufficient for all the silvicultural work likely to be worthwhile. In any situation, it is logical to first apply those treatments that will yield the greatest increase in value of benefits per dollar of investment.

The first stage in the evolution of silvicultural practice is where continued production is actively sought but without any monetary investment (Barnes *et al.*, 1998). This "no-investment" silviculture places emphasis on treatments that can be accomplished by removing merchantable timber without significantly increasing harvesting costs. The removals cannot exceed the productive growth capacity of the forest. Some forests are sufficiently easy to control and give reasonably good results. This kind of silviculture is practiced over wide areas of temperate and boreal native forests and will likely continue for a long time. The idea of taking values out of the forest without really reinvesting anything in future production has a powerful appeal. It almost completely dominated American silviculture for many decades. There are still many instances in which it is consciously or unconsciously regarded as the only economical alternative. Tropical forest has been managed in this way under so-called selective logging but the harvest of timber has generally exceeded the productive growth capacity of the forest, leading eventually to a depletion of standing timber value and land conversion to agriculture.

Orderly policies of long-term investment in silviculture emerge if economic conditions and natural productivity are favorable, and provided that adequate management experience has developed within the country or region. The kind and amount of investment are limited only by the economic law of diminishing returns. The actual amount expended on this type of silviculture varies widely but can be considerable. Currently, growing and cultivating forests in the developed world, such as in the US, are considered attractive, long-term investments that can provide multiple economic values. The "free" wood of cutting old growth is no longer considered acceptable. Old growth is better preserved for its intrinsic value and for the multiple service benefits that it provides to society.

Variations in Intensity of Practice

The amount of effort expended on the treatment and care of stands – that is, the intensity of silviculture – varies widely, depending chiefly on economic circumstances. The converse of **intensive silviculture** is **extensive silviculture**. The degree of intensity is usually estimated in terms of such things as the amount of money invested in cultural treatment, the frequency and severity of cuttings during the rotation, and the amount of monetary returns accorded to future returns relative to immediate returns. This leads to a debate on how forests should be managed. Some argue that intensive management only for timber on the appropriate sites will conserve most other forests as reserves (Binkley, 1997; Sedjo and Botkin, 1997). Others argue for a more extensive management regime in which timber is a more intimate component of other social and product values (Panayotou and Ashton, 1992; Oliver, 1999).

In reality the appropriate intensity of silviculture varies with accessibility, markets, site quality, management objective, and nature of ownership. The proper level often must be chosen specifically for each stand because the application of a single treatment intensity will not give optimum results throughout a given forest, unless it is exceedingly small and uniform. The more favorable the combined economic effect of all factors, the higher the appropriate level of intensity of silviculture. The place for extensive silviculture is found in remote areas on poor sites, or where owners are not willing or able to make more than minimum investments. It often plays a role where timber production is secondary to other purposes of forest management. Much of the world's forests are now to be managed in this way since all of the best land has now been largely converted to permanent agriculture (Fig. 1.3; Table 1.1).

In the past, American forests have been exploited in such a manner that the poorest and most ill-treated stands are often found on the best sites and in the most accessible areas, such as those along permanent roads. This situation arises because the best and

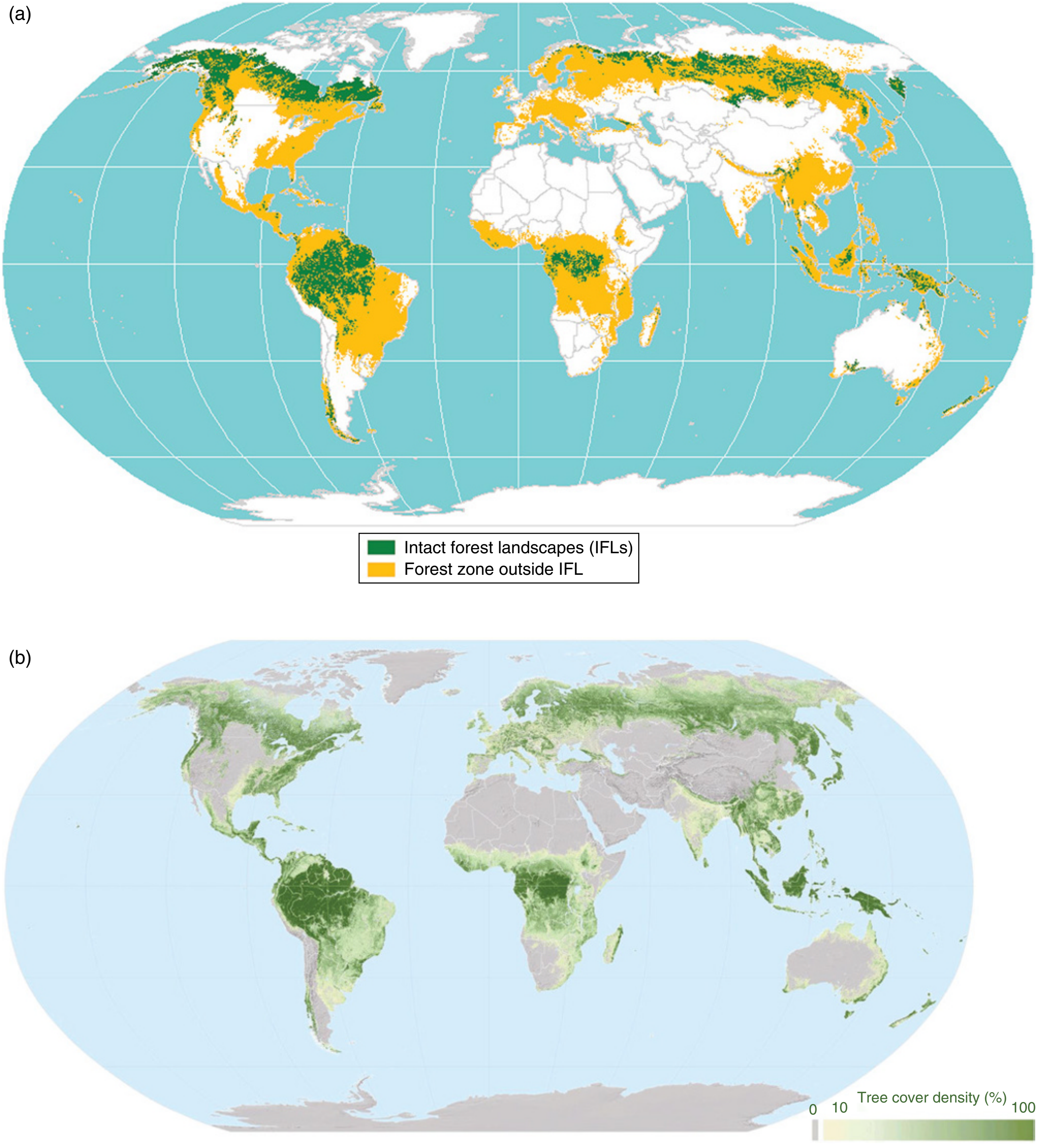


Figure 1.3 **(a)** A global depiction of the world's original forest (orange shading) and current undisturbed forests that have had little human impact (green shading). *Source*: Potapov, 2009. **(b)** A global depiction of the world's current forest cover (as measured by tree density) including undisturbed and second growth forests that have been logged or reverted back post land clearance for agriculture. *Source:* FAO, 2010. http://www.fao.org/forestry/fra/80298/en/

most conveniently located stands have been exploited first, most heavily, and most frequently. Ultimately, high-intensity silviculture should be practiced in many of these situations. Permanent roads and good markets for a diversity of forest products do not automatically ensure optimum practice, but they are essential to generate income to profitably pay for the intensive management.

Table 1.1 Hectares[1] of land by geographic region of the world's forests. Forests are defined here as woodlands and closed canopied forests; secondary forests of post agricultural origin or that have been logged and undisturbed forests. Primary undisturbed forest areas and their percent of total forest area are provided in parentheses.

Region	Forest area (in 1000s of ha)	% Land area
Africa – TOTAL	**635,412 (37,669)**	**21.4 (8.7)**
North Africa (dry temperate woodland)	131,048 (13,919)	8.6 (11.9)
East and south Africa (dry tropical woodland)	226,534 (12,241)	27.8 (5.7)
West and central Africa (wet tropical forest)[3]	277,829 (11,510)	44.1 (11.6)
Asia – TOTAL	**571,577 (87,526)**	**18.5 (15.3)**
Western and central Asia (dry temperate woodland)	43,588 (2,810)	4.0 (6.4)
East Asia (temperate broadleaf/coniferous forest)	244,682 (21,808)	21.3 (8.9)
South and southeast Asia (wet and dry tropical forest)[4]	283,127 (62,908)	33.4 (22.2)
Europe – TOTAL (temperate broadleaf/coniferous)[5]	**1,001,394 (263,948)**	**44.3 (26.8)**
North America – TOTAL	**705,849 (311,656)**	**32.9 (44.3)**
Caribbean (wet and dry tropical forest)	5,974 (60)	26.1 (1.5)
Central America (wet and dry tropical forest)	22,411 (9,139)	43.9 (40.8)
North America (temperate broadleaf/coniferous)[6]	677,464 (302,456)	32.7 (44.6)
South America – TOTAL (wet and dry tropical forest)[7]	**831,540 (601,689)**	**47.7 (76.8)**
Australasia/Oceania (temperate and tropical forest)	**206,254 (35,275)**	**24.3 (17.2)**
WORLD	**3,952,025**	**30.3 (36.4)**

1) 1 hectare = 2.471 acres
2) FAO statistics are fraught with potential error but it is the best estimate available. The statistics are dependent upon proper interpretation and supply of information by government officials of each country
3) Most of the primary forest that remains is in the central African country of the Democratic Republic of Congo
4) Most of the primary forest that remains is in Laos and Indonesian Borneo
5) By far the largest proportion of both forest and primary forest is in the Russian Republic
6) By far the largest proportion of primary forest is in the Canadian boreal
7) By far the largest proportion of primary forest is in the Amazon (Brazil, Peru)

Source: FAO[2], 2005. Reproduced with permission from FAO.

The intensity of timber-production silviculture depends in large measure on the nature and objectives of ownership. Variations in the species and sizes of trees desired may necessitate different procedures on adjoining lands that are fundamentally similar. Stability or longevity of ownership also controls intensity of silviculture. Large corporations and public agencies, which are relatively immortal, are in a far better position to practice intensive silviculture than individuals or small corporations of uncertain stability, though the idea of the immortal corporation has been turned on its head to some degree. Such corporation forestlands have now mostly been sold and are now managed by timber investment management organizations (TIMOs) for a variety of forest investors, such as pension fund investments that generally have a more short- to mid-term perspective.

The intensity of silviculture often depends on the extent to which the owner processes the wood grown in his forest. The more the raw material is processed to its final product, the greater is the ability to capture the "values added" by increases in intensity of practice in the woods. Prices for stumpage (that is, standing trees), do not necessarily reflect all the values that silviculture adds by improving the quality of wood. Therefore, the owner who cannot do more than sell stumpage may not be able to practice silviculture as intensively as owners who also harvest, manufacture, and sell the final product. This relationship is modified, however, by the ability and willingness to make long-term investments. For example, public forestry agencies usually confine their operations to producing stumpage. They may, however, practice intensive silviculture without concern for profit on their investments in order to discharge their long-term responsibilities to the national economy.

Philosophical Application of Silviculture

Given the perspectives in the preceding sections of this chapter, it is clear that the practice of silviculture does not consist of rigid adherence to any set of simple or detailed rules of procedure. For example, this book cannot be used as a manual of operations. Many of the cutting techniques are described in simplified form. Absent are many of the refinements and modifications necessary to accommodate the special circumstances and local variations encountered in practice. Each procedure described in the book is merely an illustration intended to demonstrate the application of a set of treatments designed to meet a uniform set of circumstances. Even though uniform stands have important advantages that make them worthy of creation, the stands encountered in the field will likely lack uniformity and thus call for variation in treatment.

Any consideration of silviculture covers a variety of treatments wider than is likely to be practiced in any locality at a particular time. In times when all the forests of a locality are immature, silvicultural practice may be limited to intermediate cuttings. Anything connected with regeneration may be limited to the reforestation of vacant areas. In localities where it is customary to secure regeneration by planting, the forester may regard methods of natural regeneration only as matters of intellectual exercise. Conversely, where planted stands are an anathema or owners are not ready to invest in them, only natural regeneration may seem important. At times and places where economic conditions support only the crudest kind of extensive silviculture, intensive treatments may seem visionary indeed.

This book contains a wide variation in intensity of silvicultural practice because an attempt is made to describe all known techniques that seem applicable in any significant forest area, especially of North America, within the near future. The procedures characteristic of the more intensive kinds of silviculture cannot be described as briefly as those associated with extensive silviculture, and so they get more attention. This does not mean that a management program must include a long series of different treatments to be silviculture. Some of the most astute silviculture is the kind conducted at low intensity in which much is accomplished with a limited amount of treatment.

The student forester interested in only one particular region should not limit their attention to the kind of silviculture currently practiced there. Foresters move, times change, and ideas from other places are often as fruitful as the indigenous ones. Scientific knowledge and technology also grow at an accelerating pace. The demands that society places on forests continually increase even as that same society places increasing restrictions on the ways of meeting the demands.

In many places, the impractical or impossible of 20 years ago is the routine – yet may prove to be the naive, illegal, or inadequate a decade in the future. Because of cutting and growth, the forests of a locality often change, and this calls forth new methods of treatment. This is especially true in North America, where the forests of localities tend to be in uniform condition, usually because in the past they were all cut over or cleared for agriculture in a short space of time. This book may seem to contain more techniques and ideas than a forester might need in a professional lifetime. Although some may go unused or quickly become outdated, there are really only enough to provide a start.

It is not enough for the forester to know what to do and how to do it. The important questions in silviculture begin with the word "why". As in other applied sciences, action proceeds from the knowledge represented by the answer, or sometimes the merest inkling of an answer. The forester can find as many solutions in the woods as in the printed word. However, it is necessary to ask oneself the questions that generate the solutions and also to be ready to take the time to observe how the flora and fauna of the forest develop over time.

Silviculture as a Body of Knowledge

Silvicultural Literature

Modern silviculture literature was originally based on a series of treatises that were careful descriptive observations on the nature of light within a forest, the concept of shade tolerance, and on the growth of trees for the propagation of timber (Evelyn, 1664). Such books originally served as the core knowledge base for the early development of silviculture that Hartig (1808) and Cotta (1817) systematized into a discipline. All of this literature came before the German scientist Ernst Haeckel first defined the discipline of ecology in 1866 as "Ökologie". Ecology (from Greek: οἶκος, "house"; -λογία, "study of") is the study of interactions among organisms and their environment. As a science it now serves as the foundation for silvicultural application. But ultimately, silviculture goes beyond ecology as an applied discipline driven by social values, as James W. Toumey states so eloquently in his first forest ecology text for North America (Toumey, 1928).

Ralph Hawley wrote the first silviculture text for North America in 1921. It was directly modeled after the German texts and silvicultural systems of the day. This book is the direct lineage of Hawley's 1921 book, that then evolved to Smith in 1954 (Hawley and Smith, 1954), and to us (Ashton and Kelty) in the 9th edition (Smith *et al.*, 1997). As the 10th edition, this book has evolved a decidedly more nuanced and more North American perspective on silviculture based upon much more concrete ecological theory and a more sophisticated understanding of social and ecological circumstance. Each chapter of this book ends with a listing of the references cited in that chapter. These references are the most significant and relevant to the topics discussed. Other books that should be recognized as significant regional or resource issue contributions upon which this textbook is based are Kevin O'Hara's 2014 book on *Multiaged Silviculture* and the book by Tappeiner *et al.* (2015) on *Silviculture and Ecology of Western US Forests*, and the work by Savill and colleagues on plantation forestry (Savill *et al.*, 1997). Other texts that should be recognized in the English-speaking literature are works by Daniel *et al.* (1979), Mathews (1991), and Nyland (2016).

The use of computerized information-retrieval systems is growing rapidly. More detailed information and many additional literature references about silviculture in the United States can be obtained from consolidated publications. In *Regional Silviculture in the United States* (Barrett, 1994), various silviculture professors have written about their localities. Research scientists of the US Forest Service (Burns, 1983; Burns and Honkala, 1990) have summarized information about the ecological characteristics of tree species and about the silviculture of the important forest types. One advantage of these sources is that they will help locate many of the large numbers of publications issued by research and extension agencies of governments and universities.

The *Forestry Handbook* of the Society of American Foresters (Wenger, 1984) presents much information about silviculture and closely associated topics, as do similar compendia designed to help the practicing foresters of a locality. The written word can bring the forester ideas from distant places. Not all of the problems of growing loblolly or ponderosa pine have to be solved exclusively by study of these individual species. Much has also been learned about the silviculture of pines in Finland and Australia; knowing about teak in Asia may also help. In fact, new and useful insights often come faster from distant sources. Most of the world literature of forestry is in English, although English-speaking forestry students should be more ambitious about mastering other languages.

A forester should not read about silviculture just to absorb information. Reading should be a stimulus to thought, a way of synthesizing new patterns of understanding, and of both expanding and testing ideas. It can make comprehension of processes seen in the woods surer and more serviceable.

Current Research Issues

The research and topic areas that are at the forefront of silvicultural research are diverse. In the last 30 years the concept and paradigm of stand dynamics have advanced silvicultural thought on how to treat mixed stands (Oliver and Larson, 1996) (see Chapter 3). This work continues to be pushed and elaborated upon by quantifying relationships that were only conceptual and qualitative such as our understandings of self-thinning and growth-and-yield (O'Hara and Gersonde, 2004). Work has moved forward especially on our understandings of how intimate mixtures of tree species grow in time and space (O'Hara, 2014).

The explosion of computer technology has provided a whole new field of quantifying space and time at stand and landscape scale models of treatments and management impacts (Bettinger and Sessions, 2003). In the last 20 years, a great deal of work has advanced modeling technology for silvicultural application (Pacala *et al.*, 1996; Vanclay and Skovsgaard, 1997).

A third topic is that our understanding of species and structural diversity of forests has also progressed. In the last 20 years, multiple ecological theories have been tested and explored around density dependence, intermediate disturbance, and niche hypotheses, for example. All are providing stronger theoretical arguments for applying silvicultural treatments judiciously based on ecology (Wright, 2002; Puettmann, Coates, and Messier; 2012; O'Hara, 2014) (see Chapters 5, 11, 13, and 28).

A fourth area has been the never-ending work that focuses on reforestation, planting technologies, and forest restoration, now centered particularly in the tropics (Ashton *et al.*, 2014; Griscom and Ashton, 2011) and within North America, particularly in the inland west (Fule *et al.*, 2001; Baker, Veblen, and Sherriff, 2007; Stanturf, Palik, and Dumroese, 2014). This is an old theme that continues to advance given its continuing dominance as an ecological and social issue around the world (see Chapters 16 and 25).

Fifth, great strides have been made in understanding the constraints and drivers of forest productivity, particularly in plantation systems focused on timber, another long-lasting theme of research (Fox, 2000; Fox, Jokela, and Allen, 2007) (see Chapters 16, 18 and 30).

Sixth, given the role of fire, fuels, insects, and climate change in the western USA, understanding this triad of relationships and drivers is critical toward restoring fire and forest health back into more resilient forests that are currently fire and insect prone (Dale *et al.*, 2000; Logan, Regniere, and Powell, 2003; Stephens *et al.*, 2012) (see Chapters 26 and 27).

Finally, a good deal of attention has been focused on the non-monetary service values that forests and trees provide. Whole new themes on urban trees and forests (Dwyer *et al.*, 2000), forest watersheds and drinking water supplies (Naiman, 1992; de la Cretaz and Barten, 2007), forest carbon and climate mitigation (Amato *et al.*, 2011; Ashton *et al.*, 2012), and bioenergy and wood technologies that substitute for other more energy intensive products (Dickman, 2006) have all been strong areas of research focus.

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2

Silviculture and its Place in Managing Current Forests and Woodlands

Introduction

This chapter provides an introduction to the book and its contents. It first defines the purpose of silviculture in context with examples of its application to current resource issues. The scope of silviculture and the use of its terminology is then described by providing the overarching theme that silviculture should: (1) imitate as much as possible the processes of nature, and (2) maintain and protect the inherent productivity of the site. Within this construct there are four guiding principles that silviculture can potentially strive to achieve, given both social and economic objectives and values. They are: (1) control structure and process; (2) control composition; (3) control stand density and spatial arrangement; (4) control rotation length, harvest intervals, and the life cycle of the forest. Then a framework is described to implement these principles within the construct of emulating nature and maintaining site productivity. This is done by: (1) defining the spatial scale at which silviculture is applied by introducing the concept of the stand; (2) defining the two basic sets of silvicultural treatments applied within stands, namely: regeneration methods and post-establishment treatments; and (3) defining treatments to the individual tree (e.g., pruning).

The Purpose of Silviculture Today

Definition of Silviculture

Silviculture has been defined in various ways, including the art and science of producing and tending a forest for the various social and economic values demanded by individuals and society. It has also been defined as the application of knowledge of autecology or silvics in the treatment of a forest. Finally, it has been defined as the theory and practice of controlling forest establishment, composition, structure, and growth. Since silvicultural practice is applied forest ecology, it is also a major part of the biological technology that carries ecosystem management into action.

Silvicultural practice consists of the various treatments applied to forests to maintain and enhance their utility or service for any purpose. The forester must analyze the natural and social factors that affect each stand, and then devise and conduct the silvicultural treatments most appropriate to meet the objectives of the landowner. Silviculture is to forestry as agronomy is to agriculture, in that it is concerned with the technology of growing vegetation. Like the rest of forestry itself, silviculture is an applied science that rests on the more fundamental natural and social sciences. The immediate foundation of silviculture in the natural sciences is **silvics**, which deals with the growth and development of single trees and other forest species as well as whole forest ecosystems. Among the sources of information about silvics is a very long legacy of books upon which silviculture is based by: Daniel, Helms, and Baker, 1979; Spurr and Barnes, 1980; Kimmins, 1987; Burns and Honkala, 1990; Oldeman, 1990; Whitmore, 1990; Kozlowski, Kramer, and Pallardy, 1991; Lassoie and Hinkley, 1991; Packham, *et al*., 1992; Barnes *et al*., 1998; Kimmins, 2003; Waring and Running, 2007; and Perry, Oren and Hart, 2008.

The competent practice of silviculture, whether it be crude or elaborate, demands that a forester acquire as much knowledge as possible of ecology and all its subdisciplinary areas (e.g., population, community, ecosystem), as well as fields such as plant physiology and morphology, entomology and pathology, biogeochemistry, hydrology, biometeorology, and soil science. It is also through silviculture that a major part of the growing store of knowledge about trees and forests is applied. In addition, it is essential to understand the fundamentals of individual human community and society behaviors, their cultural and religious values, and their economics, if silviculture is to achieve the goals and objectives of managing forests, woodlands, and trees successfully. This knowledge is not learned once for a lifetime. The forestry practitioner must keep abreast of new information and ideas through communication with other members of the profession and maintain familiarity with the results of research. Silviculture can therefore be considered a sub-discipline that is at the very heart of training a forestry professional (Fig. 2.1).

The Practice of Silviculture: Applied Forest Ecology, Tenth Edition. Mark S. Ashton and Matthew J. Kelty.

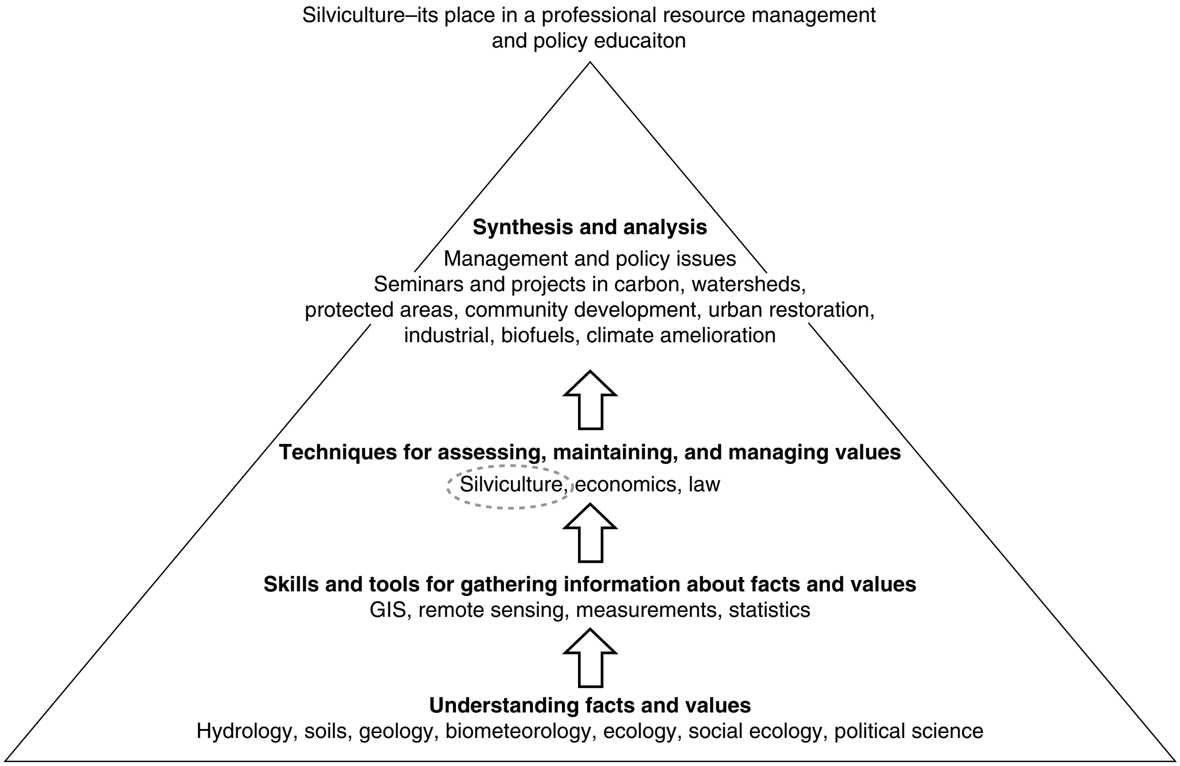

Figure 2.1 A graphical depiction of where the subject lies within the multi-disciplinary training of a professional forester. *Source:* Mark S. Ashton.

Although formal research is indispensable, it does not lead to total knowledge, nor does it relieve the forester of responsibility for additional thought and continual observations in the forest. In applied sciences, such as silviculture, in the absence of total knowledge we are always condemned to act on the basis of thoughtful judgment. Skillful practice itself is a continuing, informal kind of research in which understanding is sought, new ideas are applied, and old ideas are tested for validity. The observant forester will find answers to many silvicultural questions in the woods by examining the results of earlier treatments of the forest and accidents of nature. This component of silviculture can be considered the art of silviculture and is based on the forester's inherent adaptive learning experience, intuition and understanding of the science, keen sense of observation about the natural world, and ability to understand human behaviors and desires as well as translate this understanding into practice. The forester is a naturalist in the broadest sense of the word, and every forester should strive for these attributes.

The Purpose of Implementing Silviculture

Silviculture is designed to create and maintain the kind of forest that will best fulfill the objectives of the owner and the governing society. The production of timber, though a common objective, is neither the only nor necessarily the dominant aim in silviculture. Frequently, especially with public forests and private non-industrial forests, benefits such as recreation or aesthetics may be more important, and water and wildlife always have to be taken into account.

Most silvicultural practices are applied in the course of timber harvesting because the value of the wood removed greatly reduces the cost of the operations. It is through the manipulation of growing space by removing trees that much of the other values such as improving wildlife habitat, creating vistas, or encouraging a vigorous groundstory for surface watershed protection can be achieved. This is true even if timber production is only a secondary or tertiary objective of management. Silviculture for the cultivation of both wood and non-wood products (fruits, fiber, resins) is also the most intricate kind because the species and quality of trees are of greater concern than they would be with other forest uses. Designing silviculture for wildlife management is also complicated, but mainly because of the difficulty of determining the kinds of vegetation that mobile and elusive animal populations require. Once the kind of required habitat is selected, the silviculture is not difficult to design.

Some of the biggest problems in silviculture include getting owners and society to define their management objectives and, especially, the degree of priority attached to various uses. It is the responsibility of foresters to work out the details, which include the design and implementation of silvicultural treatments, but owners, the public, and legislative bodies must determine the actual policies about allocations. Management cannot continue if the difficult and often argumentative decision making is left to single-minded user groups. Even worse problems can be caused by amateur prescription of silvicultural practice through simplistic rules ordained by legislatures, courts, or accountants.

Resource Issues Applicable to the Use of Silviculture

Resource issues are extremely varied given the enormously wide social and economic circumstances within which forests and woodlands can be found. Forests are: used for subsistence living in remote regions; irresponsibly cleared for unsustainable agricultural projects (and thus threatened with destruction and degradation); managed for intensive industrial use; conserved as wildlife habitat; maintained as a source of drinking water for downstream cities; and developed for open-space recreation and city parklands. Important resource values are listed below by the products and services that trees and forests provide and for which silviculture is directly applicable.

Products

1) Biomass and wood fuel. Two-thirds of people in the world, mostly from developing nations, are still dependent upon fuelwood or charcoal for cooking and heating. Now coming full circle, modern technologies are being developed to use biomass, primarily from fast-growing biomass plantations, but also a secondary product from other forest harvest operations, as an energy source in developed nations.
2) Fiber. Paper, ropes, and other fiber products were predicted at the start of the computer age to dramatically decrease in use. Instead they have significantly increased and are projected to continue to do so. Though recycled paper products have become much more common, even recycled paper requires replenishment with virgin fiber.
3) Composite materials. Over the last 50 years, technology has developed a variety of composite wood products (plywood, particle board, and oriented-strand board) that are cheaper substitutes for dimensional sawtimbers and that are derived from what was once considered waste. Such materials are now widely used. More recently, wood–plastic composites have been developed for a range of uses that were formerly restricted to plastics, ranging from shoes to the bodies and interiors of cars, planes, and boats.
4) Dimensional construction and support timbers. Worldwide, demand for timber products for building construction will continue to increase. Timber products are one of the most carbon-neutral and energy-efficient products. These timbers are increasingly coming from intensively managed plantations (e.g., Douglas-fir, *Eucalyptus* spp., loblolly pine, and radiata pine).
5) Luxury timbers and veneers. High-value woods used for furniture, artisanal products, musical instruments, flooring, paneling, and building interiors will always be demanded by society. These timbers continue to come from native forests, and are increasingly from second-growth origin. Plantations of luxury timber are rare (e.g., teak), because of their time to reach maturity.
6) Tree fruit and nut crops. Cultivation of fruit and nut trees requires silviculture treatments in native forests, mixed tree gardens, and orchard plantings. Such treatments focus on the condition of individual tree crowns to maximize nut and fruit productivity.
7) Tree resins, oils, and saps (e.g., rubber, maple syrup, turpentine). Trees managed to produce resins, saps, and oils from the stem need specific silvicultural treatments for both native forests and for their cultivation in plantations.
8) Lianas and vines. Many products (rattan, basketry, medicinals, cordage, vegetables) are garnered from vines. However, vines and lianas require trees and shrubs for support and stages of successional habitat that silviculture can provide.
9) Understory plants. Understory plant crops (e.g., spices, medicinals, coffee, cacao) of forests, plantations, and agroforestry systems require shade and soil-fertility conditions that trees can provide.

Services

1) Supplying clean water. The cleanest water comes from forested watersheds that act to filter and/or sequester pathogens and pollutants from water and air. Many urban areas are focused on acquiring and protecting upstream land from development in order to manage it as forest for drinking water supplies to reservoirs.
2) Stormwater mitigation. At a regional scale, forested swamps and floodplains are usually the frontline for mitigating stormwater and flooding events and controlling shoreline erosion caused by typhoons and storms. In addition, wetlands, swamplands, and forests can control and regulate seasonal meltwaters and monsoon or rainy season floods. At a more local scale, trees and woodlands within cities can mitigate local stormwater runoff, reducing downstream pollution and excessive discharge. At both scales, silviculture is needed to actively reforest and create the optimum conditions for mitigation.
3) Carbon sequestration. Since the 1990s, the focus in reducing atmospheric greenhouse gases has shifted towards natural carbon sequestration by forests and trees, which depends on minimized deforestation, reforestation, and management practices that delay harvesting and increase growth.
4) Urban climate and environmental mitigation. Within cities and towns, trees and woodlands can be planted

and cultivated to locally reduce glare, sound, temperatures, and winds.

5) Open-space recreation. Silviculture can be used to create vistas, screens, and recreational trails for biking, hiking, and skiing.
6) Wildlife habitat. Forests and woodlands provide critical habitat for all sorts of wildlife. Particularly important to some societies are the opportunities to hunt game animals, and mandates to conserve endangered species. Silviculture can be used to both create the habitat and maintain it through manipulating forest structure, composition, and site.
7) Forest health and restoration. Silviculture can be applied for: (a) controlling invasive plants, insects, and diseases; (b) regulating and controlling fires; (c) restoring and conserving biodiversity; and (d) stabilizing and protecting fragile landscapes.

The products and services listed can often be produced together in a stand within the forest, plantation, or agroforestry system. In other circumstances they are incompatible and have to be managed separately. Different regions of the world, and even within the same region, have very different sets of priorities and values because of social, economic, and biological circumstance.

Scope and Terminology of Silvicultural Practice

Silvicultural practice encompasses all treatments applied to forest and woodland vegetation and their sites. Although there is much more to the understanding of these treatments than their definitions and nomenclature, the terminology must be understood and used carefully and precisely. **Sloppy use of the terms causes all manner of misunderstanding within the forestry profession and in dealings with the general public. For example, some foresters categorize all cutting as either "clearcutting" or "selective cutting." This not only stunts the development of their own understanding of forestry practice and causes blunders, but also generates continued confusion.** The terminology in this book generally adheres to that promulgated by the Society of American Foresters Silviculture Instructors Sub-Group (1994) and the Commonwealth Forestry Bureau (Ford-Robertson, 1978). It departs only where further improvement in clarity or precision seems imperative.

Silviculture should be governed by several guiding principles. The first two are of the greatest importance, dealing with the imitation of nature and the conservation of site productivity. The other four principles are to be used as reminders to forest practitioners by serving as a check for potential unintended consequences of poor silviculture judgment. The following is a brief description of each of the six principles.

Principle 1: Imitating Nature Through Silviculture

The most magnificent forests that are ever likely to develop were present before the dawn of civilization and grew without human assistance. It is therefore wise to recognize that nature's forests and woodlands are the result of millions of years of exposure to risks of climate, disease, pestilence, and disturbance. Therefore, dramatic silvicultural deviations in species composition, successional process, and stocking can often have detrimental consequences. Human purpose is introduced by preference for certain tree species, stand structures, or processes of stand development that have desirable products and/or services. Where fine forests have developed in nature, they are usually found to have been the result of disturbances followed by long periods of growth. In silviculture, natural processes are deliberately guided to produce forests that are more useful than those of nature, and to do so in less time. Silviculture is therefore an anthropocentric discipline guided by ecological constraints. Whatever society or individuals demand of a forest, whether utilization or preservation, with active or passive management approaches, those decisions are human ones, and they all have immediate consequences and future impacts on a forest that should be recognized.

Principle 2: Conservation of Site Productivity

Paramount among the objectives of forestry in general and of silviculture in particular is the maintenance of the productivity of the living forest. The site is the total combination of the factors, living and inanimate, of a place that determines this productivity. The site factors that are most subject to long-lasting harm are those of the soil, which is one of the least renewable resources used in silviculture (see Chapter 5).

Forests are usually the result rather than the cause of geographical precipitation patterns, though recent evidence is suggesting that forests that are large enough most definitely mitigate climate change and can promote processes of local precipitation such as convectional thunderstorms. However, the basic supply of solar energy is the most vital site factor and is beyond silvicultural control. Silviculture therefore rests heavily on manipulation of the microclimate of a site. Its effects on the macroclimate are limited to those caused by photosynthetic removal of carbon dioxide from the atmosphere and by transpiration of humidity into it.

The living organisms of a place are site factors themselves. However, they can reproduce themselves and are thus the epitome of the renewable resource. If none are rendered extinct, damage to these living components of the site is not likely to be permanent, even though it can be serious and long-lasting. There are always uncertainties over the extent to which silviculture should discriminate against "undesirable" forms of life.

The most obvious and least repairable kind of damage to the soil is physical erosion. Careless treatment, especially when associated with roads and trails used for timber extraction, can cause accelerated erosion that may negate the soil formation processes of a thousand years. A more subtle kind of chemical erosion can result if the remarkable capacity of forest vegetation to recycle nutrients in place is so impaired that large amounts of vital chemicals are lost to surface runoff or leaching. These two kinds of erosion cause double harm because they reduce not only the productivity of the soil but also the quality of the water that flows from it. Soil damage impairs the capacity of the site to yield all of the primary tangible benefits of the forests – vegetation, animal forage, and good water.

It is entirely possible to conduct forestry permanently without the degradation that is almost inevitable in most agriculture and in other "higher" uses of land. However, realization of this potentiality is not automatic. The productivity of the managed forest as a whole is improved through attainment of the four guiding principles described in the next few sections.

Principle 3: Control of Stand Structure and Process

Silviculture is a kind of process engineering or forest architecture aimed at creating structures or developmental sequences that will serve the intended purposes, be in harmony with the environment, and withstand the burdens imposed by environmental influences. Because stands grow and change with time, their design is more sophisticated and difficult to envision than that of static buildings. Furthermore, stands alter their own environment enough that the forester is partly creating a new ecosystem and partly adapting to the one that already exists.

As will be described in more detail in Chapter 4, the possible variations in stand structure and process are almost infinite. The shapes and sizes of stands can be altered for many purposes. Among these are controlling silvicultural treatments and harvesting, creating attractive scenery, altering animal habitat or controlling pest populations, trapping snow, and reducing wind damage. The shapes of stands should be fitted to the patterns usually already found in nature that are dictated by soils and terrain. While the arrangement of stands in checkerboard patterns has a certain administrative appeal, the natural characteristics of land are not, and should generally not be arranged in ways that conflict with the topography of the land.

The internal structure of a stand is determined by considerations such as variation in species and age classes, the arrangement of different layers or stories of vegetation (usually differing as to species), and the distribution of diameter classes. Much of this book is concerned with the purpose and means of achieving these kinds of variations in structure and developmental process.

Principle 4: Control of Composition

One important objective of silviculture is to restrict the composition of stands to what is most suitable to the location from economic and biological standpoints. This frequently means that the total number of species in a managed stand or forest is less than that of the natural forest at that site.

Species composition can be controlled basically by regulating the kind and degree of disturbance during periods when new stands are being established. In this way, environmental conditions can be adjusted to favor desirable vegetation and exclude undesirable species. Regulation of the regeneration process by itself is not always sufficient to provide adequate control over stand composition. It is often necessary to supplement this approach by removing the undesirable vegetation during or after periods of stand establishment. Cutting, poisoning, controlled burning, or regulated herbivorous browsing may be used to restrict the competition and regeneration capacity of undesirable vegetation.

Desirable species and genotypes can be favored in a more positive way by planting or artificial seeding. In some circumstances it is also possible to improve on nature through the introduction of species that do not occur in the native vegetation (e.g., timber and fruit trees; nurse trees in agroforestry), provided that they are adequately adapted to the environment and do not become invasive.

Principle 5: Control of Stand Density

Managed forests are often too densely or too sparsely stocked with trees. This is subjective based upon what human values are being managed for. If stand density is too low, the trees may be too branchy or otherwise malformed, and the unoccupied spaces are likely to be filled with unwanted vegetation in wetter climates. This condition arises from failure of natural regeneration or establishment of planted seedlings. This phenomenon of unoccupied growing space is therefore most common in the early life of a stand, but its consequences may linger after the surviving trees have grown to occupy all of the space available. Excessively high stand density causes the production to be distributed over so many individual trees that none grow at an optimum rate and too many decline in vigor. Unless stand density is controlled at the time a stand is established or during its development, it is almost sure to depart from optimum density for growth at some stage of its life.

Without proper management, many areas of land potentially suited to growth of forests tend to remain unstocked with trees (Fig. 2.2). Legacies of past land abuse (fires, destructive logging, grazing, agricultural

(a)

(b)

Figure 2.2 Much of silviculture has always consisted of rehabilitation efforts and of knowing what will happen as a result of treatments of the forest. This sequence of pictures from 1938, 1949, and 1969 shows a planted stand at a National Forest in northern Idaho, in three stages of development. The tract had been cut-over from a logging railroad in 1930–1931 and was both burned and acquired just before the first picture **(a)** was taken. Planting of western white pine and Engelmann spruce was done in 1939 and 1940. The subsequent pictures **(b** and **c)** show the development to age 30, of the mixture of planted trees and other conifers that seeded-in naturally. *Source:* **(a–c)** US Forest Service.

(Continued)

(c)

Figure 2.2 (Continued)

clearances, and other kinds of forest devastation) have already created many large open areas that can be reforested only by planting. In many regions, **restocking** of deforested areas can be considered a common silvicultural goal.

In many stands, severe losses are caused by damaging agencies such as insects, fungi, fire, and wind. Substantial increases in merchantable production may be achieved merely by salvaging material that might otherwise be lost, but this decision needs to be considered carefully. Jumping into action too quickly to salvage forests sometimes can further exacerbate such issues by causing severe erosion or facilitating further spread of insect or disease. Protection from damaging agencies can result in further increases in production. Forest protection often involves modification of silvicultural techniques. Those areas set aside for wilderness, scenery, or scientific study clearly require protection. Sound policies about the stewardship and use of these preserves inevitably involve something other than leaving them absolutely alone.

Principle 6: Control of Rotation Length

Stands of trees are not immortal. In most commercial situations, there is an optimum size or age to which trees should be grown. The period of years required to grow a stand to the desired condition of either economic or natural maturity is known as the **rotation**. Controlled reductions of stand density or such measures as fertilization and drainage can shorten rotations by making the final-harvest trees grow to the desired sizes at earlier ages. Trees in commercial circumstances allowed to grow beyond the optimum size do not continue to increase in value at rates sufficient to provide an acceptable return on either the costs of growing them or the investment represented by their own value. The risk of decay or other damage may increase the possibility that the trees will decline in value, be lost, or become a hazard. The reservation of overmature trees or even of dead trees is now the norm to maintain some element of structural diversity even within the most intensively managed forests. This is to benefit some wildlife species, microbiota, or simply for scenery or cultural legacies. Increased sequestration and storage of carbon can also be a financial incentive to lengthen rotations in many commercially managed forests.

In the virgin forest, large timber, like gold in the hills, is usually first exploited. The greater the amount extracted, the more difficult and expensive it becomes to find and extract more. It can be extremely difficult to correct the impacts of exploitation in forests that are intended to be sustainably managed for products (timber or non-timber). In fact, many are simply converted to other forms of land use because their commercial timber value has been so depleted. In a managed forest, the growth of stands can be planned so that any use of them is on a more efficient, economical, and predictable basis. It helps to create good stands that are so located that the cost of transporting timber from them is kept under control. Planned reductions in the number of trees on an area not only makes them reach merchantable size more quickly but also leaves more space between trees for extraction of logs during partial cutting.

The Silviculture Framework for Managing a Forest

This section provides a conceptual framework for thinking about how silviculture should be implemented using the guiding principles that are listed and described in the preceding section. Taken together, this provides the forester a guide upon which to develop a silvicultural set of treatments for the unique biophysical and social circumstance that they face. The set of treatments devised by the forester is defined as a **silvicultural system**. The framework should be based upon the ecological and social knowledge and experiences of the forester. The system devised is by no means taken as a general recipe equivalent to a "cook book." Unfortunately too many of these "recipes" exist in forestry and land management.

Defining the Spatial Scale of Management: The Stand and the Forest

A **stand** is a contiguous group of trees sufficiently uniform in species composition, arrangement of age classes, site quality, and condition to be a distinguishable unit. It is the basic and usually the most refined management unit upon which silvicultural treatments can be applied. The internal structure of stands varies mainly with respect to the degree that different species and age classes are intermingled. The simplest kind of structure and developmental pattern is that of the pure, even-aged plantation. The range of complexity can extend to a wide variety of combinations of age classes and species in various vertical and horizontal arrangements. The development of stands over time, or **stand dynamics**, is considered in Chapter 4.

From the standpoint of forest management, the term "forest" has a special meaning and denotes a collection of stands administered as an integrated unit, usually under one ownership. Putting stands together into forests is especially important in regulating harvests of products (timber and non-timber), as well as managing wildlife populations and large watersheds.

One objective of this type of planning for timber is to achieve a sustained yield of products. The forest, not the stand, is the unit from which sustained yield is sought. Management studies of prospective growth and yield determine the volumes of the products to be removed from the whole forest in a given period. The silvicultural principles listed earlier should govern the sequence and manner in which individual stands reproduce the required structures, yields and compositions. The tendency to treat large groups of dissimilar stands as if they conformed to a uniform, hypothetical average should be studiously avoided. However, a decision must be made regarding the minimum size of stand delineation.

Silviculture that is concerned with natural processes involving wildlife, flowing water, and whole landscapes also involves the arrangement and juxtaposition of stands. Differences between adjacent stands and the distribution of stands across landscapes need to be taken into account as part of the management of forests or ecosystems at much larger landscape, watershed, and regional scales.

The size and number of stands recognized depend on the intensity of practice, the economic values and social drivers of the stands, the diversity of site conditions, and the ease of mapping. Where intensive forestry is feasible, stands as small as 0.6 acres (0.25 ha) may be recognized. But under crude, extensive practice, the same forest might be divided into units no smaller than several hundred acres. The best policy is to recognize the smallest stands that can be conveniently delineated on the maps of forest types and age classes used in administration. Even after stand maps have been put on paper, the forester must still deal with variations that actually exist within each stand. From a technical perspective, each portion is best treated separately, although acceptance of too many variations would eventually create a mosaic of conditions that would be awkward for most operations. With remotely sensed data that can be obtained to the nearest 10 ft^2 (1 m^2), technologies make the identification and delineation of stands almost a continuous process as forests change and develop over time. This makes silviculture and its associated treatments more harmonious with the continuums and gradients of ongoing natural processes.

The production of benefits by forest stands is controlled by the stand developmental processes, whether these benefits be wood, wildlife, water, forage, or scenery. The processes start with the birth of the stands, continue with competition between trees, and end with the death of old trees and their replacement. The simplest kind of stand development process is that of the **pure even-aged stand** in which the trees are "pure," that is, all of one species, and start together after the previous stand is removed. Such stands are often ones that have been planted. **Uneven-aged stands** (two to three age classes are considered **multi-aged**; more than three age classes are considered **all-aged**) have trees or (more commonly, groups of trees) of different ages and much more complicated developmental patterns. **Mixed stands** have more than one tree species, and the interaction between them makes their development even more complicated, especially if they also have more than a single age class of trees. The development of these different kinds of stands is discussed in Chapters 4 and 5 and Chapters 8–13.

Defining Kinds of Silvicultural Treatments

The act of replacing old trees, either naturally or artificially, is called **regeneration** or **reproduction**. These two words, which are synonymous in this usage, also refer to the new growth that develops.

There is also the question of the terminology used for silvicultural treatments. There are two broad categories: (1) **methods of reproduction** refer to treatments of stand and site during the period of regeneration or establishment, while (2) **tending** or **intermediate cutting** refers to post-establishment treatments that occur at other times during the rotation (Fig. 2.3).

Reproduction or **regeneration cuttings** are made with the twin purposes of removing the old trees and creating environments favorable for establishment of regeneration. The period over which such regeneration treatments extend is the **reproduction** or **regeneration period**. Regeneration cuttings range from one to several in number, and the regeneration period may extend from several years to several decades. In truly uneven-aged stands, regeneration is almost always underway in some part of the stand. The regeneration period begins when preparatory site and cutting treatments start, and it ends when young trees, free to grow, are dependably established in acceptable numbers. The **rotation** is the period during which a single crop or generation is allowed to grow.

The names of the various methods of regeneration (see Chapter 6) are primarily defined by regeneration origin and secondly by the patterns of cutting in time and space that determine the structure of the new stands created. They distinguish between reliance on reproduction from seeds or reproduction from vegetative sprouts and may tell a little about the degree of shading of new seedlings. Later chapters describe how clearcutting is associated with pure, shade-intolerant even-aged stands (Chapter 8); seed trees with a dependence on a nearby seed source (Chapter 9); shelterwood methods and their uneven-aged (multi-aged) variants, with advance regeneration (Chapters 10 and 11); coppice methods, with sprout regeneration (Chapter 12); and the selection system, with uneven-aged (all-aged) stands (Chapter 13). The names of the methods, systems, and kinds of stands usually only begin to describe fully the details of silvicultural management programs.

Silvicultural treatments are not limited to ensuring regeneration. Other treatments may be applied after the stand is established and during the long period that elapses while the stand grows through various stages until it is ready for replacement. Various **intermediate cuttings** or **tending operations** are conducted to improve the existing stand, regulate its growth, create particular structure, treat individual trees, and/or provide for early financial returns, without any effort directed at regeneration. Sometimes these treatments are referred to as **stand improvement operations** or **timber stand improvement (TSI)**, when they yield no products or services (Chapters 19 and 22).

Intermediate cuttings that are aimed primarily at controlling the growth of stands by adjusting stand density or species composition are called **thinnings** (Chapters 21 and 22). Treatments conducted to regulate species

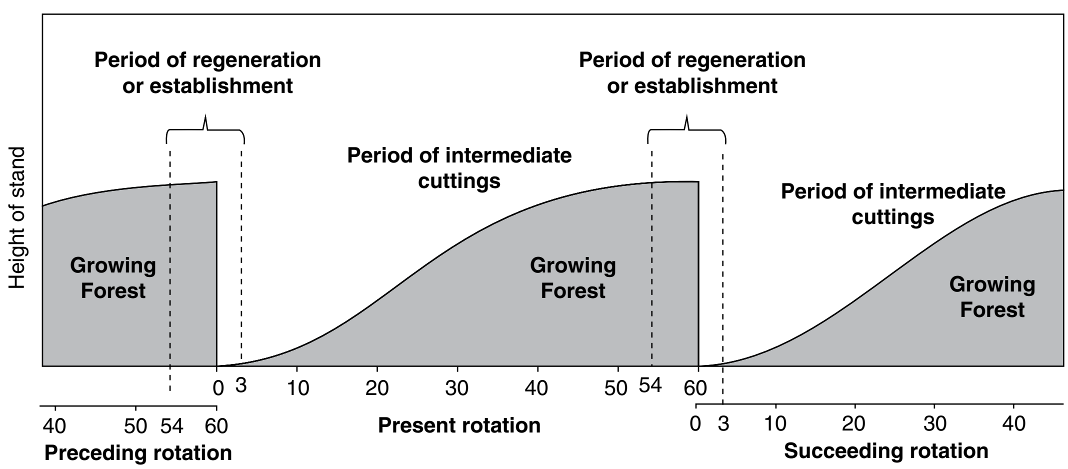

Figure 2.3 The relationship between the period of regeneration and the period of intermediate cuttings is shown for a sequence of even-aged stands managed on a 60-year rotation according to the shelterwood system. In this system the new stand is started before the older one is completely removed. *Source:* Yale School of Forestry and Environmental Studies/Mark S. Ashton.

composition and improve very young stands are **release operations** (Chapter 20). Those that involve only the branches are **pruning** (Chapter 19). Many kinds of intermediate cutting or tending can now be accomplished without actually cutting down trees, for example, by girdling and use of herbicides.

Protection against injury is as much a part of silviculture as harvesting, regenerating, and tending of forests. It is so important that it has led to fields of specialization in forestry such as restoration ecology, entomology, pathology, control of invasives, and fire control, and now impacts of climate change. Chapters 25, 26, and 27 are devoted to outlining the silvicultural aspects of these fields. The details of almost any successful silvicultural system include significant modifications designed to reduce injuries. Where such measures fail or are inadequate it is sometimes desirable to conduct **salvage cuttings** to recover the values represented by damaged trees or stands.

A program for the treatment of a stand during a whole rotation is called a **silvicultural system**. The silvicultural system is usually given the same name as the regeneration method that is used during stand replacement. This is because these regeneration methods determine the kinds of stands and stand developmental processes that occur during a whole rotation.

Role of Cutting in Silviculture

The techniques of silviculture proceed on the basic assumption that the vegetation on any site tends to extend itself aggressively to occupy the available growing space. The limit on growing space is usually set by the availability of light, water, inorganic nutrients, or carbon dioxide. Generally, the most limiting of these factors will determine the available amount of growing space, although an abundant supply of one factor can partially offset deficiency of another. If the vegetation nearly fills the growing space, the only way that the forest can be altered or controlled is by removing trees and other plants to open up growing space. In reproduction cutting, this is done to provide room for the establishment of new trees; in intermediate cutting, it is done to promote the growth of desirable trees already in existence. Paradoxical as it may seem, useful forests are created and maintained chiefly by judiciously choosing and destroying some of their parts. One of the characteristics of life is death; if there were no death, there would be no space for new life. Simply put, silviculture usurps nature's role by creating new trees rather than waiting for disturbance and by facilitating the survival of chosen existing trees by intentional thinning rather than natural self-thinning.

The ax and other means of killing trees can, in other words, be used for the construction as well as the destruction of the forest. What is left or what replaces what is harvested is more important silviculturally than what is cut. Unfortunately, much of the general public as well as some loggers have eyes only for what is cut and regard the harvests as simply the mining of a non-renewable resource.

Preoccupation with the trees should not cause foresters to overlook the lesser vegetation and the animals that are a part of the forest community. The animals ultimately depend on the vegetation for food and thus do not compete directly for the growing space. However, whether they be defoliating insects or carnivores that feed on herbivorous mammals, they exert major influence on the nature of the vegetation even as they are, in turn, controlled by it. The fauna and non-woody vegetation of the forest are as affected by cutting as the trees are.

Effect of Cutting on Growing Stock

Cutting trees controls not only the composition and structure of forest stands, but also the relationship between trees reserved for continued growth and the space created for new trees. It is therefore important to understand the long-term, cumulative effect of cutting operations in building or degrading a forest.

The trees that must be reserved somewhere in the forest to continue production are the **growing stock** or **forest capital**. The volume of wood that is grown in the future depends on the quantity and condition of growing stock that is maintained. Cuttings regulate the amount of this growing stock and its distribution within individual stands or among the various stands that comprise the forest. The regulation of growing stock is of most crucial importance in silviculture when partial cuttings are applied within stands.

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Part 2

Ecological Foundations of Silviculture

The ecological foundations for silvicultural practice through understanding the complexities of site and scale; the development and dynamics of forest stands; and the nature of forest regeneration in relation to disturbance.

3

Ecological Site Classification, Stands as Management Units, and Landscape-Scale Planning

Introduction

The Ecosystem Concept

It was recognized long ago that both study and application of ecology suffered from excessive compartmentalization. The total flora of interacting forest plants is far more than just trees; the total biota of a place includes not only plants but all the orders of the animal kingdom that are present. An ecosystem, however, is more than just the living organisms. It also includes the non-living physical and chemical factors that interact with the living organisms (Tansley, 1935).

In applying silvicultural treatments, a forester is, in some degree, manipulating many sizes of ecosystems simultaneously (Reichle, 1981; Perry, Oren, and Hart, 2008). At one extreme are the world cycles of carbon, oxygen, and water; the microenvironment around a pine seedling in the shade of a log is at another; and in between are the cycles of mineral nutrients and the combination of different kinds of forest stands on a hillside. **Forest ecosystem management** includes the design and application of silvicultural solutions that are based on analysis of all the ecological factors known to operate in the system involved. In other words, silviculture has always been ecosystem management, provided that it is conducted on the basis of such analysis. Ecosystem management is one of the keys to maintaining biodiversity for it requires consideration of the interaction and habitat requirements of all living organisms.

Silvicultural treatments achieve their results through deliberate manipulation of the forces represented by physical, chemical, and biological processes that alter ecosystems in somewhat the same manner that purely natural forces produce changes in ecosystems. In ecosystem management, it is necessary to consider the spatial arrangement of stands of differing ages and species composition and how they vary within an ecological site condition. In other words, it is best if silvicultural planning and forest management are not restrained by boundaries of stands and ownerships. Insofar as possible, such planning should consider the landscape scale in which ecosystem boundaries are defined by watersheds, climate, topography, and the ranges of plant and animal species.

All good ideas survive to be overdone, and the ecosystem concept is no exception. It is too easily translated into the philosophically attractive concept that each biotic community is a superorganism in which each constituent species is indispensable and somehow depends on every other species. Although it can perhaps be said that every part of an ecosystem has some effect, even if minuscule, on every other part, each part does not depend on every other part. There are many important interactions between particular species, such as symbiosis and competition, predation and parasitism, or simply shading of one plant species by another. Although these interactions need to be recognized (and used) in silviculture, they do not mean that all parts are like essential cogs in a whole engine. The vast majority of species are adaptable to many different conditions and often move around independently of their associates. If two different species are dependent on each other, they are usually adapted to move or respond to change together.

Natural disturbances and subsequent development processes commonly lead to the development of particular combinations of species of trees, lesser plants, animals, and other forms of life on particular kinds of sites in a given climatic region. These are called **communities**. Some species within them are dependent on others. For example, pines depend on mycorrhizal species of fungi; herbivores, on the foliage; and bark beetles, on dead or dying trees. However, most of the trees and other organisms are not dependent on each other, and the weight of evidence is against the idea that they have, as is often claimed, lived in association and been dependent on each other for millions of years.

Evidence from pollen deposits shows that most tree species have moved around quite independently of each other since the continental glaciers started to shrink about 15,000 years ago. Most modern plant communities, including those in the tropics, are less than 8000 years

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old and have responded to climatic changes that have taken place even more recently (Davis, 1983; Delcourt and Delcourt, 1987; Hunter, Jacobson, and Webb, 1988).

There does, therefore, seem to be some entirely natural precedent for silvicultural changes in species composition of forest ecosystems. However, this does not mean that all changes, subtractions, or additions are safe or desirable. Changes should be made only in the light of the best knowledge available about relevant mutual relationships between species in natural forests of a locality. Foresters who deal with any managed forests should always watch for undesirable (and desirable) consequences of departures from more natural conditions and be ready to act on the knowledge.

In considering silvicultural manipulations of ecosystems, it should be recognized that the same degree of "naturalness" cannot be maintained in all forests. Not all silviculture should mimic the old-growth stage of development, even if there was enough freedom from disturbance to allow it. Just as there are variations in intensity of silvicultural practice, so should there be variations in "naturalness." It is also necessary to recognize that most forests situated where silvicultural management is feasible are already significantly modified by human action (Whitney, 1996), so it may be virtually impossible to return to a pure state of nature.

Natural preserves should be extensive enough to maintain all native species and represent all natural habitats; it is not enough to confine them to forests, such as wilderness areas that are merely difficult of access. Many stands from which wood is harvested can be expected to maintain most of the biodiversity of an area if appropriate attention is given to the relative dominance of species and the characteristics of silvicultural disturbances. Intensively managed forests, such as plantations, do not necessarily maintain a high degree of natural diversity; however, even these maintain most of the basic ecosystem equilibria, such as high biological productivity, uptake of carbon dioxide, retention of nutrients, control of erosion, and regulation of hydrologic processes.

This chapter systematically describes the ways foresters should first interpret the differences in forest vegetation and in the variations of soil and environment across a landscape. These interpretations create the basic planning units upon which to apply silvicultural treatments. This process and its end products include an understanding of: (1) ecological site classification; (2) stands and stand maps as the basic management units in silviculture; and (3) protocols for integrated landscape-level assessments and planning. They can be considered the basic building blocks for any vegetation management of a forest, woodland, or natural resource landscape, whether in a wildland area, an agricultural landscape, or in an urban environment. This chapter first provides a rationale for identifying and classifying sites and then describes the different methods of developing a site classification, either indirectly through measures of tree height (site indices) or plant indicators, or directly through soil analysis and measures of landform. Ecological site classifications are conveyed through case study examples. This chapter then describes the protocol for defining the spatial and temporal scale of stands as the basic management units of silviculture. Stands are usually defined within a site classification system, and are identified by similarity in age-class distributions, species composition, and stocking densities of vegetation. Finally, a rationale and protocol for landscape- and regional-scale planning are provided using ecological guides and benchmarks based on an understanding of natural forest disturbance regimes.

Ecological Methods of Identifying and Classifying Sites

One of the ideals of silviculture is to place the right tree in the right place with just the right amount of growing space at each stage of development. Questions about what is right usually involve much opinion and analytical thought about ecology and social objectives. One extreme view is that the vegetation composing a stand should consist of those species and genotypes best adapted to survive and reproduce on the site as a result of many generations of natural selection. However, the attributes that provide for survival of the species are not necessarily those that meet the requirements of people and societies. The natural composition is, furthermore, neither static nor well defined; it is instead dynamic and subject to continual changes resulting from developmental processes initiated by competition or natural disturbance. This means that even if one adheres to the natural composition ideal, a choice must still be made about which developmental stage or developmental pathway to imitate. Another problem with this approach is that human disruptions have made it very difficult to know what natural compositions might have existed in many locales.

At the other extreme is the view that silvicultural engineering can make people's desires for a particular species composition come true, as is the case with much of modern-day agriculture. This is the idea of modifying the site to fit the crop or plant selected. However, problems such as getting trees to survive through dormant seasons cause foresters to stop short of fully imitating the intensive agriculture of arable annual crops. One may move maize from Central America to Minnesota, but the same cannot be done with Honduran mahogany. In fact, one cannot safely move trembling aspen from a moist site to a dry one within a Minnesota farm woodlot.

Because neither natural factors nor human wants can be ignored, the most logical courses lie between these extremes and also vary with the circumstance. The first step in this course setting is to determine the limitations imposed by the environmental factors that collectively constitute the site. This restricts the number of species to be considered in the second step, which is to choose the species (plural or singular) that will most nearly meet the social and ecological objectives of stand management. A third step is consideration of the degree of artificial control that will be exerted over the genetic constitution of selected species. This may range from simply accepting the existing genetic makeup of a species to using intensive breeding methods in order to develop more desirable genotypes.

The basic objective is to use genetic material that will not only survive and thrive on the site but also yield the wood, fiber, biomass, or some other environmental benefit (e.g., fruits, medicinals, resins, aesthetics) at some optimum rate. However, it should be noted that suitable "genetic material" is seldom any single genotype. Even if only a single species is to be used, it is best to maintain some degree of genetic variation within each stand with multiple genotypes. A better choice may also be a combination of many species in mixture.

Nature of Site or Habitat

Anything that is done in silviculture should be based on knowledge of the capacities and limitations of the site or habitat in which the trees are to be grown. Although the term **site** is the traditional one denoting the total environment of a place, **habitat** more fully denotes the idea that the place is one in which trees and other living organisms exist and interact. As far as trees and other plants are concerned, the site is controlled mainly by the total physiologically available supply of light, water, carbon dioxide, and various nutrients. The primary driving forces that control these supplies are the input of solar radiation and precipitation, which together define the climate of a region. Total annual levels of radiation and precipitation are important, but growing conditions are also affected by seasonality throughout the year, producing wet and dry seasons and summer and winter.

Solar radiation is controlled largely by latitude, and so it varies on a regional scale. It sets the absolute limits on the productivity of a site, both as the energy input for photosynthesis, and more generally in controlling the temperature range in which organisms must function. Precipitation levels vary in more complex patterns largely associated with the movement of humid air from oceans onto land masses. The balance between temperature and precipitation strongly affects plant survival and productivity. Much greater precipitation is required in Florida than in Ontario to support forest growth, because of the greater potential for evaporation from both soils and leaf surfaces in the hotter region.

For a particular location on the landscape, the effect of climate is modified by the landform, which is the nature of the surficial geological material plus topography. Landform characteristics influence the amount of solar radiation that reaches the ground through the steepness and orientation of the slope. In mountainous regions, elevational differences can directly affect the climatic inputs of precipitation, but most landform modifications of water supplies deal with how water moves after it has reached the ground. The depth and porosity of the soils govern whether water is drained freely or is retained for some time in the rooting zone. The topographic position on the landscape (e.g., hilltop, lower slope, or floodplain) further affects the water status of a site. And lastly, the specific nature of the soil texture (sand, silt, clay content) adds a further modifying force by affecting water retention and the capacity for nutrient exchange. However, most of the important attributes of a site can be described by **climate** and **landform**.

Sites can be usefully categorized in terms of the limitations imposed on plant growth by shortages of one or more of the basic factors (light, temperature, water, nutrients). The supply of water is generally the most important factor that differentiates sites. The physiological availability of water is limited by absolute shortages (e.g., freezing from low temperature), or the inability of roots to take up water that does not have enough oxygen to allow root respiration, such as in bogs and swamps. Carbon dioxide is deficient in some circumstances, though with ever increasing levels in the atmosphere there are signs that this is acting as a fertilizer, but in other instances another nutrient becomes more limiting (Ainsworth and Long, 2005; Finzi *et al.*, 2006; Finzi *et al.*, 2007). Solar energy mostly varies on a regional scale, but slope and aspect in steep landscapes can alter temperature regimes and consequently the water status of a site, even if precipitation is not affected. The effect of soil nutrients is exceedingly variable; in general, they affect growth rates more than species composition and tend to be less important than water, though there are plenty of exceptions to this, particularly on nutrient-deficient sandy or highly weathered clayey soils (Schoenholz, Van Miegroet, and Burger, 2000).

The interaction of these physical and chemical factors clearly determines what kinds of organisms can survive on a site and also how well they can grow there. However, the organisms themselves become additional factors to consider within the local environment. Consideration must be given to how they interact with each other and how they may affect the particular species that the forester may be trying to grow either in a facilitatory (e.g., nitrogen fixation) or negative way (e.g., browsing). In this sense, browsing animals, mycorrhizal fungi, insects, or other plant species, to name only some, become part of the site or habitat factors. Regardless of the semantics, these biological factors are also part of the environment that must be carefully considered in any silvicultural decisions. In summary, the choices of tree species should be dictated by pests and other damaging agencies, as well as by physical conditions of the site mentioned earlier.

The Use of Site Analysis in Silviculture

Because it plays such a fundamental role in controlling the factors important to forest growth, regional climate should be the first consideration in site classification. Koeppen's classification of climate (Kottek *et al*., 2006) is especially helpful because it is an attempt to categorize physical climatic data by using the vegetation as the most sensitive measuring device. However, if the silviculture relies entirely on species and genotypes already existing in the region, there is little real necessity of assessing the climate because it can be presumed that the plants are well adapted to it (though this may now be negated to some extent with climate change). However, it is always critical to know about the climate when choosing to make the decisions of introducing a new species or genetic variety through planting or seeding.

Site quality assessment should be incorporated into silviculture in the following way. The first step is to measure site quality at one or more points by making observations or measurements. These usually involve tree heights and ages, presence or absence of certain indicator plants, or measures of soils, as will be described later in this chapter. The goal of such an assessment is either to determine quantitatively the productive potential of the land in order to predict yields, or to identify the ecological sensitivity and uniqueness of the land for conservation and land use planning. In industrial forestry, so much emphasis is placed on yield prediction that the utility of site classifications for guiding decisions about silvicultural treatment and species composition is often overlooked. These classifications provide diagnostic clues about those factors of the particular site that will control such variables as the susceptibility and vulnerability of trees to damaging agencies, the nature of problems with competing vegetation, and responses to various silvicultural treatments. It is only after defining site quality using a site classification system that smaller management units within this can then be defined as **stands**, the base vegetation unit for silvicultural treatment. Stands are further distinguished based on differences in land use or disturbance history (i.e., vegetation age class), species composition, and stocking (i.e., spatial arrangement and density of vegetation) (Fig. 3.1).

A problem common to many site classification methods is that they do not provide a clear way of expanding the assessment of site conditions from a point or plot to a spatial scale (Carmean, 1975; Rowe, 1996). Also, the size of the landscape unit that has a uniform site quality is not necessarily the same as an area with a uniform vegetation type or **cover type**. Cover types are the result not only of site conditions but also derive from a variety of human and natural disturbances. Foresters generally must rely on their knowledge of correlations between soils, landforms, and vegetation in a region to make an estimate of the spatial extent of uniform site conditions. Frequently, no systematic technique is available to guide this step of the process. This means that to achieve a proper stand and site classification map the first step is to construct preliminary cover-type maps. Within this map, stand units can be delineated, based on age, composition, and stocking. It is only after more resources are provided and more field experience has been gained that a site classification is developed that then allows the forester to better redefine stands within the inherent productive capacity of the landscape.

There should be two kinds of maps available for foresters to use in managing forest land. One depicts current vegetation in the form of a **stand map**; the other is a **landform map**, classifying units that define site and that predict suitability for different ecological communities, species, and growth rates. The development of the second type of map requires a good deal of time and effort, but, once available, it reduces or eliminates the need for point assessments of site when considering treatment alternatives for a stand. For these reasons, there is increasing interest in developing site assessment techniques that lend themselves to mapping. Such examples have been well developed particularly in the upper midwest (Host *et al*., 1996) and the west (Pojar, Klinka, and Meidenger, 1987).

Various methods of site assessment used in silvicultural practice are described in the next sections of this chapter. More complete reviews of these techniques can be found in Hagglund (1981), Tesch (1981), Vanclay (1992), Kimmins (1997), and Barnes *et al.* (1998).

Use of Tree Growth as an Indicator of Site Quality

The most common methods of assessing site quality depend on using direct measurements of vegetation productivity as the basis of classification. Prediction of the timber yield of a given single species on a site is frequently the specific interest, and the best criterion of this is a recorded history of production on the specific tract itself. However, this is available only where detailed records of careful management have been kept for many decades. In the absence of such records, it has become common to use rates of growth in height of the largest trees of a given species as substitute indicators of stand productivity.

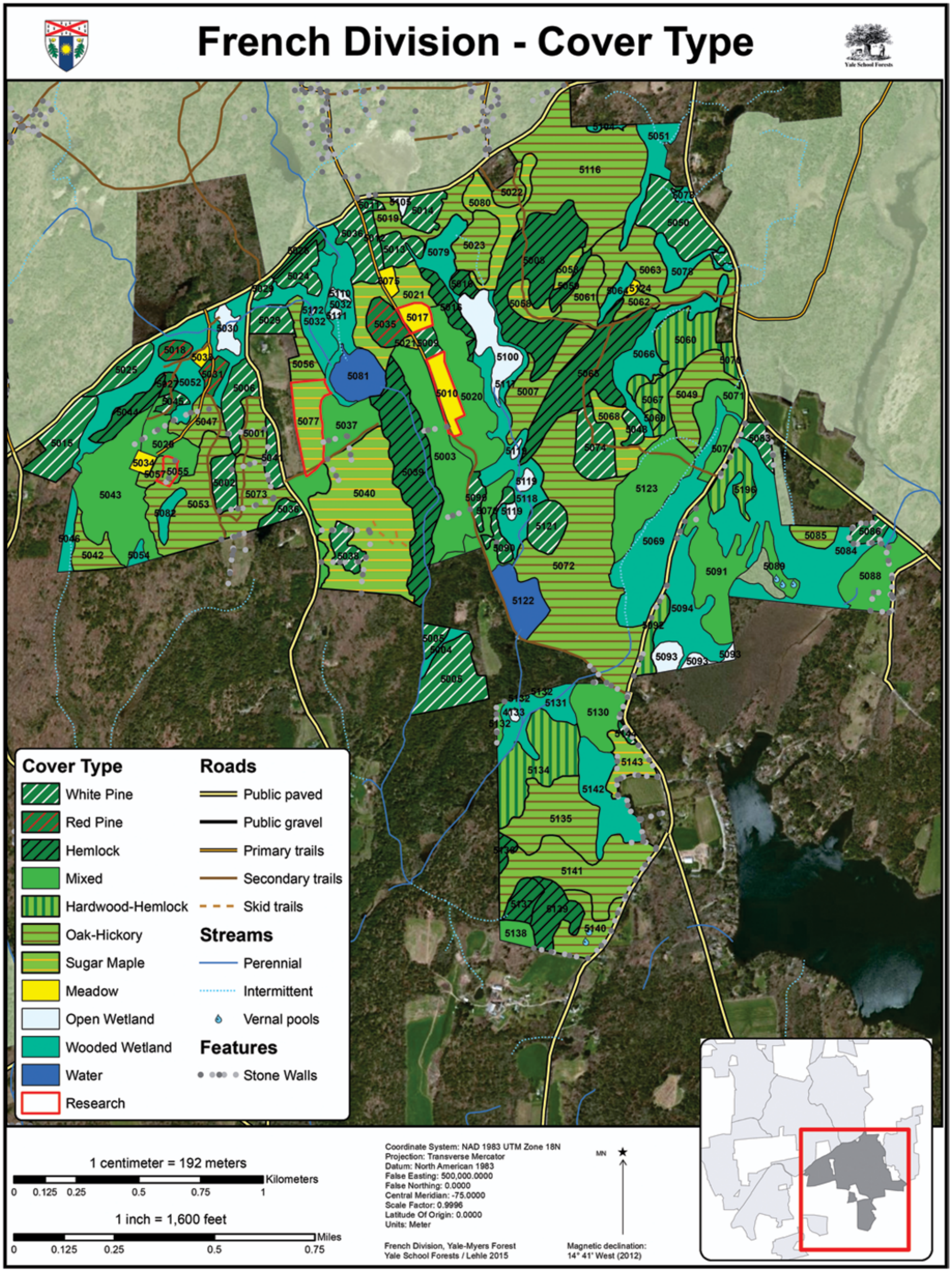


Figure 3.1 Depiction of a cover type and stand map for a division of The Yale–Myers Research and Demonstration Forest in northeastern Connecticut. The stands are identified by numbers. The cover types are depicted by color codes in the key. *Source:* Yale School of Forestry and Environmental Studies.

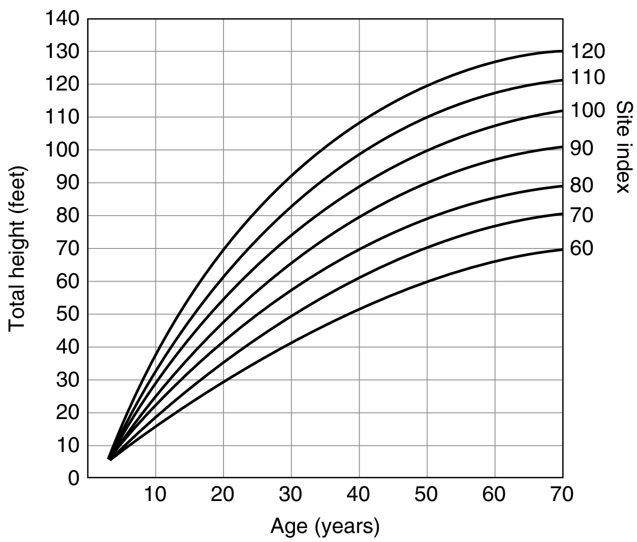


Figure 3.2 Site index curves for loblolly pine based on stem analyses of trees growing in the coastal plains of Virginia, North Carolina, and South Carolina. These curves use base age 50 at breast height as the basis for measurement and indicate seven site classes ranging from 60 to 120 feet. *Source:* Hamilton, 2000.

The most common method in use is **site index**, the average height of the dominant and codominant trees of an even-aged aggregation of trees at some index age. The index age is 50 years unless otherwise stated; the logical index age is ordinarily somewhat less than that of a normal rotation for the tree species in question (e.g., 50 years is commonly used for oak with rotation ages of 100). Other common index ages are 20, 25, and 30 years for some of the faster-growing pines and eucalyptus species. Curves of average height over age for dominant and codominant trees have been developed using stem-analysis techniques for many species in several regions (Fig. 3.2). In practice, site index is measured by determining the height and age of a sample of trees of a single species on a site. The appropriate standard curves are then used to extrapolate from the measured heights and ages to determine height at the index age. This height is referred to as the site index. The inference that can be drawn from an index is that the tree species growing on a particular site will follow the height growth pattern of the standard curve for that site. The number of trees measured and the method of choosing those trees can affect estimates of site index (Zeide and Zakrzewski, 1993). The criterion of crown class is frequently used, with the average height of a sample of dominant or codominant trees being the most common selection protocol, but the average height of dominant trees alone can also be used. The number of trees selected for measurement varies widely. More precise selection methods have also been developed, and two that are frequently used are: (1) **predominant height**, defined as the average height of the tallest 40 trees/acre (100 trees/ha); and (2) **top height**, defined as the average height of the 40 trees/acre with the largest breast-height diameters (Spurr, 1952; Clutter *et al.*, 1983; Avery and Burkhart, 2002). Other systems use a fixed percentage of trees of a certain class rather than a fixed number. Although sampling techniques vary and are identified by different names, they do not differ from site index in concept. What is important is understanding how the site index is constructed and what specific sampling regime and measurements are recommended.

The site index approach is based on the observation that the rate of height growth of the leading trees is well correlated with the productive potential of a site but is not altered significantly by ordinary variations in stand density (although very high or low density may influence the height growth of species). In the simplest application, it is necessary that the index trees have always been the leading dominant trees and have not been suppressed at any time. Periods of very slow diameter growth observed in increment cores taken to determine age are used as an indication that a tree was overtopped for part of its life. Such trees are generally eliminated from use as sample trees for site index measurement. Many dominant trees grow slowly in height during an early establishment period. This occurs when seedlings compete with dense weeds or start as advance regeneration. One way of avoiding this problem is to assess each tree's age at breast height and to take that point as the zero height level. This approach has been incorporated in some standard site index curves (Fig. 3.2).

Use of site index has become widespread, partly because it is incorporated into the yield tables developed for many commercial timber species. In fact, site index is sometimes expressed in terms of the mean annual increment of stands where growing space is fully occupied instead of height, but this is simply a matter of using the value from the associated yield table. The basis for determining site class of a stand is still the measurement of the height and age of a sample of its largest trees.

Determining tree age from increment cores is the most time-consuming part of measurement and often limits the data collection to only a few trees. Site index is easiest to use in plantations or other stands with a narrow range in ages, where only heights need to be measured for most trees. These are the situations in which a sample size of as few as 5 trees/acre (15 trees/ha) is sometimes used. In many other cases, where stands are more variable in age class, as many as 40 trees/acre (100 trees/ha) are measured.

In cases where measurement of a large sample of trees can be used in conjunction with height curves developed for that region, a precise estimate of site index can be determined. However, in most situations, there are enough sources of error in data collection, extrapolation using height growth curves, and other aspects of "measuring" a site that it is good to refrain from the spurious precision implied by expressing site index to the nearest foot or meter. One common antidote to this is the practice of assigning sites to not more than five or six rather broad categories of site quality classes, commonly denoted by Roman numerals. This is often a sufficient level of precision for making decisions about silvicultural treatments.

The different uses of site index can be seen in the example of management of eastern white pine in the northeast. White pine can grow on a wide range of sites, with productivity increasing on landforms and soils with greater moisture-holding capacity. Site index curves and associated yield tables can be used to predict the productivity of pure pine stands. However, because of the difficulty of controlling early hardwood competition on moist sites, pine is generally grown in pure stands only on relatively dry soils. The site index of oak is frequently used as a standard to classify sites based on the competitive ability of hardwoods. Sites have been divided into three categories with recommendations for (1) converting to pure pine; (2) favoring mixed pine and hardwood; or (3) favoring pure hardwood stands being associated with increasing values of oak site index (Lancaster and Leak, 1978).

Some methods of expanding or simplifying the use of site index have been developed. If the tree species of interest is not present on the site, procedures can be developed to predict the site index of one species from that of another (Doolittle, 1958; Foster, 1959). The height-intercept method can also be used, in which the index variable is the number of years required to grow from one stated height level to another. This method works with trees that produce one internode annually, so that height growth can easily be determined for levels close to the ground. Current site indices are being constructed from longer-term plots and more permanent growth records than those that were originally constructed. Now more sophisticated dynamic site equations are being used that more closely model height growth relationships over time and change in site (Cieszewski, 2001; Diéguez-Aranda, Burkhart, and Amateis, 2006).

Site index is most useful for conifers because they have a well-defined height that is relatively easily measured. Many hardwood species have rounded, spreading crowns that are more difficult to measure. The range of heights obtained in even-aged hardwood stands, even with careful measurement, is sometimes so wide as to make site index calculations almost useless. Most site indices have been constructed for species that can tolerate a wide range of sites, thus the usefulness of an index. Such techniques are not useful for tree species that are site restricted and thus their presence or absence can be used as more an indication of a particular kind of site. And finally, site indices have generally been constructed primarily for tree species that are of commercial value and so gauging their productivity on a range of planting or regeneration sites is important. In North America, such species include but are not limited to: loblolly pine (Amateis and Burkhart, 1985), lodgepole pine (Cieszewski and Bella, 1989), ponderosa pine (Milner, 1992), slash pine (Borders, Bailey and Ware, 1984), Douglas-fir (Monserud, 1985), trembling aspen (Chen, Krestov, and Klinka, 2002), white pine (Beck, 1971; Parresol and Vissage, 1998), white spruce (Alemdag, 1991) and the upland oaks (Carmean, 1972).

Other methods have been devised to replace site index in order to overcome its limitations in assessing site conditions. These include methods that: (1) lend themselves to dividing a landscape into easily mappable management units; (2) work when no trees are present on a site; (3) work in tropical regions where trees do not necessarily form annual or even seasonal rings; or (4) are based on field observations that do not require measurement of tree heights and ages. Many of these methods involve prediction of site index from other parameters.

Understory Plant Indicators and Habitat Types

Species composition can also be used to assess potential productivity, limitations set by environmental factors, and species suitability. The best-known methods, originally developed in Finland by Cajander (1926), involve use of the herbaceous plants that grow beneath stands. The underlying principle is that some of the small plants are much more sensitive to variations in site factors than large trees are (Daubenmire, 1976). Some of these plants have high indicator significance, whereas others, those with broad environmental tolerances, have little. More recently, the quantitative testing of niche theory and the applied use of understory species as site indicators have substantiated the work of the older more qualitative literature (Gilbert and Lechowicz, 2004). However, this work has also clarified the more complex interactions that can occur irrespective of site in regards to anthropogenic and natural disturbances. Such disturbances also influence understory species' presence and abundance, and therefore can be a misleading indicator of site productivity (e.g., fire history; colonization by invasives; herbivory impacts from deer) (Honnay, Hermy, and Coppin, 1999; Knoepp *et al.*, 2000; Rooney *et al.*, 2004). Use of plant indicators for site classification is therefore most successful where climatic conditions are restrictive, as in the boreal forests where these methods were originally developed. In those and other forests where large areas are dominated by a single overstory generalist species, distinguishing among several understory species can be used to predict site index without measuring tree heights or ages. There are, for example, large areas covered with Douglas-fir (Green, Marshall, and Klinka, 1989), but much information can be obtained about the site by noting whether the understory has sword ferns (an indicator of richer, higher-fertility site) or rhododendrons (an indicator of a poorer, lower-fertility site). In most cases, understory plant indicators are no longer used alone but are incorporated into more holistic approaches such as in the white spruce and lodgepole pine regions of Canada (Strong *et al.*, 1991; Meilleur, Bouchard, and Bergeron, 1992).

Especially in western North America (Daubenmire and Daubenmire, 1968; Steele *et al.*, 1981), some success has been achieved with using the late-successional plant communities as the basis for site classification. In this approach, a set of site units, referred to as **habitat types**, is identified by the characteristic overstory and understory species that occupy certain elevation and physiographic conditions; the names of the habitat types are taken from dominant species in each layer (e.g., *Pseudotsuga menziesii/Symphoricarpus albus* habitat type). A taxonomic key based on the presence of indicator species was developed and is used as the basis for field identification. Field techniques involve the use of **releves** – a method of plot measurement that quickly assesses the relative abundance of species in each vegetation layer without detailed measurement. Precise measures of species' abundances are not necessary because the presence or absence of certain indicator species is often the criterion most indicative of site conditions.

Habitat-type mapping has been used throughout the Rocky Mountain region as the basis for predicting site quality, assessing wildlife and livestock forage productivity, estimating water production, and other purposes. This mode of site analysis and mapping works best where species composition is mostly the result of natural processes (e.g., Fig. 3.3). Even in those cases, it is necessary to use elevation and other landform features to guide mapping where late-successional vegetation is not present. This is most easily done where strong variation in elevation and topography exists.

The habitat-type approach has been used on a more limited basis in areas that have been heavily disturbed by agriculture, such as the Great Lakes region (Kotar, Kovach, and Locey, 1988), southern and central New England (Whitney and Foster, 1988) and the White Mountains of New Hampshire (Leak, 1980, 1982). Important differences in site types have been determined by studying correlations between physical site characteristics and the composition of relatively undisturbed vegetation in the limited areas where such vegetation

(a)

Figure 3.3 (a–e) A series of photographs showing old-growth forest vegetation characteristic of markedly different sites, each requiring correspondingly different silvicultural treatment, all in northern Idaho. **(a)** The lowest and driest site with a pure stand of ponderosa pine.

(b)

(c)

Figure 3.3 (Continued) **(b)** An open stand of ponderosa pine on a south-facing, dry slope at middle elevations. A closed stand of the so-called western white pine type, such as shown in c, occupies the opposite north-facing slope. **(c)** A mixed stand of the western white pine type on a mesic north-facing slope. The nearest tree is a western larch; the one to its left is a western white pine; the one with vertically striped bark to the left of that is a western redcedar; some of the understory saplings are white firs.

(Continued)

(d)

(e)

Figure 3.3 (Continued) **(d)** A 225-year-old stratified mixture of the western white pine type on a mesic valley-bottom site below the stand shown in b. Among the other species present are western larch, western redcedar, and western hemlock, with the two latter species in the lower strata. **(e)** A pure stand of white-bark pine characteristic of very cold sites at high elevations in the same locality as a and d. *Source:* **(a–e)** US Forest Service.

could be found. In these regions, landforms and soils have been used as the basis for mapping because of the scarcity of undisturbed vegetation over most of the landscape. The importance of landform in identifying habitat types in the field is evident in the White Mountains classification system. Here the type of glacial deposit is the fundamental basis for mapping land into one of 11 habitat types and is also used as the name for each type, instead of using the names of indicator species (Leak, 1982). There is therefore a rich history of using plant indicators of site but its usefulness varies by region and land-use history.

Analysis of Soils and Topography

Considerable interest has long existed in developing ways to predict potential forest productivity directly from soil and topographic variables, without using trees or other vegetation as indicators. Many studies have developed predictive mechanisms in the form of multiple regression equations in which site index is determined from a number of independent site variables (Armson, 1977; Pritchett, 1979). This approach to site classification often requires deep digging to examine the soil structure and collect samples for subsequent determination of physical and chemical properties (Soil Survey Staff, 1975). Because it has generally proven impractical, there are few examples of such systems being put into practice. These techniques have been most useful where large plantation projects have been established in areas in which forest vegetation was sparse or absent. No alternative methods were available in these situations, and financial resources were available for detailed soils analysis and mapping. One example of this is the Baker–Broadfoot (1979) method used to evaluate sites for hardwoods of the lower Mississippi region of the southern USA. The method uses simple site/soil characteristics for selecting species for reforestation. It has proven useful despite the flat landscape, just small topographic differences can cause dramatic changes in hydrology and soil texture.

The greatest value of soil-site studies has generally been for basic research that has elucidated the most important factors controlling forest growth, even if some of these are not easily measured. The variables that define the availability of water have been identified as the most critical. These include depth to bedrock or hardpans, which determines the depth of the rooting stratum, and soil texture, which governs the capacity of that stratum to store water (Barnes *et al*., 1998). Variables that measure nutrient status have generally been less important. To be useful in silvicultural practice, this technique depends on assessing factors that can be measured on one visit to the site. Therefore, the annual regime of soil moisture must somehow be deduced from appropriately selected, semi-permanent, observable parameters of soil and site.

The shape of the terrain is often key, usually because it tells so much about the water relations that are usually the chief ruling factor for plant growth. For example, the lower slopes of most hillsides are concave; thus, they receive more water from upslope than directly from the sky. Water from the convex hilltop seeps downslope, leaving the upper slopes robbed of soil moisture. The boundary between convexity and concavity sometimes defines differences in species composition and productivity. Unless they have sandy soils, very flat areas can be poor sites full of stagnant, oxygen-deficient water. If the terrain is steep, the slopes that face the sun can be very dry while the opposite shaded ones are comparatively moist. This difference can be enough to induce grassy brushfields on sunny slopes and closed forest on shaded ones in climates with long dry seasons, such as in the Rocky Mountains. Good examples of the use of terrain as an index to site productivity have been developed for the Appalachians (McNab, 1989, 1993). Current use of digital elevation maps and geographic information systems (GIS) can be very useful for developing a terrain index (Bolstad, Swank, and Vose, 1998). High-resolution spatial imagery can now depict topographic relief at refined scales that allow modeled water, solar radiation, and temperature gradients to predict and create vegetation and productivity maps (Dymond and Johnson, 2002; Thenkabail *et al*., 2003; Wulder *et al*., 2004).

An analytical and predictive understanding of site variables can often be based on good knowledge of geology and especially geomorphology. The climatic factors that have weathered rocks and moved the products of natural erosion also determine the composition and shape of the parent materials from which soils are formed. If it is known how the parent materials got where they are, it becomes possible to learn a good deal about the extent of a particular kind of terrain form and its ability to support forest growth merely by viewing it from a distance or on a topographic map. Knowledge of surficial geology helps not only in determining species composition and predicting yield, but also in developing wildlife habitat areas, building roads, planning logging, protecting watersheds, and controlling erosion.

The shortcomings of direct soil analysis techniques described above can be overcome by using soil type maps. These are available for many parts of the world and contain information on the variables that are difficult to determine in field sampling. However, these maps have proven to be of surprisingly little value for silvicultural use because nearly all soil classifications have been devised with agricultural needs in mind and therefore only focus on the characteristics of soil in the top 3 ft (1 m). Forests are much deeper rooting and require additional characteristics for interpretation of their growth. Although people who map the soil must have a detailed understanding of the relationship between topography and soils, landform characteristics are generally not an integral part of the soil-typing process. However, landform and its association with soil depth are signature characteristics that can be used to interpret growth and composition of forests (Rowe, 1984). A case in point is that the old Soil Conservation Service maps (now digital) still used throughout the US are a useful first effort, but they often need considerable verification and realignment when on the ground.

Each kind of landscape – mountain ranges with volcanic deposits, ancient peneplains with heavily weathered soils, rolling terrain with glacial deposits, and many others – has a distinctive set of landforms. Knowledge of these is often more important to foresters than are the details of soil structure. Maps of soils that use landform as an integral part of the definition of mapping units are very valuable for silvicultural planning (Rowe, 1984). One example of the effects which different kinds of landforms and soils have in controlling the composition and vigor of forest vegetation is found on the flood-plains of snakelike meandering rivers. Frequent flooding events continually destroy and rebuild the "bottomlands" through which they flow (see Box 3.1).

Ecological Site Classification

Most of the site classification methods described in this chapter are not used alone, but are combined with others to make them more useful and more efficient in application. Some multifactor systems explicitly recognize that a combination of the four basic parameters (climate, landform, soil, and vegetation) provide the most complete approach. In many regions, maps already exist for all or most of these factors, and some efforts at multifactor classification are based on using these multiple layers of information to define a set of distinctive site units. However, unless these are based on recognition of the relationships between these four elements, such systems cannot be considered "ecological" (Barnes *et al.*, 1998), and may be difficult to implement.

Ecological site classification is based on a hierarchy, with climate as the dominant factor at the regional scale, and landform and soil at the landscape unit scale (Bailey, 1995). These factors generally vary along gradual gradients rather than across sharp boundaries. The importance of vegetation in the development of such systems comes in defining distinctive climates, landforms, and soil characteristics that are correlated to important differences in vegetation composition and productivity. Thus, an ecological approach would seek to define a classification of these distinctive units before mapping can commence.

This approach is the basis for defining different climate types, as in British Columbia (Pojar, Klinka, and Meidinger, 1987), where large geographic units with similar climates and forest types have been defined and mapped (Fig. 3.4). These "biogeoclimatic" units are useful for such things as identifying fire-climate zones for protection purposes or defining zones for the movement of seeds, but their most fundamental use is for defining the boundaries within which a smaller-scale site-classification system can be applied.

Site units ranging in size from 10–100 acres (approximately 4–40 ha) are of greatest value in silviculture, and are defined by landform and soil within a climatic zone. These fundamental units are considered "natural" or "ecological" units because they are not based on a derived feature (such as the height growth rate of a particular tree species).

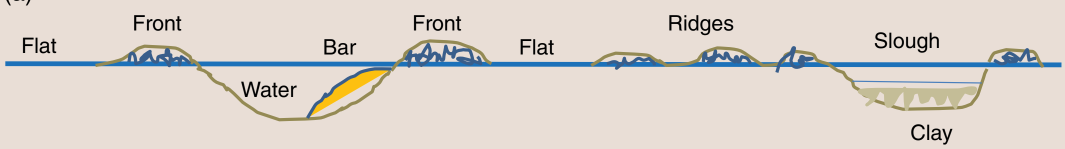
Box 3.1 A cross-section, in exaggerated vertical dimension, of the different landforms that develop on the flood-plains of meandering rivers, shown at a time when the water level is normal (i.e., not at flood stage).

Fig. 1 shows most of the kinds of terrain; differences in elevation of as small as 3 ft (0.9 m) can cause major changes in forest composition. Hodges (1995) described these remarkable differences in the bottomland hardwood forests of the southeastern US. The highest terrain, best soils, and richest species composition are found in the "fronts" right on the banks of the rivers where fine sand is deposited when floodwaters are decelerated as they spill over the banks of the river. "Ridges" are former fronts that have been left when the course of the river shifts sideways or a loop is suddenly cut off. Their luxuriant forest vegetation, which may include such species as cherrybark oak, yellow-poplar, and sycamore, differs little from that of the fronts. The series of ridges shown is a place where the river course gradually shifted from left to right before it was cut off. The "slough" that formed in the cut off loop is a place where water stands most of each year and very tight clay formations are deposited. The species that grow slowly there are those such as bald-cypress, tupelo gum, and water hickory that can survive in standing water. "Bars" composed of coarse sand form along the main river where the current is decelerated slightly as it flows around bends. Fast-growing, intolerant, light-seeded species, such as willows and cottonwood poplars, start on the bare soils exposed there. The "flats" are level soils full of clays that are deposited there when water stands for many weeks after typical floods. These wet, poorly aerated soils support such species as red maple, green ash, sweetgum, Nuttall oak, and sugarberry, that can withstand physiological dryness. Similarly distinctive guilds of species grow on these kinds of landforms along meandering rivers throughout the world.

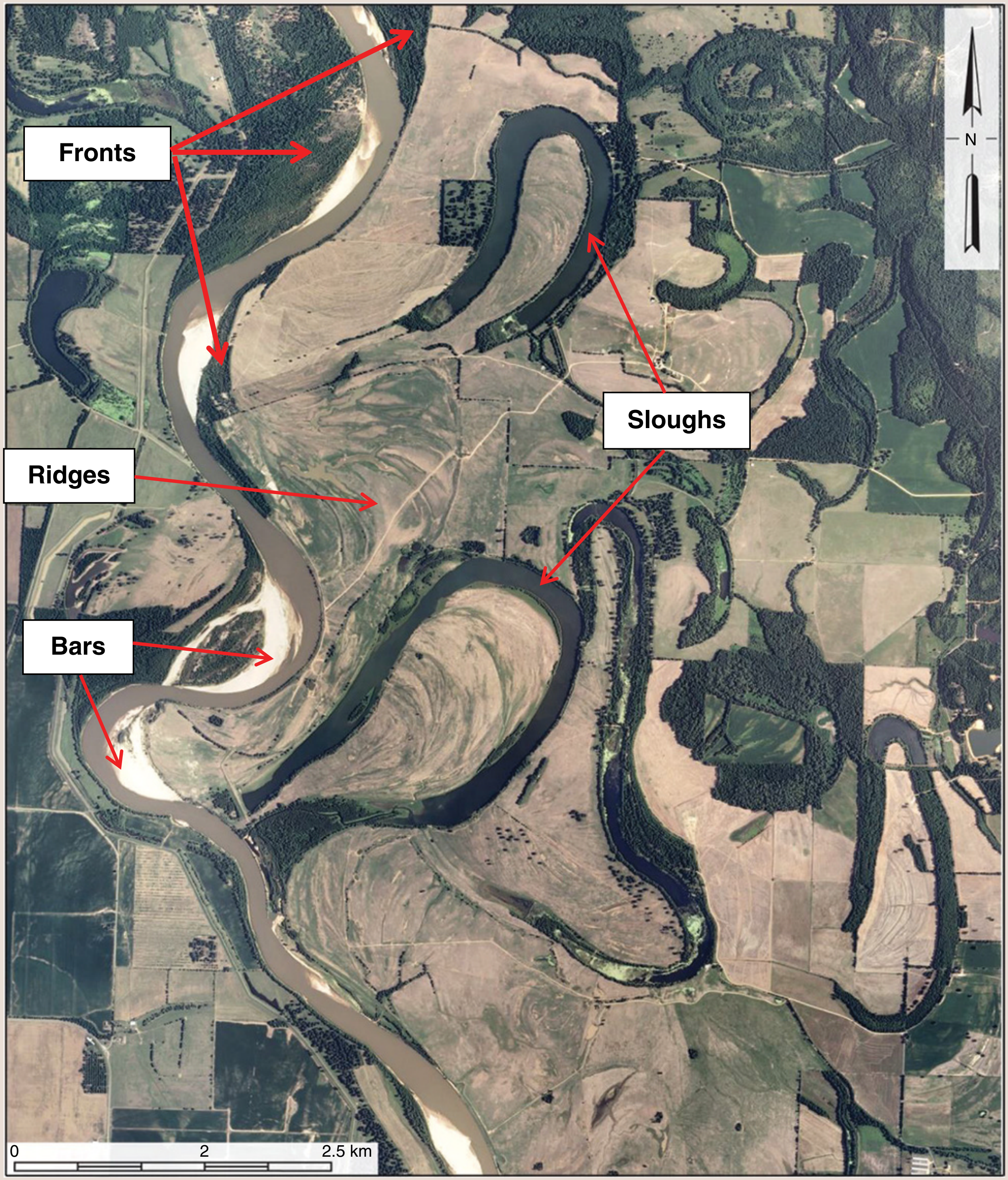
The Baker–Broadfoot method of site evaluation (Baker and Broadfoot, 1979) for southern bottomland hardwoods is a reflection of the landform processes described above, that determine changes in species composition. The site classification guide suggests species suitability for plantation establishment and is determined by using tables that describe the ranges of soil physical properties, moisture availability during the growing season, nutrient availability, and soil aeration. The guide is commonly used across the Gulf States for bottomlands.

Box 3.1 (Continued)

(a)



(b)



Box 3.1 Figure 1 **(a)** Topographic relief of a bottomland in the lower Mississippi. *Source:* Mark S. Ashton. **(b)** An aerial depiction of topographic relief of the Red River, Arkansas, a tributary of the Mississippi River. *Source:* Wikimedia Commons, The Free Media Repository.

(a)

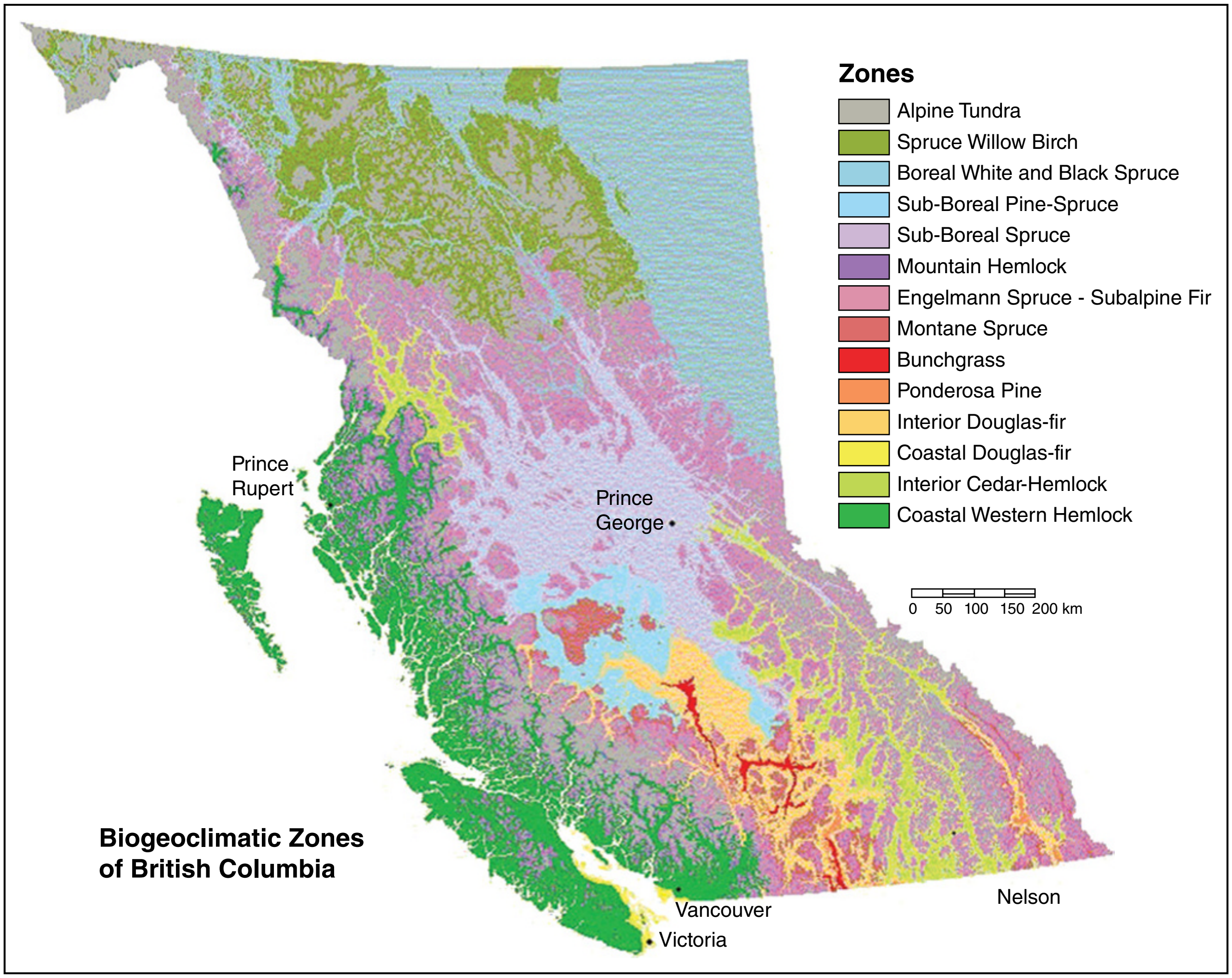


Figure 3.4 (a–c) Ecological site classification for British Columbia with an example of the mountain hemlock type. **(a)** An illustration of the biogeographic climate forest zones of British Columbia.

Rather, they are defined by the combination of climate, landform, and soil that controls the energy and material inputs to the ecosystem and are correlated with characteristic vegetation. Mapping these units can be done using a combination of topographic and surficial geology maps, examination of soils, and identification of indicator plants. Because each unit defines a consistent set of environmental conditions, it can be used to predict many parameters, including stand productivity.

One such example of an ecological site classification system was developed for a glaciated, rolling landscape in the Great Lakes region where northern hardwoods, red pine, and white pine are the principal species (Barnes *et al.*, 1998) (Box 3.2). A principal use of the system has been to identify those sites that are suitable for conversion to red pine and those that are best managed for mixed hardwood stands dominated by sugar maple. Because the site units are fundamental divisions of the landscape, they should maintain their usefulness as new management questions arise. Choice of species and other silvicultural decisions should be guided by an analysis of site or habitat, regardless of the method of classification or how the categories are named.

Stands as Management Units

The **stand** is the base management unit for applying any silvicultural treatment. **A stand is the smallest unit in forest mapping and can be defined as a spatial area where a group of trees is more or less homogeneous in regard to species composition, density, and age-class distribution**. Stands as spatial management units are usually delineated at smaller spatial scales as compared to a site-classification system. This is because within a site class, both natural and anthropogenic disturbances can vary, creating different successional compositions, age classes, and stocking densities,

(b)

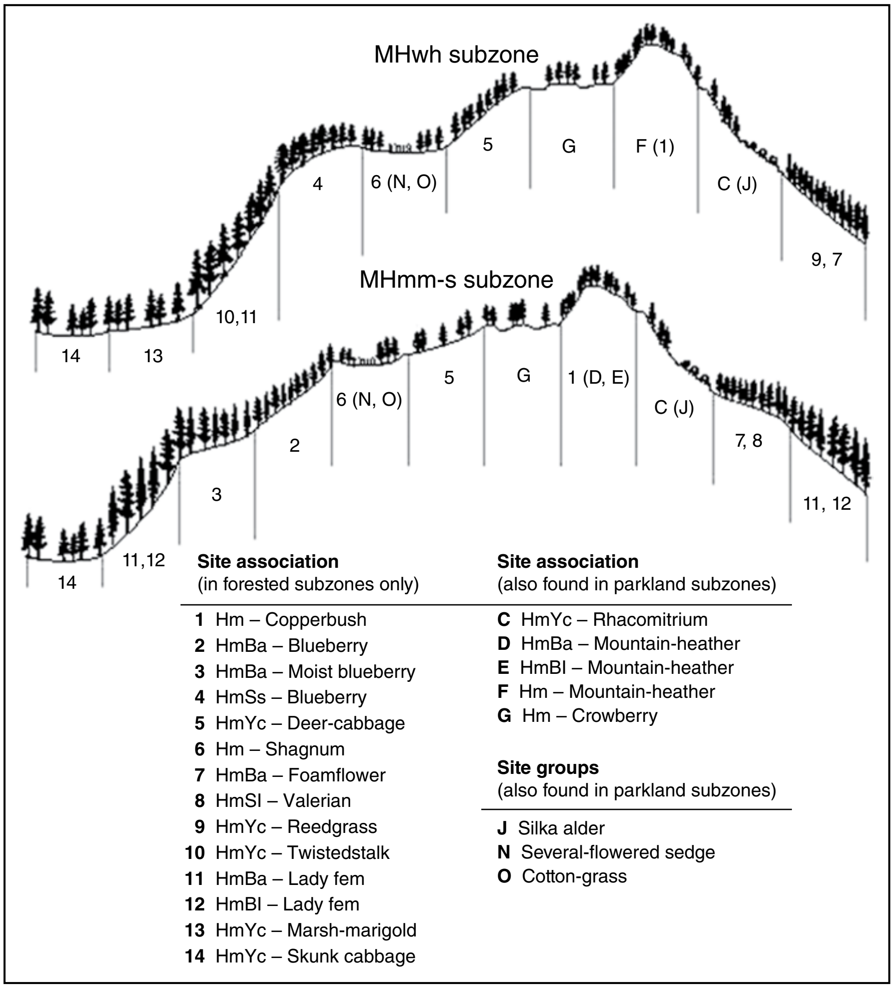


Figure 3.4 (Continued) **(b)** A cross-section of the Mountain Hemlock Zone physiography as an example of defining site differences within a forest climate zone. The Mountain Hemlock Zone is restricted to the subalpine elevations of coastal mountains of southwest British Columbia.

(Continued)

all of which create differences in forest structural heterogeneity and growth and therefore stand management units. It is unusual to define a stand at spatial scales larger than a site class. This is because stands that cross a site classification by implication would mean differences in site productivity, growth rates, and species composition making any one silvicultural treatment across such an area very difficult to implement. However, it does occur for extensive kinds of low-intensity management and for social values that are not intimately and directly dependent on forest structure and composition, such as in watershed management.

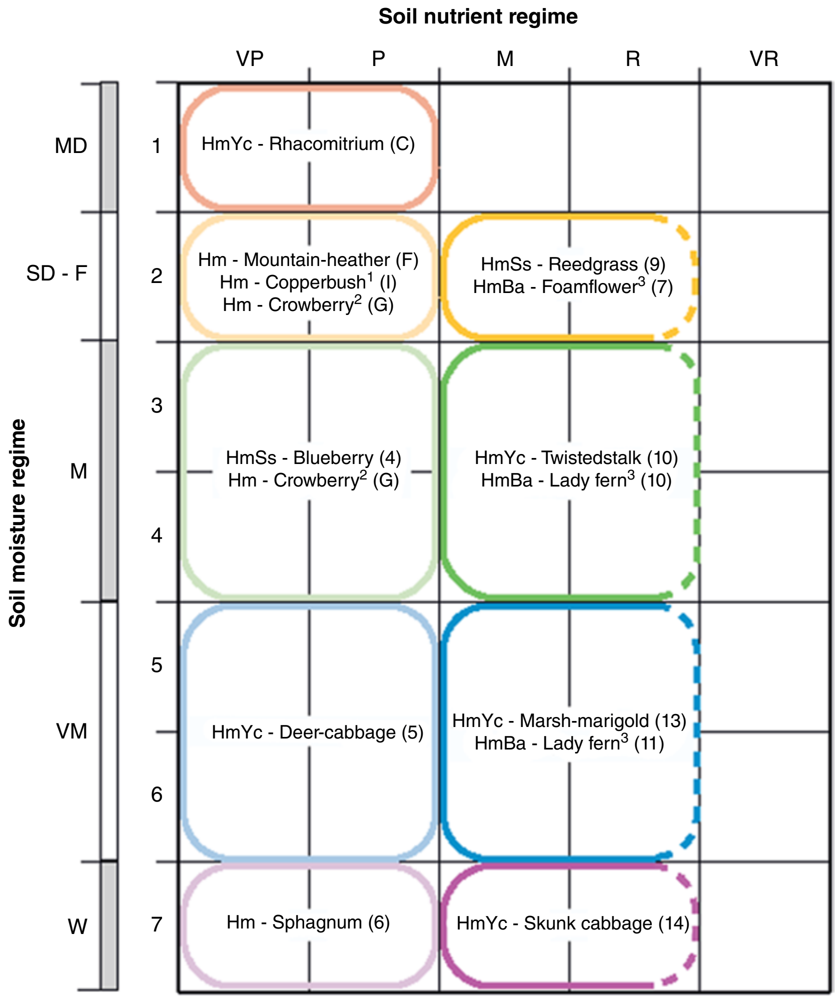
Stands as Defined by Age Class

Defining differences in age class is one very important method of delineating a stand. Regenerative disturbances, whether naturally or artificially induced, determine when new trees appear or start active development on any given unit of ground area. Each aggregation of trees that starts as a result of a single disturbance is defined as a single **cohort**. If the range of ages of trees within the cohort is very narrow, the new aggregation is regarded as a single **age class** which is also **even aged**.

For purposes of planning for cuttings and forecasting the future growth and yield of stands, it is necessary to ascribe ages to stands or components of stands that have arisen at different times in the past. This is no problem if the trees all germinated or were planted during the same year because they are clearly of the same even-aged class.

Quandaries develop when the effects or characteristics of the disturbances and the sources of the regenerating trees are so variable that the true ages vary widely. Confusion can be reduced by recognizing the difference between **chronological age**, which is the true age of the plant, and **effective age**, which is the number of years since the trees were free to start rapid growth and development into a new forest. This would be very much the

(c)



[1]only in the mainland portion of the MHwh subzone on slightly dry sites
[2]only on fresh to moist sites at the upper elevation limit of the MHwh subzone on flat terrain
[3]only in the mainland portion of the MHwh subzone

Figure 3.4 (Continued) **(c)** The temperature–moisture association with herbaceous indicator species for the Mountain Hemlock Zone. Soil nutrient regime: VP – very poor, P – poor, M – medium, R – rich, VR – very rich; soil moisture regime: W – wet, VM – very moist, M – moist, SD-F – somewhat dry, MD – moderately dry. *Source:* **(a–c)** British Columbia Ministry of Forests, 1995a. Reproduced with permission from the Province of British Columbia.

case with release-type disturbances whereby seedlings of advance reproduction origin could be many years older and of varying chronological ages as compared to their effective age at time of release. For all intents and purposes, age from release has been the defining attribute for determining age class.

A cohort therefore has an effective age even if the chronological age varies widely. It may include trees that germinated or were planted in a single year, those that sprouted from stumps or roots that were really hundreds of years old, advance regeneration of many different heights that had accumulated over many decades, or new seedlings that slowly appear for several decades after a severe disturbance. In such cases, the effective age of the whole is best dated arbitrarily from the time of the regenerative disturbance. This does not mean that one may blithely adopt any assumption that the trees of the cohort are all the same because they were all put in the same pigeonhole.

In this book, the term cohort will not be used except in cases in which chronological and effective age might often differ. Terms such as age class, even aged, and uneven aged will be used not only where the range of chronological age within a class is very small but also where it simplifies discussion to refer to a cohort as an age class. The most notable examples of the latter exception involve long-established distinctions between “even-aged” and “uneven-aged” stands that are used in developing management for sustained yield (as in Chapters 11 and 13).

Box 3.2 The major features of an ecological site classification system for the McCormick Experimental Forest in the Upper Peninsula of Michigan.

Dryland Site Units

A portion of the classification of land units, defined by landform and basic soil characteristics, with indicator species listed; a total of 21 site units were used in mapping (Fig. 1).

Deep Soils – Bedrock Below 39 in (100 cm)

A) Level to gently sloping terrain (usually 0–5%)
   1) Excessively drained sand – **jack pine/*Vaccinium***
   2) Somewhat excessively drained sand and gravel – **sugar maple/*Maianthemum***
   3) Somewhat poorly drained sand – **maple/yellow birch/conifer/*Clintonia***

B) Moderately to steeply sloping terrain (usually >5 to <30%)
   1) Well-drained loamy sand – **sugar maple/*Gymnocarpium***
   2) Moderately well-drained sandy loam on northerly aspects – **sugar maple/*Viola***
   3) Excessively drained sand on steep southerly aspects – **white pine–hardwoods/*Maianthemum***

A More Complete Description of Two Site Units

This gives assessments of productivity and other parameters and suggests appropriate management objectives. Modified from Barnes *et al*. (1998).

Site Unit 2

Flat, outwash sand plain dominated by low-vigor and low-quality sugar maple. This site has the highest sand content and greatest susceptibility to drought of any sugar maple sites.

- Total height of old-growth sugar maple 69 ft (21 m) – low productivity
- No erosion hazard
- Suitable for mechanized equipment
- Low recreation and wildlife values
- Moderately high fire hazard
- Light competition from hardwoods

Recommendation: convert to red pine for greater productivity and fertilize to improve yield.

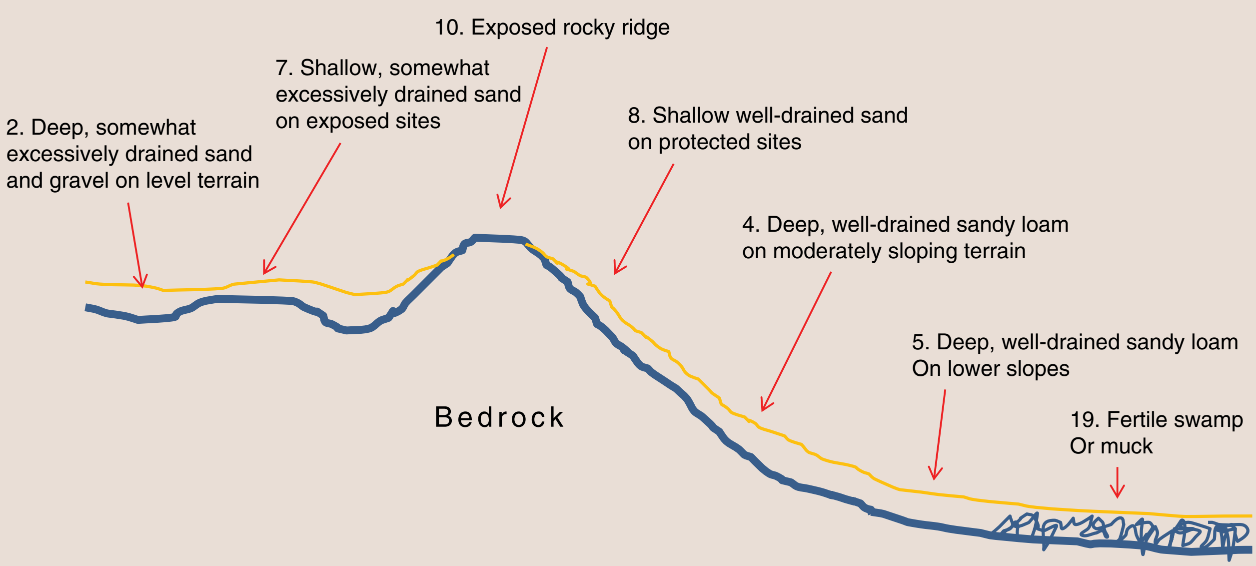
Site Unit 5

Lower slope with moist relatively fertile sandy loam soil. The site is dominated by high-quality, fast-growing sugar maple. The site has significantly less sand, more nitrogen, and higher pH than site units 1, 2, and 4.

- Total height of old-growth sugar maple 92 ft (28 m) – high productivity
- Moderate erosion hazard
- Suitable for mechanized equipment during July to November
- Moderate recreation value created by large trees and spring flora
- Low fire hazard
- Heavy hardwood competition

Recommendation: manage for high-quality hardwoods.

Source: Adapted from Barnes *et al*., 1998.



Box 3.2 Figure 1 A physiographic cross-section showing the relationship of some of the units to surficial geology and landforms. *Source:* Adapted from Barnes *et al*., 1998.

Differences in the timing of regenerative events create various spatial patterns of age classes or cohorts. The area occupied by a given cohort can be of any size, provided that it is large enough that some new trees can continue to grow in height without being arrested by expansion of the crowns of older adjacent trees. Only those truly regenerative events that leave new or small trees free to grow really affect the arrangement of age classes. Intermediate cuttings such as thinnings do not leave new trees free to grow, and thus have no effect on age-class arrangement.

There are three general types of age-class structure within stands: even-aged stands with a single age class, and uneven-aged stands. Uneven-aged stands can be further categorized as multi-aged stands with two to three age classes or all-aged stands with four or more age classes. In an **even-aged** (**single-aged**) or **single-cohort** stand (Box 3.3), all trees are the same age or at least of the same cohort. An **uneven-aged stand** that contains **two- to three-age classes** (**multi-aged** or **multiple-cohort**) represents an intermediate category in which the presence of at least **two** and sometimes **three cohorts** may be temporary or continuous. An uneven-aged stand that is **all-aged** comprises at least four age classes intermingled intimately on the same area. In reality all gradations of age distribution may be found in nature or created by cuttings designed to make way for new age classes or cohorts, but for management and communication purposes it is important to make these three basic age-class distinctions.

For some management purposes, a distinction is made between balanced and unbalanced uneven-aged stands. A **balanced uneven-aged stand** that is **all-aged** consists of four or more different age classes (or cohorts), each of which occupies an approximately equal area. The age classes are also spaced at uniform intervals all the way from newly established reproduction to trees near rotation age. Such stands, once created, may function as self-contained, sustained yield units. **Unbalanced uneven-aged stands** that are **all-aged** have four or more age classes that do not contain all the age classes necessary to ensure that trees will arrive at rotation age at short intervals indefinitely. Uneven-aged stands that are multi-aged (two- to three age

Box 3.3 Identification of age classes.

The profile of the top of a single-species stand is a good criterion of age distribution because trees of the same age grow in height at roughly the same rate, provided site conditions are uniform. An even-aged stand tends to be almost smooth on top. An uneven-aged stand is distinctly irregular in height, and the greater the number of age classes or cohorts, the more uneven the canopy.

There are several exceptional kinds of cases in which stands with more than one cohort can become rather smooth on top: (1) in very old stands, all of the trees, even those of very different age classes, may have culminated in height growth at a common level; (2) in some cases, isolated older trees that remain after cutting or some other disturbance may have decelerated in height growth sufficiently that more numerous younger trees around them catch up, and both age classes continue growing slowly in one smooth-topped stand; and (3) wind or some other climate phenomenon is continuously impeding upward canopy growth such that the canopy is flattened and windswept.

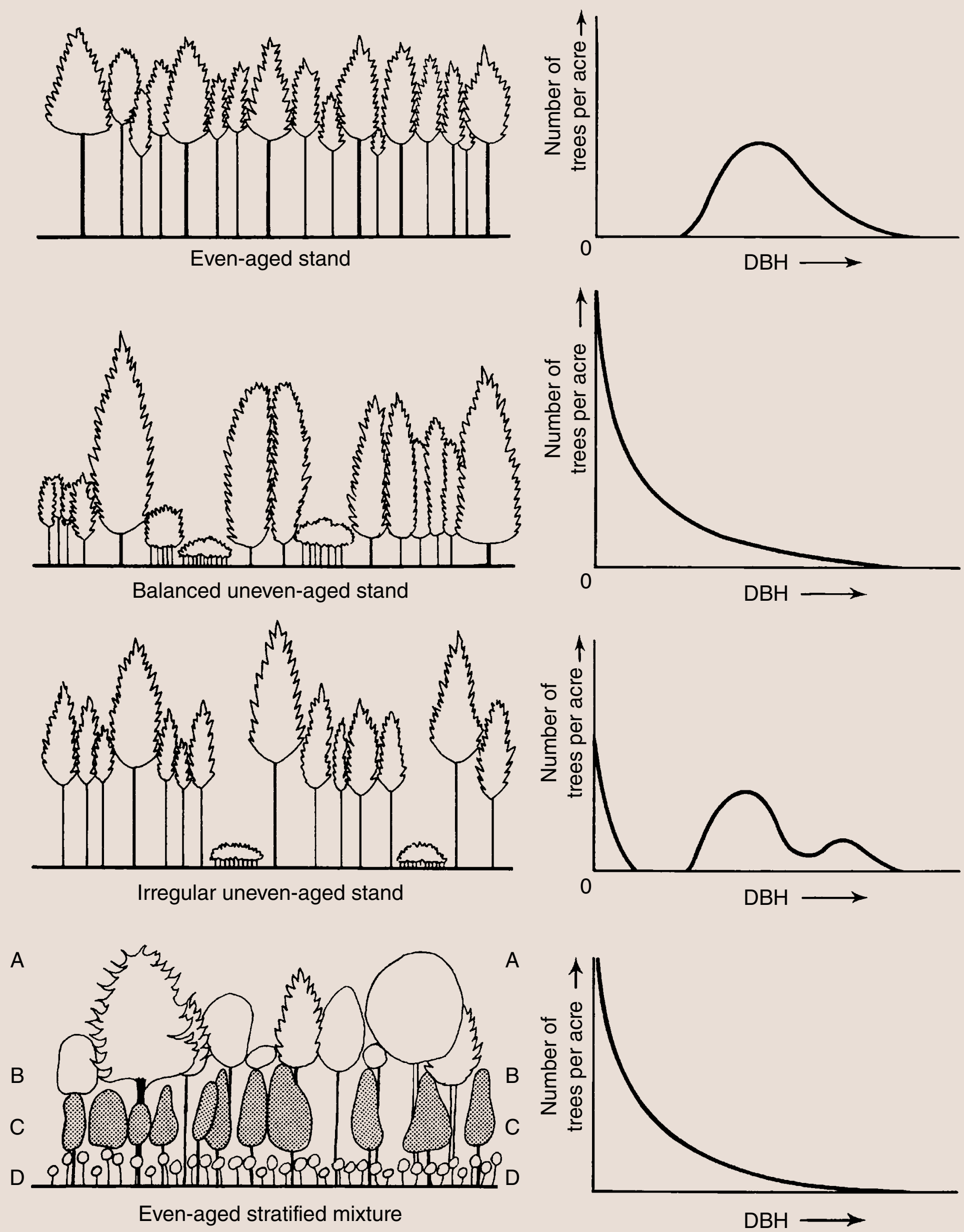
Although it might seem that fat trees are always older than thin ones, diameter is not a very good criterion of age and must be used as such with caution. The diameter growth of trees is much more variable than that in height. Therefore, the trees in an even-aged stand are not as uniform in diameter as they are in height. If a plot is made of the number of trees in each diameter class over diameter for a given pure even-aged stand, the distribution approximates the normal, bell-shaped curve (Fig. 1). The continuing loss of small trees from competition accounts for the typically abrupt slope of the left-hand side of the curve. It should be borne in mind that even-aged (single-aged or single-cohort) stands typically have a wide range of diameter classes; the age-class structure of a stand cannot be determined merely from the range of diameter classes present.

Uneven-aged stands that are balanced and all-aged are composed essentially of small even-aged groups of different ages. The distribution of diameters within each group also fits a bell-shaped curve, provided that the group consists of only one species or a number of species that grow at the same rate in height and diameter. However, as each little even-aged group grows older, competition reduces its number of trees, rapidly at first and more slowly later on; the point may even be reached where only one tree remains from 100 or more. Therefore, if each age class occupies the same area, the composite diameter distribution curve for a balanced uneven-aged (all-aged) stand (Fig. 1) follows an asymptotic relationship commonly referred to as "reverse-J-shaped," or simply "J-shaped."

If the age classes or cohorts of an uneven-aged stand differ widely in age (e.g., unbalanced), they are revealed as humps on the diameter distribution curve. The diameter distribution of each even-aged component broadens with age and will also be modified if the age class is composed of different species that grow at varying rates.

The most accurate assessment of the age-class structure of a stand comes from actual counts of annual rings. It is seldom reliable to depend on the criteria illustrated in Fig. 1 until direct age determinations have been made in representative stands typical of a locality. When such counts are made, consideration should be given to the fact

Box 3.3 (Continued)



Box 3.3 Figure 1 Typical examples of four different kinds of stand structures show the appearance of stands in vertical cross-section and corresponding graphs of diameter distribution in terms of numbers of trees per unit of area. The trees of the first three stands are all of the same species. The third comprises a multi-aged (three-aged) stand. The fourth stand consists of several species, but all of the same age. (DBH, diameter at breast height). *Source:* Mark S. Ashton.

that many species start as suppressed advance regeneration beneath older trees. In such instances, the effective age (i.e., the period since the trees were released) is more important than the chronological age. In other words, any core of fine growth rings around the pith is best discounted in assigning a tree to its proper cohort. With species in which this phenomenon is common, the number of annual rings at breast height is a good approximation of effective age if there is no tight core of rings at that level.

Differences in age distribution are most easily recognized in pure stands and in mixed stands composed of species with rates of height growth so nearly identical that the trees of a single cohort are aggregated into a single stratum in the crown canopy. However, even-aged mixtures of tree species usually segregate into different canopy strata and exist as **stratified mixtures** (Fig. 1) in which species of differing ecological status occupy different strata. The structure and development of these are considered later in this chapter.

classes) are almost always, in nature or through management, unbalanced with one dominating age class that is usually the youngest. Examples of unbalanced age distribution can include virgin old-growth stands and stands that have been partially cut without plan. Unbalanced uneven-aged stands are common and may be highly desirable, as long as they are recognized and treated for what they are. The term irregular is often used to describe unbalanced multi-aged stands of two to three age classes.

To summarize, the definitions of "even-aged" and "uneven-aged" remain similar to most interpretations by others (e.g., Nyland, 2016). The terms "cohort" and "effective age" are merged to define age, for silvicultural purposes, as the time of release or growth after disturbance and establishment. Three age classes (cohort classes) are used. These best broadly characterize the regeneration methods described in the book – single-age (even-aged); multi-aged (two to three aged, unbalanced uneven-aged); and all-aged (balanced uneven-aged). This follows the logic of Oliver and Larson's cohort classification (Oliver and Larson, 1996) but is more refined in defining age class than O'Hara's classification of multi-aged as anything more than a single age class (O'Hara, 2014).

Combining Differences in Age, Composition, Stocking, and Site to Define Stands

Species composition is another attribute defining stands. Identifying stand boundaries by species composition can be done by characterizing species change in stem density and basal area. In nature, species compositions change as a reflection of: (1) inherent differences in site quality

(a)

(b)

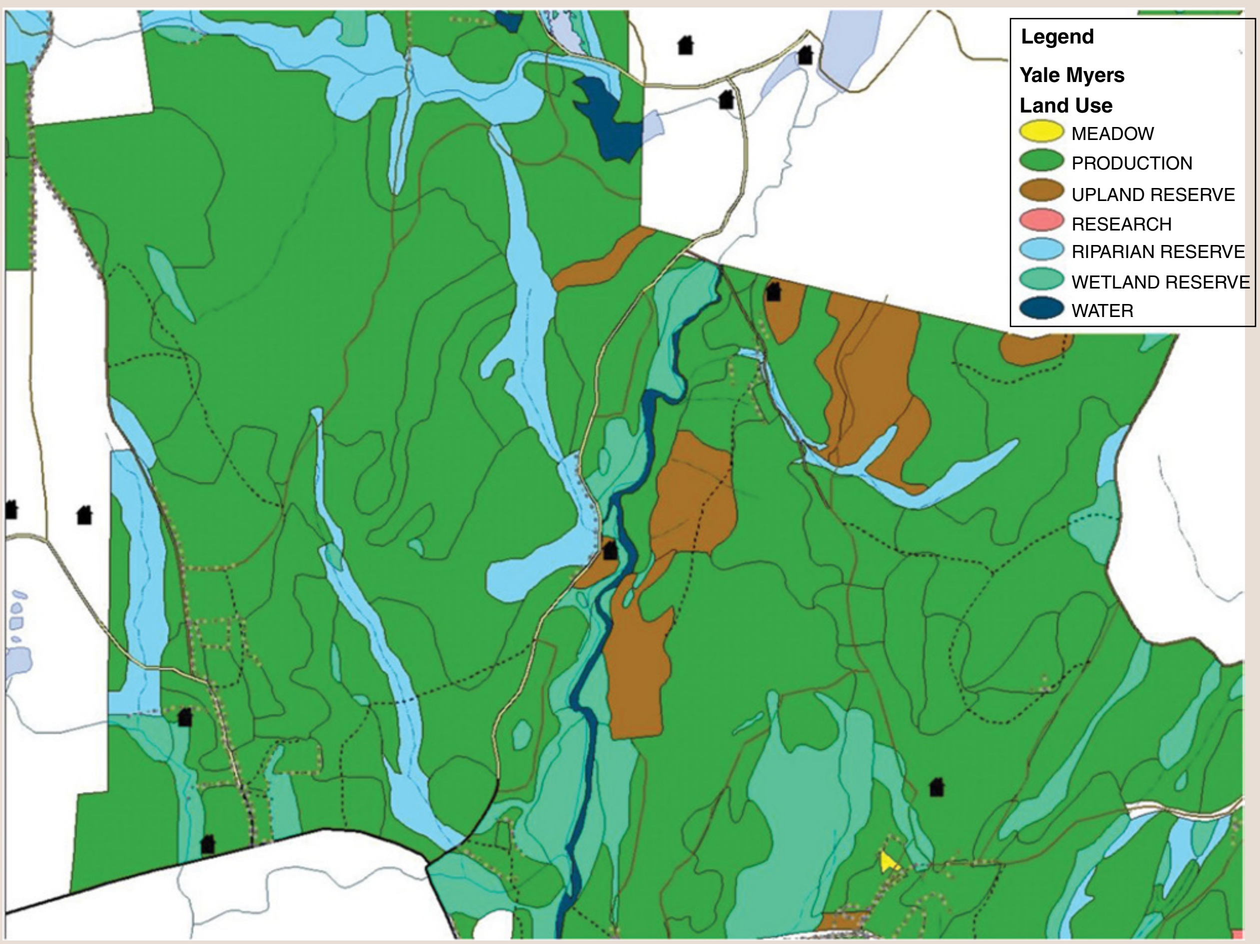
Figure 3.5 **(a)** A photograph of the foothills of the western Himalaya, India. Stands can easily be identified by marked differences in species composition across the topography. The drier spur ridges are dominated by a hard pine, *Pinus roxbughi*, while the slopes and gullies are dominated by evergreen oaks (*Quercus leucotrichophora*, *Q. floribunda*). *Source:* Mark S. Ashton. **(b)** An aerial depiction of the forest canopy and its variations in tree density, species composition, and age class across varying sites. The white lines in the foreground define various stands based on crown density and size, and species composition. Yuganskiy Nature Reserve, Siberian taiga, Russia. *Source:* Adapted from T. Bulyonkova, 2012 under the terms of the Creative Commons Attribution Share-Alike licence CC-BY-SA 2.

(site class) such as across a gradient of dry, moist, and wet topography; and (2) type of disturbance and the developmental stage of the stand (successional stage). Finally, differences in densities of trees (stocking) can also be used to define stands. In nature, densities are often different in one area as compared to another because of limitations in seed dispersal or because of competing non-woody vegetation such as ferns and grasses in some areas versus others. All these attributes taken together – age-class distribution, species composition and density, and variations in site quality and site classification – provide an integrated protocol for defining a stand (Fig. 3.5).

Since stands are the basic management unit for the application of silvicultural decisions and treatments, they are therefore the basic unit of land-use planning in forests. This requires the careful identification of stands for different social and management objectives. In some cases, management goals can be complementary, such as timber production and early seral wildlife habitat. Stands can have a number of compatible social values, but where management objectives are incompatible, stands need to be separate so decisions can be made to meet both objectives (e.g., protection of old growth and early seral wildlife habitat) (Box 3.4).

Box 3.4 The rationale and development of a stand-based land use map for the Yale-Myers Research and Demonstration Forest in northeastern Connecticut.

The core reserve design (Fig. 1) is built around the most ecologically and hydrologically sensitive sites comprising open and wooded wetlands and riparian forests that form a network of corridor-shaped stands throughout the production forest. Upland reserves comprise inaccessible ledges and areas of important upland ecological value. They are connected to the greater reserve area via the riparian reserve system. About one third of the forest is in some kind of reserve but this changes with the proportion of wetland/riparian area and steep and rocky slopes and ridges as compared to "workable" slopes and soils that are not sensitive to erosion and compaction.



Box 3.4 Figure 1 Stand-based land use map for the Plusnin and Curtis Divisions of the Yale-Myers Research and Demonstration Forest. *Source:* Yale School of Forestry and Environmental Studies.

New Developments in Landscape-Level Ecological Planning

Many researchers now argue that at the larger scales of landscape and physiographic region within which stands have been defined, the intensity of silviculture and forest management practice should emulate the disturbance cycles and the structure and composition of the original presettlement forest. Research has matured to develop a sufficient body of work that has been enough to define itself as "New Forestry" or "Ecological Forestry" (Kohm and Franklin, 1997; Seymour and Hunter, 1999; Seymour, White, and de Maynadier, 2002; Perea, Buse, and Weber, 2004; Long, 2009). However, this work has evolved in places where natural forests are extensive, human populations are low, and ownerships of such forests are large. These forest regions have strong public ownerships and influences such as Canadian Province lands and US National Forests of the sub-boreal, boreal, western temperate coastal, and intermountain regions of North America. There has been enough work now to merit changes in management of these forests to the degree that new regulations and statutes have begun to define management regimes that are first and foremost guided by benchmarks of spatial and temporal patterns of natural disturbance. These regulations consider landscape and regional-scale ecological factors as the first priority (Ontario Ministry of Natural Resources, 1996; British Columbia Ministry of Forests, 1995b). This means that economic and social considerations are constrained by overarching ecological goals of structure and function (Perera and Buse, 2004). This is unusual, and is the reverse of more populated forest regions. Forests that are more intensively utilized by people often comprise smaller or more fragmented private land ownerships with strong but contrasting social values. These forests tend to be driven first by economic and social priorities (e.g., agroforestry, urban, industrial, smallholder). The ecology and silviculture of a site are therefore viewed as constraining guides of what one can and cannot do. Both approaches can work but are obviously appropriate to very different circumstances and landscapes that are either human dominated or not so dominated.

The "ecological forestry" approach attempts to benchmark stand-level developmental processes of structure and age class to landscape-level spatial and temporal natural disturbance processes (Table 3.1). Such benchmarks gauge the natural range of variability in historic disturbance (Perera, Buse, and Weber, 2004). This is used to then define intensity and scale of silvicultural treatment and intrusion. The assumption is that this approach better attains the elusive nature and goal of sustainability – at least from an ecological perspective (Perera and Buse, 2004).

Table 3.1 Ecological attributes that can be measured to define benchmarks of natural forest pattern and process.

Disturbance attributes	Example of emulation criteria
Nature of disturbance	
Average rate for a large region and its variation	Fire-return interval, Hurricane return interval
Spatial pattern of variation	Spatial probabilities of damage (wind, fire, flooding)
Temporal pattern and variation	Intervals between fires, defoliation events, floods
Geometry	Size and shape
Consequences of disturbance	
Spatial and temporal patterns of composition	Patterns in residual vegetation, succession
Spatial and temporal patterns in age and structure	Patterns in age-class distribution

Source: Adapted from Perera and Buse, 2004

An example of an "ecological forestry" approach is the work on the northern hardwood–mixed conifer forests of northern New England and maritime northeast Canada. Based on long-term natural disturbance dynamics of windstorms, spruce budworm, and fires, researchers have developed disturbance comparability indices calculated for each stand, and a weighted average determined for various sized landscape units (Seymour and Hunter, 1999; Seymour, White, and de Maynadier, 2002; Maclean *et al*., 2009) (Box 3.5).

Such developments in silviculture that emulate the scale and temporal dynamic of natural disturbance regimes of forests do not, unfortunately, negate the conflicting values of biodiversity conservation and timber production. New developments in ecology and conservation biology have provided a better understanding of the impacts of human uses on forests and the resulting effects on biodiversity. However, it still lies with the forester who must balance these directly conflicting values when managing for both, through wise resource allocation. One such conceptual approach to achieving multiple social goals in land use allocation is the **landscape triad** approach (Seymour and Hunter, 1999). To start with a simple example, a large forest area with multiple social drivers of conservation and utilization owned by a single private landowner can plan a stand network of ecological reserves for biodiversity conservation designed to counterbalance stands allotted to production forestry (e.g., timber). To enhance ecological robustness, the production forest stands and reserves would be embedded within a matrix of forest stands that are managed for both diversity and production using the principles of ecological

Box 3.5 Benchmark examples of disturbance and return interval metrics for: northern hardwood and mixed coniferous forests; mixed oak–hickory deciduous forests of northeastern America; and forests of the Pacific Northwest.

Northern Hardwood and Maritime Spruce–Fir Region of New England and Northeast Canada

Presettlement human impacts were local and restricted to settlements on shorelines, fertile valleys and floodplain soils, and along travel routes. They reached peak impacts between 1300 and 1600 AD. Here fire was used to promote oak, hard pines, berry production, and hunting. An estimated 1–2% of the forest was impacted by such disturbances in a chronic way, occurring every few years. The majority of the forest remained relatively untouched mesophytic beech, maple, spruce, and fir.

Post-settlement human impacts in the last 200 years have covered almost 100% of the region several times over, primarily through iterations of heavier and more extensive timber cutting by large industrial and small private landowners with progression in time, particularly starting with the industrial revolution (about 1870 onwards). Some of the best soils originally settled by Native Americans were cleared for farmland and much of this remains today. The more marginal lands reverted to second-growth northern hardwood over a century ago.

Natural disturbance impacts are primarily convectional windstorms 2.5–50 acres (1–20 ha) in size and varying with topography; ice storms, usually extensive in the 2500s of acres (1000s of hectares) but varying with elevation; insect outbreaks (variable in size) recurring at intervals of several decades that affected about 15–20% of the landscape over a 100-year period. Fire of natural origin was rare and was estimated to occur at intervals of 700–2000 years.

Mixed Oak–Hickory Deciduous Forests of Southern New England and New York, Southeast Pennsylvania and the Northern Piedmont

Presettlement human impacts were extensive across the region focused on swidden cultivation on the lower-lying, more fertile soils, and mast-nut and berry cultivation in the uplands. Disturbance through extensive and recurring fires promoted hickory, oak, and chestnut. Where fires or swidden agriculture did not occur, the forest would be dominated by beech, tulip poplar, and maple. Early settler records state much of the forest looked like a savannah woodland. Some extensive grasslands occurred through almost annual burning to promote game habitat, including the woodland bison.

Post-settlement human impacts are extensive with most of the region having been converted to sedentary subsistence agriculture starting 400 years ago. Much of the land was in poor pasture for domesticated livestock (sheep, cattle) and only a fraction was actually tilled for crop cultivation. Remaining lands remained in woodlots that were repeatedly cut. At its zenith, over 60–70% of the landscape was in some kind of cleared agricultural land. With the blossoming of global trade with the Industrial Revolution and the expansion of better lands to the west, most of the poorer land reverted firstly to pine (starting around 1850) that was cut over for the packaging/box industry (1890–1920), and which was then replaced with second-growth hardwoods comprising the disturbance-tolerant oaks, hickories, and chestnuts. The absence of fire and selective cutting has now largely promoted the conversion of these forests to maple, tulip poplar, birch, and beech. In addition, today's forests are impacted by a wave of exotic diseases and insects (e.g. chestnut blight, emerald ash borer, Dutch elm disease) and fragmentation from suburbanization.

Natural disturbance impacts comprise large episodic disturbances such as tornadoes and hurricanes regionally affecting approximately 250,000 acres (100,000 ha) that occur once in approximately 100 years for a given area, to convectional windstorms in 2.5–250 acres (1–100 ha) that can occur across landscapes every few decades. Natural fires are rare.

Coastal Forests of the Pacific Northwest

Presettlement human impacts were localized to burning the most fertile valleys that created small prairies and shrublands. Fires were used to increase wildlife forage and berries. These comprised mixed-severity fires that maintained Douglas-fir and hardwood brush and grasslands. Otherwise the majority of the forest comprised mesic old-growth western hemlock–Douglas-fir. Tribal groups practiced relatively primitive swidden agriculture, with a greater reliance on gathering fruits, fishing, and hunting. These activities promoted seasonal camp movements from the rivers to the uplands following the movement of animals and fish. Tribal groups in the Pacific Northwest had some of the most complex hunting and fishing societies in North America.

Post-settlement human impacts were widespread primarily from logging that started around 1850 with the building of lumber mills along Puget Sound. With the expansion of the railroads and new technology from the late 1800s to 1940, lumber companies could exploit much larger and formerly inaccessible areas. Today, no more than about 10% of the original old growth remains in the states of Washington and Oregon. Much of this was saved in the early 1900s with the formation of the US Forest Service and National Park Service and the acquisition of their respective lands. The best lands, however, remained in private hands that today still comprise productive and intensively managed Douglas-fir plantations.

Natural disturbance impacts comprised lightning strikes that increased with elevation and continued inland. Fires from these strikes were infrequent (at intervals of over 500 years), severe, and stand replacing. The long intervals of time between stand-replacing disturbances, together with relatively fertile young soils and high precipitation, promoted a mesic coniferous forest type that had some of the highest standing basal areas in the world.

Source: Adapted from Nowacki *et al*., 2012.

Table 3.2 Conceptual allocation of land uses using the triad approach for three geographic regions across North Carolina: (1) Appalachian Mountains; (2) Piedmont; and (3) the coastal plain.

Land use category	Appalachians	Piedmont	Coastal plain
Urban/suburban	1%	5%	15%
Agriculture	5%	15%	25%
Intensive forestry (plantations)	5%	15%	30%
Low-intensive forestry (natural woodlands)	30%	50%	20%
Wildlands (parks)	59%	15%	10%

Source: Mark S. Ashton.

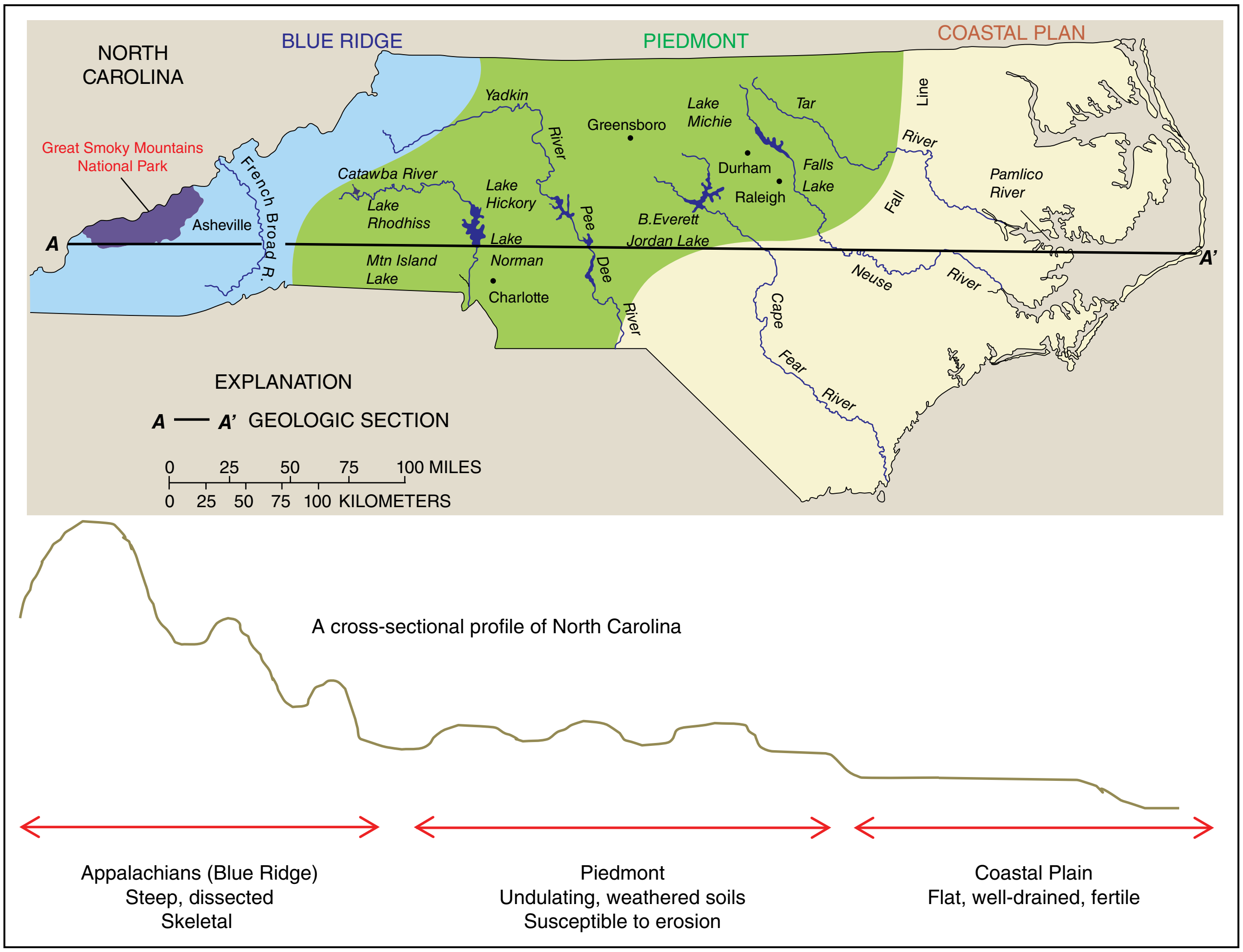


Figure 3.6 Map and cross-sectional profile of North Carolina (*A–A*) depicting the Appalachian Mountains (pale blue), Piedmont (green), and coastal plain (pale yellow) from west to east. *Source:* Mark S. Ashton.