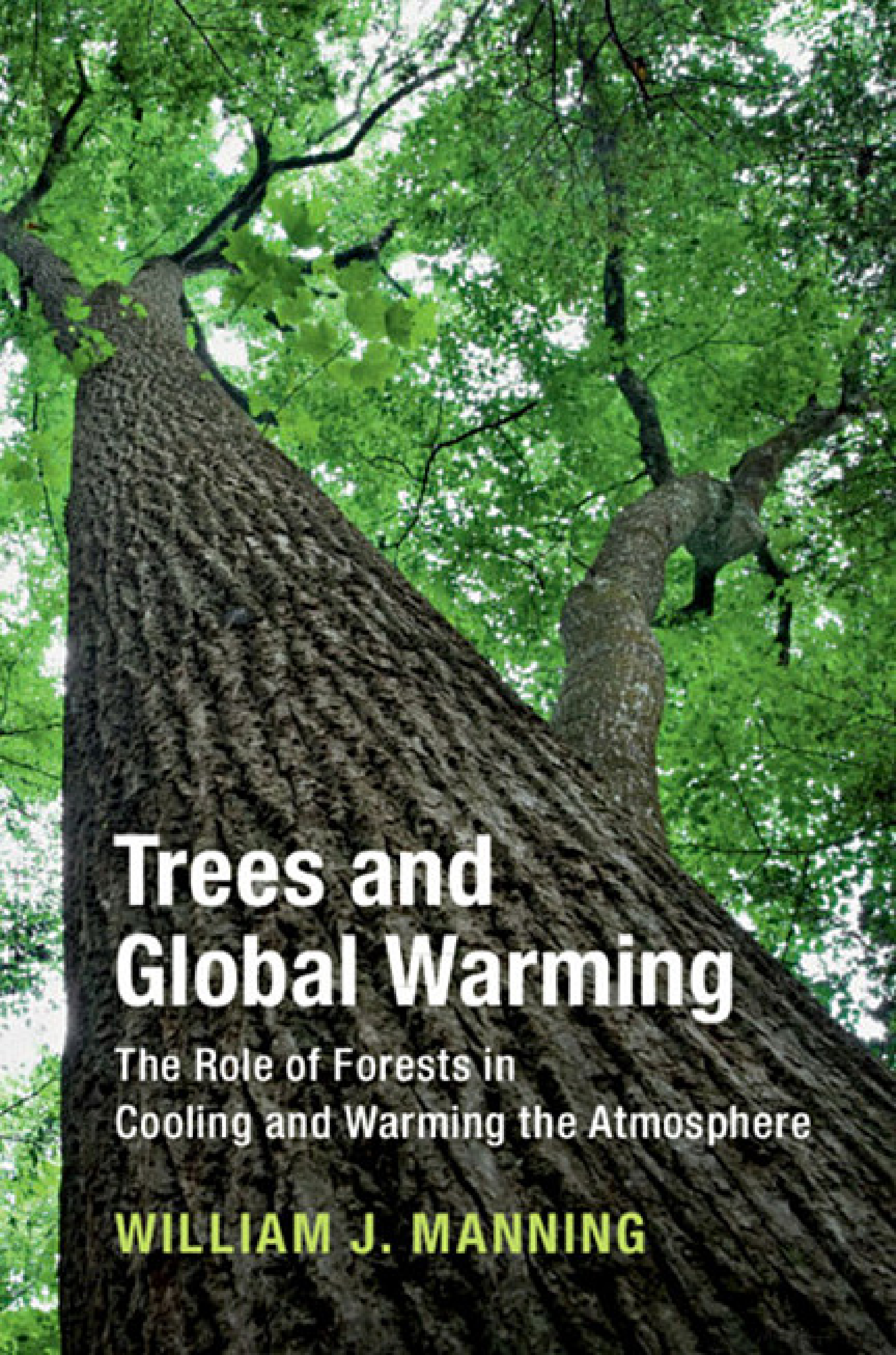

Trees and Global Warming

The Role of Forests in Cooling and Warming the Atmosphere

WILLIAM J. MANNING

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Large-scale tree planting is advocated to provide additional atmospheric cooling and reduce global warming. This raises a question about the present time. Do trees cool or warm the atmosphere? This question does not have a simple yes or no answer. Examination of the greenhouse effect, global warming and the carbon cycle, and how trees and forests function provides the basis for understanding how forests might cool or warm the atmosphere. Results from research and models indicate that cooling or warming depends on where forests are located and the type and color of trees. Cooling generally prevails over warming, but this may change. This book will appeal to anyone interested in climate change, ecology, and conservation.

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To

Gabriel, Owen, and Quinn

Bright lively sparks for the future

The Value of Forests

The value of forests to mankind in their beneficial influence on climate and the protection they exert against erosion, flood, disasters and the man-made desert has come to the fore of recent years as one of the serious questions of present-day administration and civilization. It has been recognized that in both the Old and New Worlds the results of the ignorant interference with the world's formerly existing and widespread forests and the failure to understand Nature's laws and the equilibrium she maintains when left alone has resulted in the past, and is resulting in the present day, in disasters of unforeseen magnitude. In a study of the past, India can show instances of the results of interference with Nature's delicate balance between forests and grassland and water supplies...

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The proposal for writing *Trees and Global Warming* arose after review of the scientific literature, and popular media articles, about the value of trees and forests in reducing global warming by fixing and storing carbon dioxide and emitting water vapor to the atmosphere. I am grateful to the many research scientists and authors for publishing the results of their work, enabling me to read them and write a book based on their research. It was also clear from the review that the widely held assumption that trees and forests reduce global warming was open to examination, question, and interpretation. From this emerged the subtitle of the book: *The Role of Forests in Cooling and Warming the Atmosphere*.

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1 Global Warming and Forests in the Anthropocene

> The post-1950 acceleration in the Earth System indicators remains clear. Only beyond the mid-century is there clear evidence for fundamental shifts in the state and functioning of the Earth System that are beyond the range of variability of the Holocene and driven by human activities.
>
> Steffen *et al.*, 2015

> Humans are the only creature in this world who cut the trees, made paper from it and then wrote "SAVE TREES" on it.
>
> Anonymous

1.1 INTRODUCTION

There is considerable interest and concern about global warming and climate change. In response, there is also great interest in the role that tree planting and new forests might play in partial mitigation of global warming and in reducing climate change by cooling the atmosphere now and especially in the future, as carbon dioxide increases. This interest is evident in the very large number of reports and conclusions in widely diverse scientific journals, books, and the popular media. The purpose of this book is to bring together in one place a review of background information and results from sources, primarily reports in scientific journals, about global warming and the role of forests in cooling and warming the atmosphere now and in future projections.

This chapter includes background information and reviews for the Anthropocene, global warming, atmospheric cooling and warming by forests, the influence of deforestation, land-use change, and tree planting.

1.2 GLOBAL WARMING IN THE ANTHROPOCENE EPOCH

Geological time is divided into epochs. The epoch from the end of Northern Hemisphere glaciers and the Ice Age has been deemed the Holocene ("recent whole") Epoch, including the past 10–12 thousand years. During this epoch, agriculture and settlements were developing. Rice culture began about eight thousand years ago. Human populations were small, and life spans were relatively short, so their impacts on the geology and ecology of the Earth were relatively small. Carbon dioxide levels were low and balanced between the atmosphere and the land/forest and ocean sinks. In the last two centuries, however, industrialization, technology, and the demands of a continually growing huge human population for space and resources have changed the relative stability of the Holocene forever. Rapidly accelerating new technology, fossil fuel combustion, air, water, and soil pollution, increasing temperatures, urbanization and mega-cities, industrial agriculture, mass extinctions, and global demand for middle-class lifestyles have caused great changes in the geology and ecology of the Earth (Zalasiewicz *et al.*, 2010; Waters *et al.*, 2016). Combined rapid changes since 1950 have been called the Great Acceleration, particularly in human wants and needs (Steffen *et al.*, 2011, 2015; Friedman, 2016). To satisfy continuing human demand for protein from domestic animals, Harari (2015) estimates that humans maintain populations of approximately 1 billion of each of sheep, pigs, and cattle, and approximately 25 billion chickens. The total of 28 billion animals is about four times the size of the human population. Sheep and cattle require extensive pasturelands. All require large quantities of food, often grain. Either through metabolism or microbial decomposition of feces, carbon dioxide and methane and other gases are released to the atmosphere. China has been using urbanization and mega-cities to relocate and house its huge population. Nineteen more mega-city/clusters are planned, with one planned to house 150 million people (The Economist, 2018). All of this places an enormous burden on natural regulation of carbon dioxide in the atmosphere, the land mass, and the oceans.

In 1974, Margulis and Lovelock proposed the Gaia Hypothesis that the Earth is capable of environmental self-regulation. This included atmospheric homeostasis by and for the atmosphere. They meant that the planet functions well by itself and can remediate any changes, both natural and human-caused. There is renewed interest in whether global warming and climate change are consistent with the Gaia Hypothesis in terms of self-regulation of the Earth. Conversely, global warming and climate change may be a response and self-regulating mechanism by the Earth.

Continuing population growth, and resulting human activities, needs, and desires, however, are affecting the geophysical and biological regulation of the Earth. Humans are now playing an increasingly central role in regulating the atmosphere and climate of the Earth. Recognizing this, Nobel Laureate Paul Crutzen proposed a new epoch, as he felt that the Holocene was no longer operational. He called it the Anthropocene Epoch (Crutzen and Stoermer, 2000). The geoscience community is divided on the validity and adoption of the new epoch. It would seem, however, that the Anthropocene is here.

1.3 CLEANER AIR AND GLOBAL WARMING

Global warming began with human utilization of fire for cooking and heating. Fuel combustion progressed rapidly with the Industrial Revolution and has accelerated to the present day. The rate began to increase with rapid industrialization, population growth, and deforestation during and after World War II. This resulted in largely unregulated emissions of sulfate and other chemical aerosols and gases to the atmosphere. During that time, pollution levels of atmospheric sulfate and other chemical aerosols and gases reflected much of the incoming shortwave solar energy (sunlight) back to space. This meant that less sunlight penetrated below the pollution layer, and the air was cooler. There was less returning near-infrared radiation to be trapped by the pollution layer at night. Night temperatures were cooler than they would have been if the pollution layer had not reflected much sunlight back to space. This also resulted in reductions in atmospheric visibility and a prevailing condition known as "global dimming."

Following several episodes of high pollutant effects on human health, in the 1970s clean air quality standards were adopted, and aerosol pollution levels began to decline significantly. Cleaner air meant "global brightening" with more incoming solar radiation and more retention of outgoing infrared radiation resulting in a warmer atmosphere. Mercado *et al.* (2009) estimated that global dimming provided more diffusive uniform distribution of light to interiors of trees as well as the tops of tree canopies, and increased photosynthesis by 25% from 1960 to 1999. It has been estimated that it has only been since 1990 that the impacts of the enhanced greenhouse effect and global warming and climate change have emerged and have been recognized (Wild *et al.*, 2007). The Law of Unintended Consequences at work.

Warming in the Arctic region is progressing faster than in other regions. The reasons for this are not completely evident, but reduction of global dimming may be a cause. The clean air acts of the 1970s resulted in reduction in airborne particulates from pollution emissions, particularly sulfate aerosols, in the Northern Hemisphere, resulting in stronger incoming solar radiation. Acosta-Navarro *et al.* (2016) used air quality data from the 1980s and simulation modeling to determine how increased solar radiation might affect Arctic warming. Simulated summer warming was attributed to increased solar radiation and increasing input of heat from the ocean and the atmosphere. Sea ice reduction resulted in heat transfer from the ocean to the atmosphere. This increased Arctic warming in the fall and winter.

1.3.1 James Hansen's Testimony 1988

On 23 June 1988, Dr. James E. Hansen, Director of NASA's Goddard Institute for Space Studies at Columbia University in New York, testified by invitation at a meeting of the US Senate Committee on

Energy and Natural Resources in Washington, DC. His presentation was entitled: "The Greenhouse Effect: Impacts on Current Global Temperature and Regional Heat Waves" (Hansen, 1988). The presentation was of profound importance, summarized in his three main conclusions:

- Number one, the Earth is warmer in 1988 than at any time in the history of instrumental measurements.
- Number two, the global warming is now large enough that we can ascribe with a high degree of confidence a cause and effect relationship to the greenhouse effect.
- Number three, our computer climate simulations indicate that the greenhouse effect is already large enough to begin to affect the probability of extreme events, such as summer heat waves.

Hansen confirmed that global warming and climate change were real and were here now. This introduced a controversial subject into the national conversation, where it remains controversial today. Hansen's testimony caused a sensation, and he was deemed by many in academia, government, and the general public to be mistaken and a doomsayer. Climate change denial began to hamper efforts to mitigate global warming and climate change, and this continues 30 years later. By 2016, however, 90–100% of climate scientists who publish believed that humans are the cause of recent global warming (Cook *et al.*, 2016).

Using a climate model, Hansen *et al.* (2005) proposed that greenhouse gases and aerosols had caused an imbalance in the energy of the Earth. They concluded that the Earth was absorbing more energy from the sun (0.85 ± 0.5 watts per square meter) than it was returning to space. They confirmed this by measuring heat increase in the ocean for a 10-year period. The implications of this included that, without atmospheric composition change, a global warming of approximately 0.6 °C was expected.

Since Hansen's testimony in 1988, many changes in temperature and climate have been observed and recorded. Using data from NOAA, and interviews, Borenstein and Forster (2018) have reported some of these changes. Carbon dioxide increased to over 400 parts per million (ppm) and continues to rise. The greenhouse effect increased, and as a result, the world is much warmer. Average temperatures have increased by approximately 1.6 °C in the United States. When North America and Europe are combined, the average increase is approximately 1.89 °C. The increases in temperature vary by region, with the average increase in South Central Colorado being approximately 2.3 °C. Storms and rainfall are increasing, resulting in property damage and flooding. Wildfires and droughts are increasing. Arctic ice loss is raising ocean levels and decreasing albedo (that is, reducing the ratio of reflected light to incident light), causing warming. Warming is amplifying and increasing the incidence of natural climatic events. NASA (2018) agree that naturally varying climate is being influenced by human-caused warming. They indicate climate changes that are occurring now and make predictions about future effects. These include lengthening of frost-free growing seasons, more droughts and heat waves, hurricanes becoming stronger and more intense, and both sea-level rise by 1–4 ft and the Arctic becoming ice-free by 2100. These climatic changes are caused by global warming.

Record-breaking high temperatures were recorded in 2014, 2015, and 2016 and were attributed to human activities (Mann *et al.*, 2016; 2017; Kennedy *et al.*, 2017). El Nino events increase air temperatures, and one contributed to increased temperatures in 2015 (Betts *et al.*, 2016). Also in 2015, the global carbon dioxide level increased above 400 ppm for the first time, to 400.9 ppm. Betts *et al.* (2016) predicted that the level would remain above 400 ppm. On 19 July 2018, the global average carbon dioxide concentration was 409.32 ppm. King (2017) examined temperature records from 1861–2005 and found record high temperatures in 17 years. They concluded that without global warming, only seven high temperature incidents would have occurred.

There is a direct relationship between the amount of carbon dioxide emitted and global warming. Allowing for net heat flux and carbon capture by the ocean, and carbon dioxide uptake by forests, atmospheric warming is caused by increased radiative forcing from remaining anthropogenic carbon dioxide. Today's global warming results from the beginning of significant anthropogenic carbon dioxide emissions in the 1800s (Goodwin *et al.*, 2015). Continually increasing levels of carbon dioxide make it highly unlikely that the atmospheric temperature increase can be kept at less than 2 °C or at 1.5 °C as proposed by the Paris Climate Agreement (Huntingford and Mercado, 2016). A forecast of future atmospheric temperature increases to 2100 ranged from 2.0 °C to 4.9 °C with a median of 3.2 °C (Rafferty *et al.*, 2017). Anthropogenic carbon dioxide was previously considered to remain in the atmosphere for no longer than 100 years. It is evident now that carbon dioxide will remain in the atmosphere for 1000 years or longer (Archer *et al.*, 2009; Soloman *et al.*, 2009). As Mason Inman (2008) declared, carbon is forever. This complicates efforts to keep atmospheric temperature at or below 1.5 °C.

Additional coverage of the greenhouse effect, global warming, and the carbon cycle can be found in Chapter 2, "The Gases That Cause the Greenhouse Effect", and in Chapter 3: Carbon and Photochemical Oxidant Cycles.

1.4 TREES AND FORESTS: COOLING AND WARMING THE ATMOSPHERE

Hansen (1988) was able to use data obtained by Keeling from his continuous carbon dioxide monitoring station at Mauna Loa, Hawaii, beginning in 1960. Over time, Keeling documented that carbon dioxide concentrations in the Northern Hemisphere decreased during the summer months and increased during the winter months. He attributed the summer decrease in atmospheric carbon dioxide to uptake of carbon dioxide by vegetation during photosynthesis (Keeling *et al.*, 1996). Graven *et al.* (2013) examined data from 1960 onward and verified enhanced seasonal changes in carbon dioxide concentrations. As carbon dioxide levels increased, the seasonal changes in carbon dioxide continued to grow, implying that summer vegetation growth must be increasing to enable the seasonal changes. This led to a conclusion that increasingly elevating anthropogenic carbon dioxide might act as a global fertilizing agent, increasing terrestrial vegetation, primarily forests, and resulting in partial mitigation of warming caused by anthropogenic carbon dioxide.

1.4.1 Cooling and Warming

Way *et al.* (2015) have concluded that we have considerable knowledge about the effects of elevated carbon dioxide on most plant physiological responses at the leaf level, but transferring these results to whole trees is an area of great uncertainty. Most of what we know beyond the leaf level comes from experiments with small or young trees under varying ambient conditions and very high carbon dioxide levels. The development of sophisticated and specific satellite imagery and many climate and statistical models were required to proceed further to determine the possible role of trees and forests in atmospheric cooling and warming. Mao *et al.* (2016) used satellite imagery to detect what they termed clear evidence of significant Earth greening for the past 30 years.

Sun *et al.* (2017) used data from the new sophisticated OCO-2 satellite to detect real-time induced chlorophyll fluorescence associated with gross primary production (GPP) and detect increased global vegetation attributed directly to photosynthesis. Using models and satellite data, Zeng *et al.* (2017) concluded that leaf area index had increased for global vegetation for the last 30 years. This index estimates the leaf area on trees (canopies in this case) in relation to land surface area, and thus estimates how much tree cover there is. This indicated to them that the slow increase in Earth greening had reduced the expected global land surface temperature by 0.09 °C since 1982. Seventy percent of the effect was attributed to evapotranspiration. Satellite data do not always distinguish between forms of vegetation, most of which is assumed to be likely to be trees.

Extensive modeling was done to estimate the effects of global land-use change on forests and cooling and warming. Gibbard *et al.*

(2005) modeled whether global transformation of grassland and cropland to trees would result in warming from lower tree albedo or cooling from increased transpiration. Their conclusion was that total replacement with trees would result in a global average temperature increase of 1.3 °C. Replacement of trees with grasslands would result in an average 0.4 °C cooling. Bala *et al.* (2007) modeled the effects of large-scale deforestation and concluded that increased albedo would result in a net cooling effect. Unger (2014) concluded that wide-scale forest reduction would result in atmospheric cooling. Trees release biogenic volatile organic compounds (BVOCs) which participate in prolonging the life of methane and other greenhouse gases. Reduction of BVOCs would result in atmospheric cooling.

In an extensive and widely cited review, Bonan (2008) examined results from climate model simulations and flux tower measurements in relation to cooling and warming by tropical, temperate, and boreal forests at different latitudes. Low albedo in tropical forests is offset by evapotranspiration, resulting in air cooling and promotion of precipitation. Air cooling may be global in effect. Depending on conditions, tropical forests are either carbon-neutral or carbon sinks. Boreal forests have low albedo which causes warming, weak cooling, and moderate carbon sequestration. Temperate forest trees have lower albedo than grasslands or croplands. Eastern US temperate forests may warm temperatures in the summer, which can be offset by increased evapotranspiration. Carbon sequestration is strong, especially in mature forests. Li *et al.* (2015) used satellite observations to determine atmospheric cooling and warming in forests of the world. Similar to Bonan (2008), they estimated that tropical forests cool in all seasons, whereas temperate forests provide moderate cooling in summer and some warming in winter. Boreal forests cool in summer with overall annual net warming. Spracklen *et al.* (2008), however, consider that the low albedo of boreal forests can result in an overall cooling effect. BVOCs from trees (primarily conifers) cause cloud condensation nuclei to form, resulting in clouds and cooling.

1.4.2 Transpiration and Cooling

Atmospheric temperature and climate are influenced by intensity of reflectance by albedo and by the terrestrial water flux. Evapotranspiration by forests is essential to the global water cycle. Heat, necessary for converting liquid water to a gas, provides latent heat flux. Forests provide abundant latent heat flux (Ban-Weiss *et al.*, 2011). Jasechko *et al.* (2013) determined that 80–90% of evapotranspiration is transpiration from vegetation. Anything that affects transpiration will affect atmospheric cooling. Transpiration will be used in place of evapotranspiration here. Leggett and Ball (2018) observed long-term temperature trends and concluded that most were lower than those predicted by most simulation models for the effects of elevated carbon dioxide. They concluded that there was a "temperature gap" and attributed it to the influence of transpiration.

Much attention has focused on estimating the possible effects of elevated future carbon dioxide on growth, carbon sequestration, and atmosphere temperature. Early experiments established that elevated carbon dioxide closes stomata or decreases stomatal aperture and conductance, which decreases transpiration (Long, 2012). Cao *et al.* (2010) modeled the influence of doubled carbon dioxide concentration on stomatal conductance and canopy transpiration. Their results indicated that canopy transpiration was decreased by 8%, resulting in increased land surface temperature. Elevated carbon dioxide was determined to depress transpiration more than elevated temperature in the future (Kirschbaum and McMillan, 2018).

Field experiments with elevated carbon dioxide resulted in large photosynthesis-caused increases in growth of young trees. It was assumed that this growth acceleration would continue (Long, 2012). Many of the increases in tree growth were not sustained, owing to acclimation and to limitations of soil nutrients, particularly nitrogen and phosphorus.

Fernandez-Martinez *et al.* (2015) consider that availability of soil nutrients is the key to regulating global forest carbon balance.

Wieder *et al.* (2015) projected possible limitations of nitrogen and phosphorus to 2100. Nitrogen limitation would reduce NPP by 19% and phosphorus limitation by 25%. They suggested that this would turn the global land surface into a net source of carbon dioxide. Ozone injury reduces leaf area for photosynthesis and reduces uptake of anthropogenic carbon dioxide (Unger, 2012). Forests in China are considered to be at risk for ozone effects (Li *et al.*, 2017). Ozone also reduced positive effects of elevated carbon dioxide in FACE (free-air carbon dioxide enrichment; see Chapter 7) experiments (King *et al.*, 2005).

Tropical forests are assumed to be the major global locations for uptake of carbon dioxide in photosynthesis, resulting carbon storage, and transpirational cooling. They have been extensively investigated and evaluated by satellite imagery, measurements of trees in plots, and growth ring and analyses. Van der Sleen *et al.* (2015) did not find evidence of increasing accelerated tree growth. Instead they found increased water-use efficiency (commonly associated with effects of elevated carbon dioxide) for the last 150 years. Brienen *et al.* (2015) reported that tree growth was slowing and mortality was increasing. The Amazon carbon sink is declining (Brienen *et al.*, 2015; Groenendijk *et al.*, 2015; van der Sleen *et al.*, 2015). Baccini *et al.* (2017) have concluded that tropical forests may be becoming net carbon sources.

More extensive coverage of warming and cooling by trees and forests is included in Chapters 4, 7, and 8.

1.4.3 Deforestation, Land-use Change, and Forest Loss

Crowther *et al.* (2015) have performed the monumental task of mapping the extent and distribution of the trees of the world. They report that there are approximately 3.04 trillion trees on Earth. Subtropical and tropical forests contain the most, at 1.30 trillion, followed by 0.74 trillion in boreal forests, and 0.66 trillion in temperate forests. They estimate that more than 15 billion trees are removed each year. Since civilization began, approximately 46% of global trees have been removed through deforestation. This has had a pronounced effect on the global carbon cycle.

Van der Werf *et al.* (2009) consider deforestation to be second only to fossil fuel combustion as an anthropogenic source of carbon dioxide. Deforestation is a response to human population growth and demands for resources that include wood for construction and fuel, land for agriculture and pasture, for plantations and mining. Huge new cities in China and elsewhere result in tree destruction and large carbon dioxide emissions from fossil fuel combustion (Churkina, 2016). Large forest areas in Africa and Asia are being used for charcoal production (Sedano *et al.*, 2016). Huge swaths of North American forests are being converted to wood pellets for domestic use and for export. Wood pellets are not carbon-neutral (Schlesinger *et al.*, 2018). Arneth *et al.* (2017) report that model simulations of carbon dioxide emissions from land-use change are substantially underestimated.

Drought is increasing globally as air temperatures increase (Adams *et al.*, 2009; Allen *et al.*, 2015) and is expected to continue to increase. When trees decline and die, transpiration and air cooling decrease, and the hydrological cycle is affected (Bonan, 2008). Higher temperatures and drought increase susceptibility to bark beetles that kill trees (Anderegg *et al.*, 2015). Bark beetles are increasing their range as temperatures warm. Warming temperatures and drought, together with long-period fire suppression policies, have increased wildfires in huge areas in California and the western US, Siberia, and Asia (Brandlin, 2017). Half of the boreal forests in Alberta, Canada, may be eliminated by fires in the future (Stralberg *et al.*, 2018).

1.4.4 Large-scale Tree Planting Programs

Forest loss has three negative consequences for mitigation of global warming. Fewer trees means less uptake and storage of carbon from anthropogenic carbon dioxide; less wood for construction and forest products; and more prior forest land available for agriculture and urbanization. Depending on human needs and perspective, the third consequence may be unavoidable and could be positive for humans.

Concern about global warming and climate change has stimulated enduring tree planting programs, from street level in cities, to huge national/international programs. These programs are designed to replace trees lost in deforestation and degradation, and to plant new forests. These forests are intended to assist in mitigation of global warming. The United Nations initiated REDD+ (Reducing Emissions from Deforestation and Forest Degradation) to encourage nations to reduce forest degradation and deforestation. Results-based payments were used as an incentive to encourage participation (UN REDD+ Program). The Bonn Challenge resulted from an international agreement in Germany in 2011. The goal is to restore 150 million hectares of deforested and degraded forest areas by 2030 (Bonn Challenge, 2011). The World Wildlife Fund, The Wildlife Conservation Society, and Birdlife International established the Trillion Trees program for a 25-year period. Felix Finkbeiner, a German University student, was instrumental in starting the program. He concluded that it was time to "stop talking and start planting." The Paris Climate Agreement encouraged voluntary pledges to reduce deforestation and plant new forests. Cities and municipalities across the world have initiated large-scale tree plantings. New York and Los Angeles participated in "1 million tree" planting programs. In urban tree plantings and large-scale forest plantings, it's not how many trees you plant, it's how many survive.

Many of the new forests that are being planted for afforestation and/or reforestation are designed to be plantations. Unlike natural regeneration, the trees are all the same age, planted in rows, and may be all of one species. Trees are likely to be harvested in short rotations for wood and products (Grotta, 2015). China's Grain-for-Green Program is one of the world's oldest and largest tree planting programs. Marginal agricultural land has been turned into huge tree plantations (Hua *et al.*, 2016). The China Fast-growing and High Yield Plantation Program included moving away from natural forests to plantations for wood production (Jiang and Zheng, 2003). Using high-resolution maps from satellite imagery, Ahrends *et al.* (2017)

concluded that trees in China are often planted in areas unsuitable for trees and that gains there are limited. Areas better suited for trees may be used for urbanization and agriculture. China is going green, but not necessarily with natural forests.

More extensive coverage of tree distribution, afforestation, and reforestation is found in Chapters 6 and 8.

1.5 COOLING OR WARMING?

This chapter has provided an introduction and overview of knowledge about global warming that causes climate change, the nature and function of trees and forests, and how they may influence global warming and resulting climate change. There is considerable interest in the role that large-scale tree planting might have in partial mitigation of global warming by reducing atmospheric carbon dioxide through photosynthesis. This raises an important question. What is the role of forests in cooling and warming the atmosphere? A very large wide-ranging literature review was conducted to find some possible answers to this question. Presenting the results here is the purpose of this book.

The next chapter considers the nature of the greenhouse effect and global warming.

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2 The Gases That Cause the Greenhouse Effect

> [N]on-condensing greenhouse gases provide the temperature environment that is necessary for water vapor and cloud feedback effects to operate. . . .Because carbon dioxide accounts for 80% of the non-condensing GHG forcing in the current climate atmosphere, atmospheric carbon dioxide therefore qualifies as the principal control knob that governs the temperature of the Earth.
>
> Lacis *et al.*, 2010, commenting on Schmidt *et al.*, 2010

2.1 INTRODUCTION

The nature of global warming and climate change was introduced in Chapter 1. This chapter considers in detail the greenhouse effect and the reactive gases that cause it.

The sun plays the key role in the energy balance of the Earth. The proximity of the sun to the Earth makes life on Earth possible. Shortwave and ultraviolet energy from the sun enters the atmosphere during the day; the visible part is known as sunlight. Not all of it reaches the surface of the Earth. Clouds can reflect incoming radiation back to space. Suspended aerosols and reflection (albedo) from light-colored surfaces such as ice and snow are also effective in reflecting incoming radiation: as much as 50% may be reflected, and even more on cloudy days. Beginning during the day and continuing into the night, some of the incoming radiation absorbed by the Earth returns to space in the form of long wave infrared radiation, but some is trapped down below low clouds and suspended aerosols. Atmospheric gases, such as water vapor, carbon dioxide, methane, nitrous oxide, ozone, and synthetic chloro- and fluorocarbon gases, also absorb and emit infrared radiation. Retention of infrared radiation increases the air and surface temperature of the Earth. This is the natural essential greenhouse effect. Without it, the Earth would be too cold at night to support life (Jacobson, 2002; Karl and Trenberth, 2003; Prentice *et al.*, 2012).

Since the Industrial Revolution, the balance in the Earth's energy budget between incoming and outgoing radiant energy has been changing slowly, resulting in an increase in the Earth's temperature which has become known as global warming, or the enhanced or unnatural greenhouse effect.

2.2 THE GREENHOUSE EFFECT: DAY AND NIGHT TEMPERATURES

Daily minimum temperatures are increasing 40% faster than daily maximum temperatures (Peng *et al.*, 2013). Asymmetric warming is causing night temperatures to increase more rapidly than daytime temperatures. The effects of higher temperatures during the day will provide less relief from higher temperatures at night, with important implications for human health and wellbeing. Davy *et al.* (2016) have provided a rationale for why night temperatures are increasing more rapidly. The height of the boundary layer – the lowest layer of the atmosphere – above the Earth's surface is very high during the day (a few kilometers) and quite low at night (a few hundred meters). Using carbon dioxide as the major radiative forcer, it is proposed that only a smaller volume of air at night needs to be warmed by carbon dioxide effects on infrared radiation retention, and hence the nighttime temperatures are higher.

Peng *et al.* (2013) considered how differences in daytime and nighttime temperatures might affect photosynthesis and respiration by plants and microorganisms. They speculated that warmer nights would not affect photosynthesis, but could increase respiration, and carbon dioxide release, by plants and microorganisms. Effects of this on vegetation and climate warming are largely unknown.

2.3 COMMONLY USED DESCRIPTIVE TERMS

Several terms are used to describe and explain the atmosphere and the implications of changes in a warming atmosphere. These terms are often used interchangeably, especially in common usage, and this results in confusion and possible misinformation. This is especially true for global warming and climate change. NASA has provided some useful definitions and explanations.

2.3.1 *The Atmosphere*

The air in the atmosphere contains a mixture of gases and aerosols (particles) and clouds. The gases include 78% nitrogen, 21% oxygen, and 1% other gases such as argon, carbon dioxide, and variable water vapor. There are five regions or layers in the atmosphere from the Earth's surface to outer space, based on temperature changes. We live in the troposphere that extends from the surface of the Earth to about 8 to 16 km into space, being greatest at the equator. This is a zone of turbulence, and weather happens here. The next layer is the stratosphere, where a calm layer of ozone protects us from excessive ultraviolet radiation in sunlight (Vallier-Talbot, 1996).

2.3.2 *Weather and Climate*

"Weather" includes atmospheric conditions and events that occur locally or daily or over very short periods of time. Events include wind, temperature, rain, humidity, storms, and clouds, reported and predicted by the media in weather forecasts. Weather events can change quickly and unpredictably. "Climate" includes monthly and long-term regional or global averages of temperature and precipitation over a season, years, decades, or centuries. Humidity, wind speed, and wind direction are also included. Integrating this information over time allows determination of climate for an area (Whitaker, 1996).

2.3.3 *Global Warming*

This is a specific term that refers to the upward temperature trend across the Earth, often considered to have begun in the 1750s when the Industrial Revolution resulted in release of fossil fuel emissions, primarily from the combustion of coal. It became increasingly evident in the 1980s when aerosol air pollution began to decline.

2.3.4 Climate Change

"Climate change" is a collective term that refers to a broad range of enhanced changes in environmental and biological systems and events. Sea level rise, loss of ice mass in the Arctic and glaciers in mountain regions, and increased severe weather events are examples of climate change. Warming atmospheric temperatures drive all these changes and thus are included in climate change. Global warming causes climate change; climate change and global warming are not interchangeable terms.

2.4 GREENHOUSE GASES: RELATIVE IMPORTANCE

Global warming continues because of increasing concentrations of a variety of radiative and reactive gases (Solomon *et al.*, 2010). Water vapor is the most effective in absorbing and radiating infrared radiation. Ozone is formed in the atmosphere. Water vapor and ozone do not occur in persistent concentrations, but carbon dioxide, methane, nitrous oxide, and synthetic chloro- and fluorocarbon gases do exist in persistent concentrations in the atmosphere.

Carbon dioxide is the major persistent contributor to global warming (65%) (Stocker *et al.*, 2013). The warming impacts of other radiative gases can be determined by calculating how much they would contribute to global warming compared with carbon dioxide. The gases differ from each other in how long they persist in the atmosphere and in their radiative efficiency in absorbing infrared thermal energy. Comparisons can be made between them by using "global warming potentials" (GWPs) (American Chemical Society 2012c; US EPA 2017).

2.4.1 Global Warming Potentials

Characteristics that determine a gas molecule's GWP include:

1. **Wavelength absorption window**: infrared radiation returning from the Earth is in the thermal infrared region.

2. **Radiative efficiency**: how much energy is absorbed. The more absorbed, the more effective the molecule.
3. **Lifetime**: how long the molecule persists in the atmosphere. Effectiveness increases with persistence.

GWPs estimate how much energy a known quantity of a radiative gas would add to atmospheric warming compared with the same quantity of carbon dioxide, often on a 100-year timescale (American Chemical Society, 2012c; US EPA, 2017). GWPs for a 100-year scale include the following.

- **Carbon dioxide**: has been assigned a GWP of 1.00 and is used as the reference gas. It has not been assigned a lifetime. Half of anthropogenic carbon dioxide emissions may be gone in 100 years, but the rest may persist for thousands of years.
- **Methane**: GWP of 28–36. More effective than carbon dioxide, but lifetime is only about 10–15 years, although concentrations are increasing.
- **Nitrous oxide**: GWP of 265–298. Lifetime of more than 100 years in the atmosphere.
- **Chloro- and fluorocarbons**: High-GWP gases. More effective than carbon dioxide. Lifetimes range from 1,400 to 22,800 years.
- **Ozone and water vapor**: GWPs are not calculated, as they are both variable in concentration and short-lived. As global temperatures increase, so does the amount of water vapor in the air from evaporation and sublimation, and its potential to warm the air. This adds to the effects of other more persistent radiative forcers (American Chemical Society, 2012c). Episodes of ozone at concentrations high enough to act as a radiative forcer occur in warm weather. Lifetimes of these concentrations are often short-lived. Ozone also enhances the effects of other radiative gases.

2.5 WATER VAPOR: A CONDENSABLE GAS

Water vapor is a naturally occurring, variable concentration, gaseous form of water (H_2O). As a positive radiative forcer, it is the major contributor to the Earth's energy flow and the natural greenhouse effect that allows life on Earth to occur (American Chemical Society, 2012b; Chung *et al.*, 2014). Water vapor influences transfer of latent heat from evaporation and vapor condensation, and affects incoming and outgoing shortwave and longwave radiation via clouds (Allan, 2012).

Sources include evaporation of water from bodies of water, transpiration from plants, and sublimation from ice and snow. Two of the products from burning fossil fuels are carbon dioxide (CO_2) and water vapor, with ratios for CO_2 and water vapor for gasoline, fuel oil, and natural gas (methane CH_4) of 1:1, 1:1, and 1:2, respectively. Compared with coal, fuel oil, and gasoline, natural gas is considered to be the "clean fuel", as complete combustion results in release of only carbon dioxide and water vapor. Both, however, are strong radiative forcers. Twice as much water vapor as carbon dioxide is released. Water vapor is much more effective in absorbing outgoing infrared radiation than carbon dioxide. Unlike carbon dioxide, water vapor concentrations are variable and short-lived.

While humans can have some local influence on water vapor, temperature controls water vapor on a global basis. This affects evaporation and precipitation. A warming atmosphere increases water vapor and increases its interactions with other positive radiative forcers (American Chemical Society, 2012a, 2012b, 2012c; Chung *et al.*, 2014).

2.5.1 Clouds

Water occurs in the atmosphere in several forms or states. Water vapor is invisible, but when combined with temperature, we can feel it as relative humidity. Water is visible as ice, snow, rain, and clouds. All forms of water are involved in climate change. Clouds are particularly important as they can be either positive or negative radiative forcers. Warm air containing water vapor rises, and the vapor condenses to water droplets or ice particles, making clouds visible. As much as 70% of the Earth's surface may be covered with clouds at any point in time (US National Science Foundation).

A warmer atmosphere could result in more clouds. By their nature, some of them could be positive radiative forcers, increasing the amount of returning infrared radiation trapped beneath them, or they could be negative radiative forcers, reflecting incoming shortwave radiation from the sun. Elevated concentrations of carbon dioxide can cause plant stomata to close, reducing transpiration and photosynthesis (and thus carbon dioxide uptake). The reduction in transpiration output can cause a reduction in low cloud, resulting in warming (Field *et al.*, 1995; Doutriaux-Boucher *et al.*, 2009). Furthermore, biogenic volatile organic compounds (BVOCs), emitted by trees, play a key role in cloud formation. Extensive coverage of BVOCs and their function is found in Chapters 4 and 7.

The three most important types of clouds are stratus, cirrus, and cumulus. How effectively they function depends on their thickness and heights (US National Science Foundation).

2.5.1.1 Stratus Clouds

These are low clouds that are widespread and consisting of ice crystals. As they are low-hanging and gray in color, they can reflect incoming shortwave radiation from the sun. This can cause a cooling effect below, so they are negative radiative forcers.

2.5.1.2 Cirrus Clouds

These are high-elevation, white, detached clouds consisting of ice crystals that allow considerable passage of sunlight to the Earth. Effective in trapping outgoing infrared radiation, they may function as positive radiative forcers enhancing atmospheric warming.

2.5.1.3 Cumulus Clouds

These are high-elevation, large, dense clouds shaped like irregular mounds or towers that are white when exposed to sunlight, but with darker horizontal bases. These clouds can block sunlight, serving as negative radiative forcers, or trap outgoing infrared radiation and function as positive radiative forcers. Size and thickness or density affect whether the effects are positive or negative (US National Science Foundation; National Weather Service).

2.6 NON-CONDENSABLE GASES

Unlike water vapor, radiative gases such as carbon dioxide, methane, nitrous oxide, ozone, and human-synthesized chloro- and fluorocarbons do not condense at atmospheric pressure and temperatures. This allows them to exceed any sink capacity and accumulate in the atmosphere (American Chemical Society, 2012a).

2.6.1 Carbon Dioxide

Carbon dioxide is a normal, important part of the atmosphere. Until the Industrial Revolution, atmospheric concentrations were relatively stable, with sources regulated by natural sinks such as oceans and forests. More than 50 years ago, however, Charles D. Keeling began a continuous air monitoring program for carbon dioxide at Mauna Loa, Hawaii. Two things soon became evident. The concentration of carbon dioxide in the atmosphere had increased considerably from the estimated average concentration of 280 ppm and was likely to continue to rise. Keeling also identified a regular seasonal cycle of lowered carbon dioxide concentrations in the summer in the Northern Hemisphere, implying that forests and other vegetation through photosynthesis were acting as a sink for some of the elevated carbon dioxide. Both were key findings that helped to begin the science of global warming and climate change (Keeling, 2008).

2.6.1.1 Anthropogenic Emissions of Carbon Dioxide

Elevated concentrations of carbon dioxide are considered to be the most important persistent cause of global warming and climate change. Carbon dioxide is the best-known radiative forcer and has become the "poster child" for global warming. Most of the research and attention has focused on the sources and effects of anthropogenic emissions of carbon dioxide. A more detailed consideration of carbon dioxide in relation to the carbon cycle will be found in Chapter 3.

2.6.1.2 Carbon Dioxide Sources and Sinks

Natural sources of carbon dioxide include emissions from volcanoes, evaporation from the surface of oceans, and decomposition of dead plants and animals. The impact of carbon dioxide emissions through respiration by billions of humans and animals is not clear. Natural sinks include the oceans, phytoplankton and other aquatic plants, and land-mass vegetation, mostly trees and forests (American Chemical Society, 2012b).

Anthropogenic emissions of carbon dioxide result primarily from combustion of fossil fuels, wood, and other carbon-containing materials. Fossil fuel combustion and global cement production account for 75% of emitted anthropogenic carbon dioxide (American Chemical Society, 2012b; Betts *et al.*, 2016). Deforestation and land-use changes for agriculture and permanent development make up the rest (Prentice *et al.*, 2012).

Increased levels of carbon dioxide have caused approximately an 81% increase in radiative forcing during the past decade and approximately an 82% increase during the past 5 years (World Meteorological Organization, 2016).

Coal, oil, and natural gas are natural carbon sources derived from prehistoric vegetation millions of years old. The carbon dioxide emitted from them is somewhat different than the carbon dioxide in the air before the Industrial Revolution. Different isotopic forms of carbon dioxide occur in ratios, and fossil fuels have a lower ratio of ^{13}C to ^{12}C than the carbon dioxide in the atmosphere (because of the preference of the ancient plants for the lighter isotope). The atmospheric ratio of ^{13}C to ^{12}C has been declining, beginning in the twentieth century. This has been proposed as convincing evidence that increasing carbon dioxide concentrations in the atmosphere are caused by anthropogenic carbon dioxide emissions from fossil fuel combustion (American Chemical Society, 2012b).

Carbon dioxide concentrations in the atmosphere have increased on average by approximately 2.1 ppm/year for the past 10 years. The annual growth rate is variable, depending on how climate affects carbon dioxide sources and sinks. This became evident in 2016 when a record high increase of carbon dioxide was noted at Mauna Loa. Correlation was found between increased carbon dioxide and the effects of the 2015–2016 El Nino/Southern Oscillation (ENSO). Carbon dioxide concentrations tend to increase during the peak of the cyclical El Nino events in the Southern Pacific Ocean. In this case, less carbon was taken up by vegetation in tropical areas, and carbon dioxide was released from trees killed by drought and fires. Betts *et al.* (2016) investigated the 2015–2016 El Nino effects on carbon dioxide. Based on their model results, incorporating carbon dioxide emission data and Southern Pacific sea surface temperatures, they forecast that carbon dioxide at Mauna Loa would for the first time remain above 400 ppm all year.

The sinks for anthropogenic carbon dioxide are the same as for carbon dioxide from natural sources. Before the Industrial Revolution, the concentration of carbon dioxide in the air was maintained by the balance between the atmosphere and the ocean and land-mass sinks. By 2015, carbon dioxide levels had increased to 144% of pre-industrial levels (World Meteorological Organization, 2016). The oceans and the land-mass sinks are no longer capable of absorbing all of the elevated concentrations of carbon dioxide. It is estimated that as much as 40% remains in the air and persists on a timescale of 100 years to several thousand years. This carbon dioxide is the most important contributor (representing 65% of the radiative forcing by long-lived greenhouse gases) to global warming and climate change (Archer *et al.*, 2009; Prentice *et al.*, 2012; Arneth *et al.*, 2017). There are no indications from the results from models or in the scientific literature that the concentrations and effects of anthropogenic carbon dioxide can be mitigated or substantially reduced in the foreseeable future (Archer *et al.*, 2009).

2.6.1.3 Carbon Dioxide Controls the Temperature of the Earth

Water vapor is a condensing gas in the atmosphere, with varying concentrations in time, and, while not self-sustaining, yet plays a major role in the greenhouse effect. Non-condensing greenhouse gases, such as carbon dioxide, methane, ozone, nitrous oxide, and chlorofluorocarbons, determine the air temperatures that determine how long water vapor and clouds can be sustained in the atmosphere. The effects of the non-condensing gases determine the relative contribution of water vapor and clouds to radiative and reradiative effects (Lacis *et al.*, 2010). Schmidt *et al.* (2010) estimated that water vapor accounted for 50% of the greenhouse effect, with clouds contributing 25%, carbon dioxide 20%, and other greenhouse gases and aerosols 5%. As water vapor and clouds are not self-sustaining, carbon dioxide (20%) and the other greenhouse gases (5%) control the extent of the greenhouse effect. Carbon dioxide is 80% of the non-condensing greenhouse gases that control the extent of the greenhouse effect. Lacis *et al.* (2010) conclude that carbon dioxide therefore can be considered as the thermostat or "control knob" that governs the temperature of the Earth.

2.7 METHANE

Methane (CH_4) gas is a normal part of the atmosphere. It is a natural, powerful radiative climate forcer that absorbs some longwave infrared radiation as it moves from Earth back to space. This results in some beneficial warming of air in the atmosphere. Together with other gases, it helps to regulate the Earth's temperature budget to allow life on Earth as we know it. Methane concentrations, however, slowly began to rise with the start of the Industrial Revolution. Methane is now increasing more rapidly with the continuing growth in extensive agriculture needed to feed an ever-growing population (Montzka *et al.*, 2011; Saunois *et al.*, 2016; Rigby *et al.*, 2017). This has resulted in an increase of the radiative climate forcing capacity of methane and other gases to cause increased global warming and resulting climate change. Methane is the second most important greenhouse gas after carbon dioxide. It has increased to 256% of its value in 1750 (World Meteorological Organization, 2016). It is estimated that methane contributes approximately 17% to radiative climate forcing (Montzka *et al.*, 2011; Stocker *et al.*, 2013).

2.7.1 Natural Sources of Methane

It has been estimated that 40% of methane in the atmosphere is from natural sources.The principal natural source is anaerobic microbial activity in wetlands, lakes, and soils. Slow decomposition of organic matter under anaerobic conditions by methanogenic bacteria results in release of methane. Warm tropical wetlands release the most methane (Montzka *et al.*, 2011; Friedlingstein *et al.*, 2012). Wetlands and lakes occupy approximately 7% of the Earth's surface but wetlands are disappearing all across the globe.

2.7.1.1 Termites

Termites are found on approximately 66% of the Earth's terrestrial surface. Common in tropical grasslands and forests, often in huge colonies in mounds, termites utilize plant materials for nutrition. Depending on the species, anaerobic digestion involves action by symbiotic bacteria or protozoans. Methane is released in the process. Clearing forests for use in agriculture increases termite infestations (Zimmerman *et al.*, 1982). Methane emission from termite colonies is considered less important than emissions from wetlands, but the potential levels of release have not been intensively investigated.

2.7.1.2 Wetland Forests

Trees growing in wetlands can be considered as conduits for methane release from soil to the atmosphere via roots, stems, and leaves (Rice *et al.*, 2010; Pangala *et al.*, 2015). Methane release from trees occurs more extensively and for longer periods of time in warmer tropical and subtropical wetlands. Pangala *et al.* (2017) concluded that tropical tree stems in the Amazon floodplain are a major source of methane. The Amazon floodplain may contribute as much as one-third of global wetland methane. The contribution of methane release from trees growing in other wetlands to atmospheric levels of methane has not been extensively investigated (Carmichael *et al.*, 2014).

2.7.1.3 Upland Temperate Forests

Concern about rising levels of atmospheric methane has stimulated research on the possible contribution of forest trees growing in well-drained upland soils to levels of atmospheric methane. That trees in upland forests release methane to the atmosphere is accepted. The source of the methane and how this happens, however, is more controversial. Two methods have been proposed: the first is formation in and release from leaves, the second release from internal wood decay and coarse debris.

It has been proposed that methane is formed under aerobic or oxic conditions in leaves and then released to the atmosphere. This is based on results from experiments with incubating tree and grass leaves under controlled conditions and then measuring methane. How and why methane was produced and then released was not determined (Keppler *et al.*, 2006). Definitive verification of this proposed process has not been found by others (Covey *et al.*, 2012).

In the alternative proposal of methane release from internal wood decay, it has long been known that as forest trees age, the probability increases that the internal dead heartwood will be invaded by methanogenic bacteria, which cause an anaerobic rot called wet wood, or by brown or white rot fungi (Covey *et al.*, 2012; Warner *et al.*, 2017). Methane is released from tree trunks and from coarse debris on moist soil surfaces. Internal decay can be detected in living trees by sonic and electrical tomography (Brazee *et al.*, 2011). It is likely that internal wood decay is more prevalent than previously thought, and this is not being considered in estimations of atmospheric methane concentrations. (Covey *et al.*, 2012; Carmichael *et al.*, 2014). Internal decay is also not being considered in forest management where stem diameter (known as dbh, for diameter at breast height) is used to assess tree growth and assess carbon storage in wood. Parfitt *et al.* (2010) detected wood decay fungal DNA in the sapwood of 11 forest tree species (angiosperm species). They suggest that wood decay fungi are latent in sapwood of live angiosperm trees and that environment may control the development of internal wood decay. Part of their title is appropriate for the ecology and productivity of forest trees: "Do all trees carry the seeds of their own destruction?"

2.7.1.4 Permafrost

Permafrost is a subsurface layer of continuously frozen soil that contains organic matter. It is found chiefly in polar areas, with more in the Northern Hemisphere than in the Southern Hemisphere. Approximately 24% of the land area in the Northern Hemisphere is in permafrost (National Snow and Ice Data Center, 2017). Surface thawing during short summer periods may allow microbial degradation of some organic matter and release of carbon dioxide and methane (Anthony *et al.*, 2016). Given the huge amounts of organic matter in global permafrost, there is concern that continued global warming will accelerate permafrost thawing, microbial degradation, and release of considerable amounts of carbon dioxide and methane, both of which could increase positive climate feedback that would further accelerate permafrost thawing and release of even more carbon dioxide and methane. Permafrost degradation has been occurring for as long as 40 years. It is not, however, well understood how this has contributed to positive climate feedback (Anthony *et al.*, 2016). A recent analysis in Alaska did not find significant increases in long-term methane emissions with increasing air temperature (Sweeney *et al.*, 2016). They pose two important questions to address about the future of emissions of methane from permafrost:

1. What fraction of mobilized soil organic carbon will be released as methane?
2. What is the sensitivity of methane emissions to temperature change?

The potential for extensive methane release from permafrost is there, but it is not clear if this will happen soon.

2.7.2 *Human-induced Sources of Methane*

Human activities increase natural methane emissions by 60%. An increasing population, with rising expectations of a better, more affluent lifestyle, especially in Asia, fuel the demand for food and energy sources, resulting in increases in methane emissions (Montzka, et al., 2011; World Meteorological Organization, 2016).

2.7.2.1 Rice Culture

Rice is grown primarily in Asia in flooded paddy fields that generate and release methane. Rice production and methane emissions are increasing. Emissions are influenced by factors such as temperature, fertilizer applications, and water levels (Augenbraun *et al.*, 1997).

2.7.2.2 Animals Raised for Food

Increasing population and rising affluence increase the demand for food from domestic animals. Dairy cows and cattle release the most methane during microbial-aided rumen digestion. Pigs, sheep, and goats also contribute (Augenbraun *et al.*, 1997). To meet demand, there has been an enormous increase in domestic ruminants (Stocker *et al.*, 2013). Increasing animal populations also means increasing quantities of methane from manure. Feedlots release methane and ammonia.

2.7.2.3 Methane from Fossil Fuels

Methane is released during coal mining and natural gas extraction from the ground. It is also vented or burned off as waste product during oil refining (Augenbraun *et al.*, 1997). Methane is leaking at increasing rates from ageing underground distribution pipes to homes, institutions, and industry. It is promoted as the "clean fuel." Complete combustion of methane, however, results in release of carbon dioxide and water vapor (2:1 ratio), the two most important positive radiative forcers.

2.7.3 Increasing Levels of Atmospheric Methane

Until 2007, atmospheric methane levels were relatively stable and were increasing slowly. Since 2007 they have been increasing at a rate more rapid than ever before (Saunois *et al.*, 2016; Rigby *et al.*, 2017). As methane has an atmospheric residence time of only approximately

10 years, the explanation for why methane is increasing is not clear. Large increases in agriculture and fossil fuel use, particularly in Asia, are possibilities (Saunois *et al.*, 2016; Rigby *et al.*, 2017). Large increases of methane from warmer tropical wetlands is another (World Meteorological Organization, 2016). Methane is removed from the atmosphere by oxidation with the hydroxyl radical (OH) (Montzka *et al.*, 2011; Fiore, 2014). Reduction in levels of OH in the atmosphere is another possible explanation. Together with increased emissions of methane, this could result in longer residence time for more methane in the atmosphere (Montzka *et al.*, 2011). Rigby *et al.* (2017) related a decline in OH to the increase in methane since 2007. Whatever the cause, rising methane is a major concern.

2.8 NITROUS OXIDE

Nitrous oxide (N_2O) is considered to be the third most important positive radiative forcer. It has now increased to 121% of its value in 1750 and is estimated to contribute 6% to the radiative forcer menu (World Meteorological Organization, 2016). It has a residence time in the atmosphere of 125 years. It also migrates slowly to the stratosphere where it can cause breakdown of the ozone layer. Removal occurs very slowly in the stratosphere (Montzka *et al.*, 2011). In the twentieth century, a relationship between terrestrial variations in temperature and rates of emission of nitrous oxide was established (Friedlingstein *et al.*, 2012).

Nitrous oxide is formed in soils and water during microbial nitrification and denitrification during decomposition of organic matter. Water absorption by plant residues increases emissions of nitrous oxide (Kravchenko *et al.*, 2017). The largest source of natural nitrous oxides is wet tropical areas. Nitrous oxide is also released during fuel combustion. Use of inorganic nitrogen crop fertilizers, growing crops that fix nitrogen, and deposition of nitrogen from combustion to soils have led to increased emissions of nitrous oxide. Deposition increases with temperature (Montzka *et al.*, 2011; Friedlingstein *et al.*, 2012; World Meteorological Organization, 2016).

Wen *et al.* (2017) have reported that alder (*Alnus*), beech (*Fagus*), and spruce (*Picea*) emit nitrous oxides from their stems in seasonal patterns, with alder stems emitting the least nitrous oxide. They concluded that soil-based measurements of nitrous oxide in temperate forests were likely underestimations.

People in emerging economies in Asia and Africa seek to improve their lives through increased consumption of material goods, greater living space, and better-quality food. Arable land must be found to grow more food, using chemical fertilizers, especially in Africa where Nigeria is poised to become the world's third most populous country. Together with warming air temperatures, increased levels of nitrous oxide should be expected.

2.9 OTHER RADIATIVE FORCERS CREATED BY HUMANS

Humans have synthesized many gaseous molecules that have no natural sources. They exist in the atmosphere when they escape from industrial processes. They are used as coolants and propellants and as insulators in the electric power industry. As there are no known breakdown processes, their persistence time in the atmosphere may be forever. Most are fluorinated gases: they include sulfur hexafluoride, hydrofluorocarbons, chlorofluorocarbons, perfluorocarbons, and nitrogen trifluoride. All are very strong radiative forcers, and some move slowly to the stratosphere where they break down ozone. Concentrations are measured in parts per trillion (ppt). Chlorofluorocarbons are decreasing, but some hydrofluorocarbons are increasing (Montzka *et al.*, 2011; World Meteorological Organization, 2016).

2.10 ROLE OF OTHER PRODUCTS FROM INCOMPLETE COMBUSTION

Complete combustion of organic materials would result in release of CO_2 + H_2O vapor in a 1:2 ratio. This can be true for clean natural gas (methane), but it is not likely for most combustion processes. Incomplete combustion results in release of a wide variety of reactive gases that can indirectly strongly influence global warming and climate change. These include nitric oxide and nitrogen dioxide, carbon monoxide, volatile organic compounds, and sulfur dioxide. Nitric oxide, nitrogen dioxide, and volatile organic compounds are involved in atmospheric chemistry that results in the formation of ozone, an important non-persistent radiative gas. Sulfur dioxide is the main precursor for sulfur aerosol formation, which reflects sunlight and cools the area below (Global Atmosphere Watch, 2017).

Black carbon is principally elemental carbon, primarily from fossil fuel combustion, found in what is commonly called soot. It is the strongest atmospheric absorber of incoming solar radiation. Deposition is either direct or by rain or snow, with a life span of about a week. Deposition to ice or snow may cause melting (Khan *et al.*, 2017). Black carbon may also combine with aerosols to form large brown clouds that can result in global dimming (Wild *et al.*, 2007; Ramanathan and Carmichael, 2008).

2.11 OZONE

Ozone (O_3) is a natural component of the atmosphere. When present, it is considered by many to be the third most important radiative forcer. It is a more effective radiative forcer than carbon dioxide (Unger, 2012). It is very effective in the upper troposphere (NASA, 2015). Unlike carbon dioxide or methane, ozone is a secondary gas that is formed and can be reformed through complex atmospheric chemistry that requires precursor molecules and sunlight and warm temperatures. Low levels of ozone are considered as normal background. Short-lived higher levels can act as radiative forcers and also cause injury to plants and cause human health problems (Krupa and Manning, 1988; Ashmore, 2005; Sitch *et al.*, 2007). Ozone can be a radiative forcer and an air pollutant at the same time (Unger, 2012).

2.11.1 *Sources and Sinks of Ozone*

Rainstorms clean the air of particulates and ozone. If lightning occurs in a storm, the air afterward seems clean with a pleasant, slightly acrid smell. The smell is due to ozone from static discharge from lightning. Ozone can also be released during the use of older photocopiers and older trolleycar wires. Short-term high concentrations can result from temporary intrusions or dip-downs of ozone from the stratosphere (NASA, 2015).

Ozone is formed in the photochemical oxidant cycle. The chemistry is complex and involves several precursor molecules and reactions. Ozone can be formed and then broken down in a catalytic cycle that does not allow for accumulation in the atmosphere beyond normal background. To be an effective radiative forcer, ozone must accumulate beyond normal background levels. Small hydrocarbons from combustion and trees (principally isoprene) interrupt the catalytic cycle and allow ozone to accumulate and act as a radiative forcer and an air pollutant. The photochemical oxidant cycle that forms ozone is detailed in Chapter 3.

In addition to being a direct radiative forcer, it is becoming evident that ozone may be more important as an indirect radiative forcer through negative effects on photosynthesis and plant growth that reduce carbon dioxide removal from the atmosphere (Ashmore, 2005). It has been proposed that ozone effects on plants could result in more global warming through reduction in uptake of carbon dioxide than direct radiative forcing caused by ozone alone. With current and predicted rising ozone levels, this is of particular concern (Sitch *et al.*, 2007).

2.11.2 Carbon Dioxide and Ozone

Global warming and climate change are affected by a variety of human-influenced gases in the atmosphere. Water vapor, methane, and nitrous oxide are powerful radiative forcers, but are relatively short-lived. Carbon dioxide is the largest and most important irreversible persistent radiative forcer, with effects estimated to persist for more than 1000 years (Solomon *et al.*, 2009, 2010). Concentrations continue to increase in the atmosphere (Canadell *et al.*, 2007) and this has resulted in extensive increases in vegetative growth, particularly in the Northern Hemisphere (Mao *et al.*, 2016; Yakir, 2017). This is seen as a possible partial mitigation mechanism for elevated carbon dioxide in the atmosphere (Mao *et al.*, 2016; Yakir, 2017). While the effect of elevated carbon dioxide on vegetation is positive, as much as 40% of the anthropogenic carbon dioxide remains in the atmosphere and is the major cause of global warming and climate change.

Ozone is a much more effective radiative forcer than carbon dioxide, but is short-lived and variable in concentration and occurrence (Unger, 2012). Like carbon dioxide, ozone enters leaves via stomata during gas exchange in photosynthesis. It can cause cellular and tissue damage which reduces growth and gross plant productivity. Depending on the concentration, ozone can also cause stomatal closure and limit uptake of carbon dioxide. With foliar damage or stomatal closure, or both, the uptake of carbon dioxide and resulting carbon sequestration can be reduced by ozone, and more carbon dioxide remains in the atmosphere. Elevated levels of carbon dioxide, however, can also cause stomatal closure, which could limit entry by ozone and thus provide protection from ozone damage and plant growth reduction. This is the potential protective effect of carbon dioxide in ameliorating ozone damage in plants (Paoletti and Grulke, 2005).

As Sitch *et al.* (2007) point out, there is a complex and not well-understood or documented interaction between ozone and carbon dioxide effects on vegetation. It is known that an increase in carbon dioxide can cause stomatal closure and inhibit ozone uptake, and conversely that an increase in ozone can also cause stomatal closure and exclude carbon dioxide. A modified global land carbon cycle model was used to assess whether stomatal closure caused by carbon dioxide would protect plants from damage due to increases in ozone concentrations, or whether ozone would reduce the effects of carbon dioxide to ameliorate reductions in photosynthesis caused by ozone. Using data from empirical experiments, it was found that as ozone concentrations increased there was a significant decrease in plant production that affected the land sink for carbon (Sitch *et al.*, 2007).

Carbon dioxide is considered to have positive effects on vegetation. Average concentrations of ozone above 40 parts per billion (ppb) are considered to have negative effects on vegetation (Ashmore, 2005). Both carbon dioxide and ozone are present during growing seasons, and both can affect trees in forests. It has been suggested that future effects of ozone on plants and land carbon storage will be determined by the interaction of ozone, carbon dioxide, and climate change factors (Sitch *et al.*, 2007). As trees and forests are the major contributors to terrestrial carbon storage, it is essential to determine how they are affected by carbon dioxide and ozone, and how this might affect their role in cooling or warming the atmosphere.

2.12 SUMMARY

Global warming was introduced in Chapter 1. In this chapter, the nature and role of the radiative and reactive gases that cause the greenhouse effect were introduced and discussed. During the day, visible light and shortwave radiation from the sun (sunlight) travels from space through the Earth's atmosphere. Some is reflected back, the rest absorbed to warm the Earth. As long wave infrared radiation (heat) begins to return to space, some is intercepted by clouds and water vapor, or absorbed by the greenhouse gases and radiated back toward the surface, retaining some warmth, and making life on Earth possible. This is the greenhouse effect.

The greenhouse effect and temperatures are increasing. Night temperatures are increasing faster than daytime temperatures. The atmosphere is generally warming.

Water vapor, a condensable, variable-concentration gas, is the major radiative gas involved in global atmospheric warming. Non-condensable radiative gases include carbon dioxide, ozone, methane, nitrous oxide, and chlorofluorocarbons, all of which are persistent and increasing in concentration, except ozone which is seasonal and variable in incidence and concentration. Together, they provide enough elevated temperature to allow water vapor to be the major greenhouse gas.

Carbon dioxide is 80% of the non-condensable radiative gases. As such, it is considered to regulate the temperature of the Earth's atmosphere. From this perspective, carbon dioxide is the most important greenhouse gas. Carbon dioxide has been increasing steadily by as much as 2.1 ppm per year for the past decade. It has passed the 400 ppm mark and is expected to remain there indefinitely. It is estimated that 40% of the current level of carbon dioxide is from fossil fuel combustion and cement production. The oceans and the terrestrial plant and soil land mass sink do not provide a sufficient sink for the 40% anthropogenic carbon dioxide. Its persistence in the atmosphere may be several thousand years.

Carbon dioxide is used by plants in photosynthesis to fix carbon used in growth. The influence of elevated carbon dioxide should have a positive effect on trees. Tropospheric levels of ozone can be high enough during the summer growing season to injure leaves and reduce plant growth stimulated by elevated carbon dioxide. This is why both carbon dioxide and ozone are important factors in the role of trees in cooling and warming the atmosphere.

The next chapter will focus on the carbon cycle and the photochemical oxidant cycle.

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3 Carbon and Photochemical Oxidant Cycles

Most of the Earth's carbon is stored in rocks. The rest is in the ocean, the atmosphere, plants, soil and fossil fuels. Carbon flows between reservoirs in an exchange called the carbon cycle. Any change in the cycle that shifts carbon out of one reservoir puts more carbon in other reservoirs. Changes that put more carbon gas into the atmosphere result in warmer temperatures for the Earth.

Riebeek, 2011; NASA

Terrestrial carbon-climate feedbacks depend on two large opposing fluxes – soil organic matter decomposition and photosynthesis – that are tightly regulated by nutrients.

Riley *et al.*, 2018

Climate change due to carbon dioxide emissions is irreversible.

Solomon *et al.*, 2009

3.1 INTRODUCTION

Reradiative or greenhouse gases were reviewed in Chapter 2. Elevated carbon dioxide is considered to be the most persistent cause of global warming and climate change, having greatly exceeded the capacity of natural terrestrial and ocean sinks. Carbon dioxide is the bridge or link between the land and ocean sinks (Box 3.1). Previously these sinks functioned to keep carbon dioxide in the air at levels that did not result in appreciable global warming. Carbon moves in the environment in slow, intermediate, and relatively fast cycles. Understanding the nature of these cycles will enhance understanding of the important role of carbon and carbon dioxide in the environment.

Carbon dioxide is essential for photosynthesis by plants. It has been proposed that future elevated levels of carbon dioxide are likely to increase photosynthesis and plant growth and increase the sink

BOX 3.1 Carbon Storage and Cycling

Land	In biomass and soil organic carbon
Atmosphere	Carbon dioxide
Oceans	Primarily dissolved organic carbon

Both land and ocean carbon stocks exchange carbon as carbon dioxide with the atmosphere.

Mackey *et al.*, 2013

capacity for carbon dioxide for land vegetation. Several factors, however, also affect the efficiency and effectiveness of photosynthesis. (These will be considered in more detail in Chapter 4.) Current levels of periodic atmospheric ozone can cause plant injury and reduce photosynthesis. Ozone can be taken up into plants via leaf stomata at the same time that carbon dioxide enters. Ozone levels have also been projected to increase in the future. This has implications for the effectiveness of photosynthesis and for ozone's role as a powerful reradiative or greenhouse gas.

More carbon is stored in soils, especially organic forest soils, than in all forms of terrestrial vegetation combined. Carbon dioxide, methane, and nitrous oxide are released from microbial decomposition of organic matter in and on soil surfaces. How warming temperatures affect the rate of emission of carbon dioxide and other gases is of considerable concern regarding present and future global warming.

3.2 CARBON

Carbon (atomic number 6) is the fourth most abundant element by mass. Each atom has four available electrons for covalent bond formation. Carbon atoms are the building blocks for formation of a wide variety of large organic molecules, ranging from long chains and carbohydrates to DNA. Carbon is an element found in and essential to all life forms. Most is stored in rocks, ocean sediments, stones, and fossil carbon in soil. The rest cycles between the terrestrial biosphere, the atmosphere, and the oceans. The terrestrial biosphere (mainly forests) and the oceans absorb, store, and release carbon dioxide (Riebeek, 2011; Royal Society of Chemistry). There is a summary for carbon storage and cycling in Box 3.1.

3.2.1 The Slow Carbon Cycle: Chemical Weathering and Carbonate

Chemical weathering of rocks in or near streams is a key component of the slow global carbon cycle. It affects the extent of uptake of carbon dioxide from the atmosphere by the oceans and storage as calcium carbonate. The process that occurs very slowly over thousands to millions of years is called the slow carbon cycle. Carbon dioxide in the atmosphere interacts with water in rain to form carbonic acid. Carbonic acid reacts with rocks and releases calcium, magnesium, potassium, and sodium ions that are transported to the oceans by rivers. Calcium ions combine with bicarbonate ions in ocean water to form calcium carbonate, which sinks to the ocean floor. Shellfish, corals and other organisms build shells with calcium carbonate. These also sink to the ocean floor when the organisms die and combine with calcium carbonate to form limestone (Riebeek, 2011). There is concern that the rate of rock weathering and calcium release may not keep up with increasing amounts of carbon dioxide in the air, and this might slow down carbonate and bicarbonate formation (Falkowski *et al.*, 2000).

In prehistoric times, organic matter from dead plants began to accumulate faster than it could completely decay. Plant remains often fell into wetlands. Over time, accumulating layers resulted in increased heat and pressure, and formation of huge deposits of peat, coal, oil, and methane. These have found use as fuel sources and are known as fossil fuels. They are the source of additional carbon dioxide and other gases driving global warming and climate change. The carbon dioxide released from fossil fuel combustion is new carbon dioxide and the amount exceeds normal carbon sink capacities (Prentice *et al.*, 2012).

Volcanoes are also part of the slow carbon cycle. Instead of capturing carbon dioxide from air and storing in an unavailable form, volcanoes emit carbon dioxide when they erupt. Carbon dioxide is released below ground when rock melts and released during volcanic eruptions (Riebeek, 2011). Volcanoes also emit huge quantities of ash, gases, and sulfate and other aerosols that affect air quality and visibility. These may go circumglobal and increase light reflection back to space.

3.2.2 *The Intermediate Cycle: Oceans*

The ocean covers the largest part of the Earth's surface. As it is divided into different regions by latitude and warmth and other characteristics, the term "oceans" will be used here. Ocean water surfaces are in continuous contact with atmospheric carbon dioxide. Prior to the Industrial Revolution, the oceans exchanged carbon dioxide with the atmosphere in a way that balanced the cations received from rock weathering. A small amount of carbon dioxide was released. This balance has changed in favor of more uptake of carbon dioxide from the atmosphere than carbon dioxide released (Riebeek, 2011). Carbon dioxide is taken up more readily in colder ocean regions and released more readily in warm ocean regions (Prentice *et al.*, 2012). The oceans are the largest of the three carbon reservoirs and contain the most stored carbon. They are estimated to take up 30–40% of the anthropogenic carbon dioxide from fossil fuel combustion, deforestation, urbanization, and land-use change. Model calculations published in 2012 indicate that net carbon dioxide uptake by the oceans has increased during the last 50 years (Ballantyne *et al.*, 2012).

Carbon dioxide enters the ocean's surface by diffusion when the concentration of carbon dioxide above the surface is higher than in the water. Carbon dioxide can remain as a dissolved gas (CO_{2aq}) or react with water to form carbonic acid, H_2CO_3. Carbonic acid dissociates and reforms releasing bicarbonate ions (HCO_3^-) and a hydrogen ion (H^+). The hydrogen ions can lower the pH of the seawater, which can affect the availability of carbonate for shell-building organisms.

Growing near the surface of the oceans are numerous common photosynthetic plant and plant-like organisms called phytoplankton. They are the basis for the food web, beginning the chain from zooplankton to fish to organisms as high as whales. The end of the chain is death and deposition in the deep oceans. Phytoplankton use carbon dioxide for photosynthesis, and this reduces carbon dioxide in the ocean which results in more carbon dioxide diffusion from the atmosphere for use in photosynthesis. The amount of soluble carbon dioxide in water is greatly influenced by the extent of phytoplankton. Photosynthesis by phytoplankton accounts for most of the removal of carbon dioxide from the atmosphere to the oceans.

Atmospheric carbon dioxide is regulated by surface exchanges with ocean carbon dioxide. The ability of ocean water to dissolve carbon dioxide from the air decreases as temperature increases, so the concentration of carbon dioxide in water is determined by water temperature. Carbon dioxide from the atmosphere is maintained in a thin surface layer of water regulated by wind-driven turbulence. Carbon flux between oceans and the atmosphere depends on surface mixing and wind speed and on the carbon dioxide gradient between water and air (Falkowski *et al.*, 2000).

3.2.3 The Faster Carbon Cycle: Atmosphere, Forests, and Soils

Carbon moves faster through the terrestrial ecosystem, both in and out of organisms, mostly trees and forests, and is stored in organic matter, primarily wood and soils. While uptake of carbon dioxide by photosynthesis and carbon storage is less than in the oceans, it is an essential part of atmospheric carbon management.

3.2.3.1 Carbon Dioxide in the Atmosphere

Before the Industrial Revolution, there was a balance between carbon dioxide uptake from the atmosphere and release that maintained carbon dioxide at approximately 280 ppm. It was the major contributor to the essential natural greenhouse effect that allowed life on Earth as we know it. Since that time, an ever-expanding human population has used increasing quantities of fossil fuels to generate energy for heating and cooling, transportation, and industrial use. Deforestation and land-use change have reduced carbon sink capacity. Carbon dioxide has increased in the atmosphere from the pre-industrial levels of approximately 280 ppm to 400 ppm and above. This global average concentration is predicted to remain and possibly increase slowly (Mann *et al.*, 2016). Industrial growth (65%), fossil fuels (17%), and reduced sinks (18%) have been identified as reasons for the increased rate of carbon dioxide (Canadell *et al.*, 2007). El Nino events have also contributed to record high carbon dioxide levels (Betts *et al.*, 2016).

Carbon dioxide greater than 280 ppm is anthropogenic in origin. Anthropogenic carbon dioxide exceeds the capacity of the oceans and the terrestrial biosphere to absorb and store all of it. Approximately 40% of anthropogenic carbon dioxide does not find sink storage. This carbon dioxide will remain in the atmosphere for 1000 years or more (Schimel, 2007; Archer *et al.*, 2009; Solomon *et al.*, 2009; Ryan *et al.*, 2010; Riebeek, 2011). It is the major cause of the global warming and climate change that we are experiencing today.

Keeling, at the Mauna Loa observatory in Hawaii, determined that carbon dioxide levels in the Northern Hemisphere were lower in summer than in winter. He attributed the summer decrease in carbon dioxide to uptake by seasonal vegetation. These seasonal variations have been documented since 1960 (Keeling *et al.*, 1996; Graven *et al.*, 2013). Using long-term data from the Mauna Loa observatory (1958–2015), Curran and Curran (2016a, 2016b) documented that carbon dioxide concentrations in the Northern Hemisphere typically decrease (drop) during a four-month period from May to September, coinciding with plant growth and carbon sequestration. Carbon dioxide concentrations begin to increase in November and remain higher than in summer until early spring of the following year. The magnitude of the intra-annual drop cycle was examined and calculated over a 57-year period, using weekly data from Mauna Loa. Curran and Curran determined that the magnitude of the summer carbon dioxide concentration began to drop rapidly in the 1960s to 1970s, reaching a peak in 2006, with small increases since then. They concluded that if the early rates of drop in carbon dioxide had continued to 2013, the summer drop in carbon dioxide would have been 8.9 ppm. The value that they determined for 2013 was 7.5 ppm. If less carbon dioxide is being taken up by vegetation in the summer, then perhaps the terrestrial carbon sink is becoming saturated. This would mean more carbon dioxide in the atmosphere in the summer, which would be a positive forcer for global warming.

3.2.3.2 Carbon Movement in Trees and Soils

Carbon dioxide is taken up by trees through photosynthesis and used for growth and carbon storage. Trees and forests are the major long-term sinks for carbon storage. Forests are estimated to absorb as much as 30% of anthropogenic carbon dioxide (Luo *et al.*, 2015). Carbon is allocated to stems, roots, branches, leaves, and seeds. It is stored in stems, branches, and roots. Small branches, leaves, and seeds are transient and become part of litter on the forest floor. Carbon is returned as carbon dioxide through respiration by shoots and roots and by microbial respiration from breakdown of litter and soil organic matter. It has been estimated that the carbon dioxide taken up in photosynthesis in a year is nearly balanced by the amount returned to the atmosphere by respiration (Griffin and Prager, 2017). The small margin between photosynthesis and respiration is stored carbon. Heterotrophic respiration from microbes decomposing litter on the forest floor releases carbon dioxide. Forest fires release stored carbon (Falkowski *et al.*, 2000).

Many factors, such as elevated carbon dioxide, light, temperature, available soil water, soil nutrients, and ozone, affect photosynthesis and respiration. With warming global temperatures, the impacts of elevated carbon dioxide, temperature, and water availability become important. Water vapor from stomata during photosynthesis cools air and affects low clouds. Models predict that elevated carbon dioxide can close stomata and increase radiative forcing owing to reduction in low cloud formation (Doutriaux-Boucher *et al.*, 2009). Increased temperatures increase photosynthesis and respiration globally, while availability may be more important locally (Jung *et al.*, 2017). There are indications of adaptation of respiration rates to higher temperatures (Griffin and Prager, 2017). Higher temperatures may stimulate and accelerate carbon dioxide release from litter by heterotrophic microbial respiration (Falkowski *et al.*, 2000).

3.2.3.3 Carbon Dioxide and Tree Growth

It has been extensively demonstrated under experimental conditions that elevated concentrations of carbon dioxide stimulate growth and biomass of trees. Data from satellite surveillance and results from models also indicate that extensive increases in global vegetative gross (GPP) and net (NPP) primary productivity, or "global greening," occurred during the twentieth century (Mao *et al.*, 2016; Sun *et al.*, 2017; Yakir, 2017). This is also known as "global carbon dioxide fertilization" (Friedlingstein *et al.*, 1995; Pan *et al.*, 2011). This trend is also consistent with other observations (Ballantyne *et al.*, 2012; Smith *et al.*, 2015; Campbell *et al.*, 2017). McMahon *et al.* (2010) presented empirical evidence that forest growth was increasing. They obtained data on tree biomass increase from 55 temperate forest plots, with known use histories and conditions, over a 22-year period. They concluded that recent biomass increase was greater than what was expected to have occurred by natural recovery from past events in the forest plots. Increased growth was attributed to the effects of utilization of increasing carbon dioxide in photosynthesis. Others have suggested that it may be due to increased water-use efficiency. Incidence of deforestation, drought, insect infestations, and fires did not appear to affect estimations of global increased GPP and NPP.

3.2.3.4 Forests as Carbon Sinks

European forests are considered to be strong sinks for carbon dioxide. There are indications, however, that forest growth may be slowing, and that this could reduce carbon sink strength. Nabuurs *et al.* (2013)

reported significant declines in the rates of increase of tree net stem volume from 2005 to 2010 for all European forests. Associated with this, land-use change and deforestation are increasing, resulting in decreased uptake of carbon dioxide. Storms, fires, and other disturbances also contribute to tree losses and reduced uptake of carbon dioxide. Taken together, they clearly indicate that the European forest biomass is in danger of becoming saturated and less effective as a carbon sink. Reichstein *et al.* (2013) raise concerns that extreme events, such as fire, drought, storms, and high temperatures, reduce the strength of the forest carbon sink. Neumann *et al.* (2017) conclude that warmer summers and changes in precipitation may be responsible for increased tree mortality in Europe.

3.2.3.5 Soil Carbon Sink

Soils are the largest reservoirs of organic carbon in plant and animal remains, and major sources of carbon dioxide (Jackson *et al.*, 2017). The carbon dioxide released from root and microbial respiration from soils is estimated to be 60 billion tonnes per year. It is estimated that this amount exceeds that from fossil fuel combustion and is nine times the total carbon dioxide emitted from all combined human inputs (Wang *et al.*, 2013; Giardina *et al.*, 2014; van Groenigen *et al.*, 2014; Carey *et al.*, 2016). Rising air temperatures and increased carbon dioxide promote shoot/biomass, larger root systems, greater respiration, and increased organic matter for decomposition (van Groenigen *et al.*, 2014). Roots exude organic compounds that accelerate decomposition and respiration. This process of accelerated decomposition has been called "priming" (Sulman *et al.*, 2014; Carey *et al.*, 2016). Decomposition is favored by well-drained and aerated mineral soils and by temperatures above 25 °C (Davidson and Janssens, 2006; Carey *et al.*, 2016). This has been confirmed by long-term study of emissions from warmed and non-warmed soil plots in forests. Warmer temperatures stimulate microbial activity which increases breakdown of organic matter and release of carbon dioxide and methane (Mellilo *et al.*, 2017). Carey *et al.* (2016) reviewed 27 soil warming studies in temperate areas, finding that soil respiration increased in all areas up to 25 °C and decreased after that. The effect was more pronounced in colder areas. Warmer temperatures in a tropical rainforest in Panama caused increased tree growth and litterfall. Additional litter stimulated microbial activity and release of soil carbon. Sayer *et al.* (2011) conclude from their findings that much of the carbon taken up by tropical tree growth could be lost because of stimulation of soil microbial activity by increased litterfall. They estimate that the amount of carbon lost from soil could be greater than the increase in tree biomass due to warming and higher levels of carbon dioxide. Deforestation also leads to soil carbon loss. This process is accelerating rapidly in tropical areas where original forests are burned and replaced by plantations of trees grown in response to demand for food and fuels by people in developed and rapidly developing countries. Native trees and shrubs are replaced by plantations of avocado, banana, cacao, citrus, macadamia, oil palm, and rubber trees. Van Straaten *et al.* (2015) reported that oil palm, rubber, and cacao plantations in Cameroon, Indonesia, and Peru resulted in up to 50% losses of soil carbon through emissions of carbon dioxide and soil leaching.

Permafrost soils in the Arctic contain large amounts of frozen organic matter. Rising temperatures there are accelerating thawing and exposure of the organic matter to decomposition and microbial decomposition, releasing carbon dioxide and methane (Schadel *et al.*, 2016).

Recognizing the importance of understanding and estimating microbe-mediated carbon dioxide release from organic matter in soils, a new carbon cycling model (the MEND model) was developed at Oak Ridge National Laboratory. By modeling rates of soil microbial decomposition in relation to temperature, estimates of carbon dioxide emissions were determined.

3.3 LAKES AND RIVERS

There are more than a million lakes in the world, plus additional water reservoirs. Microbial activity in organic sediments releases carbon dioxide. Weyhenmeyer *et al.* (2015) included carbon dioxide from surrounding land that moves via streams to lakes, especially in Sweden. They estimated that small lakes in Sweden, surrounded by agricultural land, emit more carbon dioxide than a similar lake in a forest area. Carbon dioxide emissions from lakes and reservoirs are estimated to be as much as 25% of the carbon dioxide emitted from fossil fuel combustion.

The rivers of the world accumulate large quantities of organic matter from terrestrial and aquatic vegetation, and, as we have said, microbial action releases large quantities of carbon dioxide. The Amazon river and tributaries form one of the most important river systems in the world. Sawakuchi *et al.* (2017) have extensively determined carbon dioxide concentrations and release in the lower Amazon river, which drains 13% of the total Amazon basin. This area is influenced by tides which result in wind and wave action and turbulence that increase as the river reaches the ocean. This in turn increases carbon dioxide release from the river. The surface area of the river expands as it widens, resulting in increased emission. Carbon dioxide emissions from this region of the river are considerably higher than those measured in the central basin of the river. Carbon dioxide emissions from the Amazon river system may closely match the amount of carbon dioxide taken up by tropical trees in the region. If the Amazon basin is net carbon-neutral, this has profound implications for expectations that the Amazon is or will be a major sink for anthropogenic carbon dioxide.

3.4 CITIES AND THE GLOBAL CARBON CYCLE

The 2017 United Nations estimate of the world's human population size is 7.6 billion. The UN further estimates that 183 million new humans are added daily, with most growth occurring in India and China and in developing countries such as Nigeria. Half of the world's population growth is projected to occur in Africa: 40 African countries could double the size of their populations by 2050 (Friedman, 2016; United Nations, 2017). The population size in Nigeria could increase from number seven to number three in the world, which would make it larger in population size than the USA (Friedman, 2016). Every single human has requirements and activities that have profound effects on the global carbon cycle. As population grows, these effects will increase. The population factor has received little attention in studying global warming and climate change.

Human populations require food, water, energy, and shelter. Governments have concluded that, since cities use only 2% of global land area, they are the most efficient places to provide these requirements. The current world estimate of world population living in cities is 54.4%. This is estimated to reach 60% by 2030 (Churkina, 2016; United Nations, 2017). In Western Europe, 80% of the population lives in cities. Consolidated urban areas of as many as 30 million people exist in China.

Cities require large amounts of energy to make them function. Electricity for lighting, heating, and cooling comes from fossil-fueled power plants adjacent to the cities. Fossil fuels, such as coal, gasoline, methane, and fuel oil, and in some places biofuels such as wood, are burned for transportation and heating. The products of this incomplete combustion include carbon dioxide, oxides of nitrogen, small hydrocarbons, and much more. The irregular structure of cities makes it difficult to accurately determine or estimate urban-scale fluxes and emissions of carbon dioxide. Hutyra *et al.* (2014) point out that this has discouraged detailed investigations. Velasco and Roth (2010) proposed that the eddy covariance method (EC) can be used to directly measure carbon dioxide fluxes in cities and suburban areas. They summarized results from 30 EC systems, mostly in mid-latitude cities. The largest fluxes of carbon dioxide occurred in city centers, decreasing with distance to the suburbs. They concluded that cities are a net source of carbon dioxide and attributed this to emissions from vehicles and heating buildings. Cities are considered to be the main sources of carbon dioxide from energy source combustion that accumulates in the atmosphere as anthropogenic carbon dioxide (Velasco and Roth, 2010; Lauvaux *et al.*, 2013; Hutyra *et al.*, 2014; Churkina, 2016).

Because of their nature, structure, and low albedo, cities experience heat island effects that increase temperatures, especially at night. As global warming increases, and cities increase in size, the demand for air conditioning in cities for cooling will expand rapidly in tropical and mid-latitude areas. This is particularly true in Asia where middle-class lifestyles are emerging, resulting in increased energy use (Friedman, 2016). Abel *et al.* (2017) found that increased use of air conditioners during hot weather meant that fossil-fueled power plants have to increase fuel to generate more electricity, releasing more carbon dioxide, oxides of nitrogen, and sulfur dioxide. Using data from 27 states, they found that power plants averaged an increased release of 3.32% per degree C in temperature. They estimated that increased air temperatures correlated with an increase of 140,000 metric tonnes of carbon dioxide.

3.4.1 Urban Forestry and Carbon Dioxide

There is increasing interest in preserving woodland fragments and parklands in cities to reduce carbon dioxide release by city centers. Large campaigns to plant street trees are in force in many cities and towns. In addition to enhancing life quality, it is hoped that additional trees will increase uptake of carbon dioxide and help to slow global warming and climate change. Slogans like "Plant a Tree: Save the Planet" resonate well and promote tree planting. New York City and Los Angeles have begun million-tree planting programs. Even Amherst Massachusetts, USA (population 33,000), has begun to plant 2000 new trees. The purpose is to get people involved in global warming and climate change, and to be more aware of their environment. While there are indications of significant carbon dioxide uptake by trees in temperate climate cities, there is no empirical evidence that urban trees effectively reduce large amounts of carbon dioxide or other air pollutants (Unger, 2014). Nowak and Crane (2002) modeled carbon dioxide sequestration by urban trees and concluded that the shading of buildings to reduce the need for electricity generation (and thus carbon dioxide emissions from power plants burning fossil fuels) was the principal benefit. Any benefit from carbon dioxide sequestration by urban trees was offset by the use of power equipment to prune and maintain them. Tang *et al.* (2016) concluded that total carbon sequestration by Beijing's street trees was equivalent to approximately 0.2% of the carbon dioxide emitted from generation and use of energy. Velasco *et al.* (2016) investigated the role of evergreen (sub) tropical trees and soil (the biogenic component) in carbon sequestration in parts of Mexico City and Singapore. Their assessment included tree species and the amount of open soil suitable for respiration. They concluded that the biogenic component in the area assessed in Mexico City acted as a sink for carbon dioxide (+1.4%) and in Singapore as a source of carbon dioxide (−4.4%). By including trees and soil respiration in their analysis, they were able to obtain a more realistic assessment of the role of urban vegetation as a sink or source for carbon dioxide. The value of urban trees to significantly reduce urban carbon dioxide remains in doubt.

3.5 HUMAN INFLUENCE ON CARBON DIOXIDE: ENERGY SOURCES AND EMISSIONS

Human influence on the carbon cycle began with combustion, when humans learned how to start and control fires, releasing carbon dioxide back to the atmosphere. As populations grew, release of carbon dioxide from deforestation, developing human sites, and agriculture began to affect the capacity of the carbon sinks. Industrialization and growing urban development required the use of wood and coal as fuels, greatly increasing release of carbon dioxide to the atmosphere. The discovery of oil and natural gas, and their use along with coal as fuels as replacement for wood, began the process whereby the amount of carbon dioxide emitted by combustion of these fossil fuels began to exceed the capacity of the land and ocean sinks to absorb it. Le Quéré *et al.* (2016) estimate that emissions from fossil fuel combustion became the dominant source of carbon dioxide to the atmosphere around 1920.

BOX 3.2 CO_2 Emissions of Fuels in Pounds of CO_2 per Million Btus of Energy

All common fuels contain carbon and release CO_2.

Coal:	
anthracite	228.6
bituminous	205.7
lignite	215.4
sub-bituminous	214.3
Diesel and heating oil	161.3
Gasoline (no ethanol)	157.2
Propane	139.0
Natural gas methane	117.0

Methane has the lowest CO_2 to energy content

Source: US Energy Information Administration 2017a

Continued anthropogenic influence through deforestation, agriculture, and fossil fuel combustion has resulted in a disruption of the balanced land/ocean air sinks that existed at approximately 280 ppm carbon dioxide at the beginning of the Industrial Revolution to an increase to 400+ ppm carbon dioxide today (NASA, 2019). The 40% of anthropogenic carbon dioxide remaining in the atmosphere will remain there for 1000 years or more (Archer *et al.*, 2009).

Humans require large amounts of energy for transportation, heating/cooling, agriculture, cooking, and industry. With the exception of the growing solar panel and windfarm energy programs, this energy comes from combustion of some kind of fuel containing carbon. Carbon dioxide emissions for different fuels by pounds of carbon dioxide emitted per million British thermal units (Btu) of energy are listed in Box 3.2. Methane is the most efficient fuel in terms of energy content to carbon dioxide released. Emissions from methane are 2:1 water vapor to carbon dioxide, both strong radiative forcers (US Energy Information Administration, 2017a, 2017b).

3.5.1 Gasoline and Diesel

Estimates for 2016 indicate that in the United States, gasoline-powered vehicles emitted approximately 1,102 million metric tonnes of carbon dioxide, and diesel-powered vehicles emitted 437 million metric tonnes of carbon dioxide, for a total of about 1,540 million metric tonnes of carbon dioxide. This was equal to 30% of total carbon dioxide emissions from energy generation. Addition of 10% ethanol to gasoline and 20% biodiesel to diesel can reduce emissions (US Energy Information Administration, 2017a, 2017b).

3.5.2 Wood

Wood is often a readily available non-hydrocarbon inexpensive fuel for home heating. People have been burning wood for heating and cooking for thousands of years. In addition to release of stored carbon dioxide, other elements in the wood, or those that form during the combustion process, are released to the atmosphere in smoke. These species can cause serious human health problems. McDonald *et al.* (2000) identified more than 350 elements or compounds emitted from wood burning, including fine particulates. Cooper (1980) identified compounds that were pollutants, carcinogens, hydrocarbons, aldehydes, carbon monoxide and carbon dioxide, and many more.

3.5.3 Global Waste Burning

The generation and disposal of waste or rubbish from human activities is generally managed effectively in developed countries. In large areas of the world, however, rubbish is openly burned, releasing all the products of incomplete combustion, including carbon dioxide. Wiedinmyer (2014) calculated that carbon dioxide emitted from open burning approximated 5% of global anthropogenic carbon emitted in 2010, and concluded that emissions of carbon dioxide and other gases from rubbish burning are not included in estimates of emission rates by countries.

3.5.4 Food and Household Products

Human activity and metabolism cause carbon dioxide release into the atmosphere (Prairie and Duarte, 2007). On any day, people can visit a local food store and observe an enormous variety of fruits and vegetables, meat and meat products, dry and canned goods, and household products. They can also find large sections devoted to pet foods. In 2015, there were 163 million pet dogs and cats, compared to 321 million people, in the United States (Okin, 2017). Everything in the stores is brought there by fossil-fueled trucks and airplanes, many from distances as great as several thousand miles. The amount of anthropogenic carbon dioxide emitted during transport is part of the human carbon budget.

Humans and their pets consume food containing carbon (agricultural carbon) directly fixed recently by plants and indirectly by animals. Food is metabolized and carbon dioxide is released when oxygen is inspired. Excreta also are decomposed by microorganisms, releasing more carbon dioxide and methane. It is generally concluded that the amount of carbon taken in by humans and their pets is roughly balanced by the amount released, resulting in carbon-neutrality (West *et al.*, 2009).

Humans have very strong dependencies on animals for food. Prairie and Duarte (2007) estimated that in 2007 the world's population of domestic animals was three times the size of the human population (possibly 15 billion domestic animals). This has grown considerably since then and will continue to grow as population increases. Most of the food for domestic animals is plant-based, and the carbon fixed from the air in growing the plants to feed the animals is returned when the animals respire. Considerable quantities of methane are released directly by cattle and their excreta. It should also be noted that more land will have to be cleared (deforested) to provide agricultural land to feed ever-growing populations of domestic animals and humans. This will require ever-larger quantities of chemical fertilizers. Electricity from power plants is required in the formulation of fertilizers. Land clearing and chemical fertilizer use could change the carbon budget for humans from carbon-neutral to carbon source. With increased land clearance, electricity use for fertilizer production, and carbon dioxide emissions during food and materials transport, humans could be considered as carbon sources rather than being carbon-neutral.

3.5.5 Wood Biofuels

There is considerable interest in moving away from oil and coal to biofuels such as crop residues and wood. Wood has been used since the beginning of humanity as a fuel. Thinning forests, using logging wastes, or using plantations of trees to produce biofuels has been proposed to be carbon-neutral as forest trees will grow back and replace any that have been removed. If forest trees are used, however, the time for replacement with new comparable large trees will be very long. Hudiburg *et al.* (2011) investigated the possible effects of tree removals for biofuels from 80 forest types in Oregon, Washington, and California and found that projected tree removal and use as biofuel would release as much as 14% more carbon dioxide than that released by current forest management practices.

Wibe (2012) examined wood fuels obtained from wood residues from logging in Sweden. He concluded that burning logging residues released carbon dioxide and decreased nutrient levels in the forest to support forest regeneration. He proposed that time was a key element in determining carbon-neutrality for wood biofuels. It was possible in the very long term only. He concluded that burning wood from logging residues would result in emission of approximately 60% of the carbon dioxide emitted if oil had been burned to produce the same amount of energy.

3.5.6 Wood Pellets

Small milled wood pellets can be fashioned from waste wood from logging. These wood pellets were initially thought to be very useful clean or green fuel as an alternative to use of fossil fuels like coal, oil, and gas. Homeowners with wood stoves appreciated the portability, ease of use, and low cost of the pellets.

Wood pellet use expanded greatly, and the amount of waste wood available from logging was no longer sufficient for expanded production. Wood source expansion focused on using whole softwood and hardwood trees and waste wood from logging on a very large scale. Drouin (2015) has provided a review of the nature and implications of the expansion of the use of wood pellets. Enormous wood-pellet mills have developed in the Southeastern United States. Wood pellets became the new green energy fuel. In addition to using wood pellets for heating, they also have been used on a very wide scale for electricity generation, primarily in the UK and other parts of Europe. Millions of tonnes of wood pellets, from numerous enormous American pellet mills, are shipped each year to the UK and other parts of Europe, and the amounts are expected to keep growing. The European Union considers wood pellets as a renewable carbon-neutral fuel (Cornwall, 2017). To be carbon-neutral, the carbon dioxide released from burning wood pellets into the atmosphere must be recaptured by regenerated forests. Drouin (2015) poses the question: "Wood pellets: green energy or new sources of CO_2 emissions?" Wood pellets are an energy source, but it is not clear how "green" they are. Wood pellets are a new source of carbon dioxide. How much carbon dioxide is released from the wood is unknown and the relationship between its recapture by different types of regenerating forests is also unknown. Given the phenomenal growth of the wood pellet industry, these questions will probably not be answered.

3.5.7 *Forest Fragments and Edge Effects*

Deforestation and land-use change for plant and animal agriculture are increasing in the world's tropical areas. Some areas are clear cut, while others are selectively harvested, resulting in numerous forest fragments or islands. Using satellite data, Brinck *et al.* (2017) estimate that there are 50 million fragments in the tropics, and that the length of the edges of these fragments is 50 million kilometers. Trees in the edges of these forest fragments experience more decline and mortality. Together with the effects of land-use change, this results in significant release of carbon dioxide into the atmosphere.

3.6 DEFORESTATION AND LAND-USE CHANGE

Tree harvesting so that land can be used for agriculture and other purposes removes not only tree-stored carbon, but also the utility of the harvested trees to take up carbon dioxide via photosynthesis, and results in increased soil carbon release. The long-term loss of forest carbon sinks due to deforestation is estimated to account for 10–15% of the increase in carbon dioxide in the atmosphere (Mahowald *et al.*, 2016). Baccini *et al.* (2017) acknowledge that tropical forests can be either sinks or moderate sources of carbon. Land-use and land-cover changes release carbon, while intact forests are concluded to be effective carbon sinks with carbon release and sequestration approximately equal in magnitude. General agreement is lacking about whether tropical forests are net sinks or sources of carbon dioxide. To address this, Baccini *et al.* (2017) analyzed MODIS (Moderate Resolution Imaging Spectroradiometer) pantropical satellite data from 2003 to 2014 across tropical forests in America, Africa, and Asia. Their purpose was to obtain direct measurement of net annual changes in above-ground density of live trees in tropical forests. They reported that the world's tropical forests are a net carbon source of 425.2 ±92.0 teragrams of carbon per year (Tg C yr^{-1}). Carbon gains from forest growth were 436.5 ± 31.0 Tg C yr^{-1}. Carbon losses from deforestation, land-use change, degradation and disturbances in forests were 861.7 ± 80.2 Tg C yr^{-1}. Land-use changes and deforestation are weakening the carbon sink strength of tropical forests, changing them overall from net sinks to net sources. They concluded that tropical forest carbon gains were lower than carbon losses on all three continents.

3.6.1 Global Carbon Budget 2016

Le Quéré *et al.* (2016) have published a Global Carbon Budget for 2016. Seeking input from 68 contributors, their purpose was to determine input of carbon dioxide to the atmosphere by emissions caused by humans and land-use changes, to determine the rate of growth of carbon dioxide in the atmosphere and how this might affect land and ocean sinks. Over time, a better understanding of trends in the carbon cycle is necessary to determine sink strength response to continuing increases of carbon dioxide in the atmosphere.

3.7 THE PHOTOCHEMICAL OXIDANT CYCLE

3.7.1 *Ozone*

There is considerable confusion in popular media about the nature, formation, and effects of ozone. Ozone is a colorless unstable normal constituent gas (relative molecular mass 47.9) formed secondarily in photochemical cycles involving sunlight or sunlight plus nitrogen oxides and small volatile organic compounds (VOCs) in the troposphere (8–12 km above the surface of the Earth) and the stratosphere (the zone above the troposphere). Because ozone episodes in the troposphere are often accompanied by visible haze and humidity, they are often termed "smog" events. The term smog, however, was coined in England and elsewhere to mean a highly visible toxic combination of smoke from coal fires with fog (Krupa and Manning, 1988). The term is not relevant for ozone episodes and is misleading. Also confusing is the role of stratospheric ozone holes in tropospheric air pollution. The size of ozone holes controls the amount of ultraviolet radiation in the polar regions.

3.7.2 *Ozone Formation*

3.7.2.1 *Stratospheric Ozone*

Ozone in the stratosphere is basically inert. It absorbs ultraviolet radiation and prevents much of it from entering the troposphere, making life on Earth possible (NASA). It does become a factor in the size of polar ozone holes and with occasional stratospheric dip downs. The formation cycle for stratospheric ozone formation is shown in Box 3.3.

BOX 3.3 **Stratospheric Ozone Formation**

Incoming ultraviolet radiation in sunlight begins the cycle:

$$O_2 + \text{sunlight} \rightarrow O + O$$

$$O_2 + O \rightarrow O_3$$

Oxone is unstable and breaks down and reforms quickly. This results in a continuous protective layer for ultraviolet radiation, preventing much of it from entering the troposphere.

3.7.2.2 Tropospheric Ozone

Ozone formation is different in the troposphere. The process begins with sunlight and warm air temperatures. Sunlight reacts with nitrogen dioxide (NO_2) rather than oxygen to release an oxygen atom used in O_3 formation.

Ozone in the troposphere is formed in the photochemical oxidant cycle. The chemistry is complex and involves several precursor molecules and reactions. Ozone can be formed and then broken down in a catalytic cycle that does not allow for accumulation in the atmosphere beyond normal background. To be an effective radiative forcer, ozone must accumulate beyond normal background levels. Small hydrocarbons from combustion and trees (principally isoprene) interrupt the catalytic cycle and allow ozone to accumulate as a radiative forcer and an air pollutant. A simplified version (Cleveland and Graedel, 1979; Brimblecombe, 1986; Krupa and Manning, 1988; Jacobson, 2002) of background ozone formation in a catalytic cycle and a non-catalytic cycle is shown in Boxes 3.4 and 3.5, respectively.

3.7.2.3 Background Ozone

Since the Industrial Revolution, the concentration of ozone that occurs in the troposphere during warm weather has increased from an estimated 10 ppb by volume to measured average concentrations ranging

BOX 3.4 Tropospheric Ozone Formation

Catalytic Cycle

Incoming ultraviolet radiation in sunlight warms air and starts the cycle that begins with photolysis of nitrogen dioxide NO_2:

$$NO_2 + UV \rightarrow NO + O$$

$$O_2 + O \rightarrow O_3$$

$$NO + O_3 \rightarrow NO_2 + O_2$$

Ozone does not accumulate beyond background levels of nitrogen dioxide. This is normal background ozone.

BOX 3.5 Ozone Accumulation Cycle

Non-catalytic Cycle

Ozone forms in the same way as in the catalytic cycle,
except here ozone increases beyond background and may be an
air pollutant.

Combustion increases NO_2 and peroxyradicals (RO_2) form from small hydrocarbons. Isoprene is emitted from tree leaves. Both can react with some NO, allowing some O_3 to avoid back-reacting with NO and breaking down. The ozone can then accumulate beyond background O_3.

$$NO_2 + RO_2 \rightarrow NO_2 + RO$$

from 20 to 40 ppb, sometimes as high as 50 ppb depending on location. These average concentrations are determined from data obtained from remote locations to avoid interference by anthropogenic influence as much as possible. There is some indication, however, that some of these concentrations are influenced by ozone and its precursors in long-range wind transport from Asia, principally China (Fiore *et al.*, 2002; Wittig *et al.*, 2008). Ozone concentrations in the range 20–40 ppb are normal background levels and there is general agreement that ozone is not an air pollutant at these concentrations.

3.7.2.4 Ozone as an Air Pollutant

Rapid urbanization and industrial development in the world after World War II resulted in large increases of nitrogen oxides and volatile organic compounds in the troposphere, primarily from fossil fuel combustion from home heating/cooling, industries, and vehicles. Ozone levels began to increase beyond background concentrations. Ozone episodes, with peak concentrations as high as 180–300 ppb, were recorded for recurring periods, ranging from a few days to a few weeks, depending on local climate conditions. These exposures caused breathing and lung injury in humans and visible (acute) injury in plant leaves, with growth and yield reductions. Ozone was considered to be an air pollutant when it caused injury to humans and plants at concentrations above background levels.

Governments in developed countries slowly realized that ozone levels were too high and were affecting human health and plant growth and productivity. Air quality standards were developed, and air quality monitoring networks were established to determine if air quality standards for ozone were being accomplished and if not, how they should be revised. In order to set the standards, quantitative data on human and plant responses in response to ozone exposure were needed. The US EPA has conducted inhalation studies with humans to determine ozone effects on breathing. Most of the data for human response to ozone exposure come from huge multi-year epidemiological studies, mostly in cities. Plants are considered to be more sensitive than humans to lower ozone exposures. Hundreds of papers on ozone effects on plants, mostly under experimental conditions, have been published (Ashmore, 2005). There is a more extensive empirical database for ozone injury to plants than there is for humans.

Reducing pollution levels of ozone will affect the incidence of adverse effects on humans and plants. Reducing ozone pollution effects on plants will also reduce the positive forcing effect of ozone on global warming and climate change. To this end, governments have established air quality standards. In the United States, standards are reviewed every five years. The Clean Air Scientific Advisory Committee (CASAC) of the US Environmental Protection Agency (EPA), consisting of medical researchers and ecological and plant scientists, evaluates new data since the last evaluation to advise the EPA Administrator about whether the standards are effective in protecting humans and plants or need revision. Based on their findings and advice, EPA promulgated new revised levels of both the primary ozone standard (human health effects) and the secondary standard (ecosystem and plant effects) in 2015. They set both standards at 0.070 parts per million (70 ppb). Violations of the standard will be determined the fourth-highest daily maximum, averaged across three consecutive years and averaging times of 8 hours (US Environmental Protection Agency, 2015). Establishing a new protective air quality standard for ozone would seem to be a straightforward and appropriate activity. Like most air quality standards, the new standard was based on consensus and compromise. Reaction to the new standard, however, was highly controversial. Legal challenges from manufacturers, the trucking industry, power plant operators, and others ensued. These were designed to delay, change, or reject the standard. Some politicians and economists saw adverse effects on jobs and the economy. Some environmentalists wanted a lower standard. The 2015 ozone standard is in place until 2020, when it will be reviewed again. It would seem, then, that scientific evidence can be used as the basis to determine when ozone is an air pollutant, but this is compromised and may be changed when science meets politics and economics.

3.8 AN OZONE EXPOSURE INDEX FOR EUROPEAN FORESTS

The European Union has adopted an accumulated exposure index that considers ozone exposure above a threshold concentration of 40 ppb ozone (AOT40 exposure index). The basis for the index is that forest trees will be exposed to ozone only during daylight hours during a growing season from April to September, with the assumption that stomata will be open for ozone uptake then. At the end of the growing season, the product of all measured concentrations time above the threshold of 40 ppb are summed and expressed as ppb or ppm cumulative hours. This index has been widely adopted by other countries. In areas where ozone levels are low and are near or just above ambient background levels (as high or higher than 40 ppb), this index is not useful (United Kingdom Forestry Commission).

3.9 OZONE AS AN INDIRECT RADIATIVE FORCER

In addition to being a direct radiative forcer, it is becoming increasingly evident that ozone may be more important as an indirect radiative forcer through negative effects on photosynthesis and plant growth that reduce carbon dioxide removal from the atmosphere (Ashmore, 2005). As mentioned in Chapter 2, ozone effects on plants could result in more global warming through reduction in uptake of carbon dioxide than through direct radiative forcing caused by ozone alone (Collins *et al.*, 2010; Unger, 2012). Increasing ozone is affecting photosynthesis and carbon assimilation in boreal and temperate forests, and this is reducing release of water vapor to the atmosphere, which could increase warming (Wittig, *et al.*, 2008; Lombardozzi *et al.*, 2015). With current and predicted rising ozone levels, this is of particular concern (Sitch *et al.*, 2007). Jacob and Winner (2009) predict that surface ozone in polluted areas will increase by 1–10 ppb in the near future owing to the effects of climate change, with the largest increases occurring in urban areas.

3.10 SUMMARY

Consideration of all aspects of carbon movement in the environment allows determination of sources, sinks, and consequences when sink capacities are exceeded by anthropogenic carbon dioxide. Sources not traditionally considered include rivers, lakes, cities, food production, and urban forests. Soils contain the largest reservoirs, and release of carbon dioxide by microbial action increases atmospheric carbon dioxide significantly. Carbon dioxide is removed from the air, used in photosynthesis, and some is sequestered in wood by trees. Temperature affects the balance between carbon gain in photosynthesis and loss in respiration.

Fossil fuel combustion has been the major influence on air quality since 1920. Fuel types vary considerably in energy output in relation to emission of carbon dioxide and other air pollutants. Natural gas (methane) is often considered to be the "clean fuel", as the products of methane combustion are CO_2 and H_2O in a 1:2 ratio. Both are reradiative greenhouse gases. There has been an enormous growth of the use of milled wood pellets for heating in the United States and for electricity generation in Europe. This has resulted in extensive deforestation and a large increase in emissions of carbon dioxide. Wood pellets are considered by some to be a carbon-neutral fuel, but this is controversial, and the controversy needs resolution soon, as does the amount of carbon dioxide emitted by burning wood pellets.

Carbon dioxide, oxides of nitrogen, small hydrocarbons (VOCs), and other gases and particulates are emitted by combustion of fossil fuels. Nitrogen dioxide (NO_2) in the presence of sunlight begins the photochemical oxidant cycle that produces ozone (O_3). VOCs can prevent enough of the breakdown of ozone to nitrogen dioxide and oxygen that ozone can then accumulate to pollutant levels. Ozone at pollutant levels can enter plant leaves via stomata with carbon dioxide during gas exchange. Ozone can then damage internal plant tissues and may also reduce plant growth and carbon storage. Ozone levels are predicted to increase in the future.

Chapter 4 will consider the role of biogeochemical factors such as photosynthesis and biogenic hydrocarbons on the function of forests. The role of biogeophysical factors, such as albedo, evapotranspiration and hydrology, and of ozone will also be considered. The interactive roles of biogeochemical and biogeophysical factors determine the function of trees and forests and how they affect cooling and warming the atmosphere.

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4 Biogeochemical and Biogeophysical Factors that Affect Trees

> Physiological processes of terrestrial plants regulate the land–atmosphere exchange of carbon, water and energy.
>
> Lamba *et al.*, 2017

> The Earth's carbon and hydrologic cycles are intimately coupled by gas exchange through plant stomata.
>
> Frank *et al.*, 2015

> The balance between evapotranspiration and albedo determines how vegetation changes affect local climate.
>
> Swann *et al.*, 2010; Shen *et al.*, 2015

4.1 INTRODUCTION

To assess the effects of trees and forests on the temperature of the atmosphere, it is essential to review how they function in relation to biogeochemical factors, such as photosynthesis and release of biogenic hydrocarbons (BVOCs), and biophysical factors, such as albedo, deforestation, and land-use change, evapotranspiration, and ozone. Although biogeochemical and biophysical factors can be considered separately, their interactive roles determine whether trees and forests cool or warm the atmosphere.

4.2 BIOGEOCHEMICAL FACTORS

4.2.1 Leaf Photosynthesis

Photosynthesis is the process that primarily occurs in plant leaves where interactions between infused carbon dioxide, light-activated chloroplasts, and water result in formation of carbon compounds,

BOX 4.1 Inward Stomatal Diffusion by Carbon Dioxide in Sunlight

Regulated by flux between internal and external concentrations

$$CO_2 \text{ flux} = \frac{C_{air} - C_m}{r_{air} - r_{leaf}}$$

$C_{air} - C_m$ = difference between outside CO_2 and CO_2 in substomatal cavity and chloroplast mesophyll cells

$r_{air} + r_{leaf}$ = diffusion resistance to CO_2 diffusion in outside air, plus two leaf resistance components:

r_s = resistance in substomatal cavity

r_m = mesophyll resistance during diffusion to chloroplasts

(Kramer and Kozlowski, 1979)

with release of oxygen (Pallardy, 2008). It is a biochemical process that has been known and studied for more than two centuries (Cieslik *et al.*, 2009). Details of the process can be found in hundreds of journal papers and books.

Photosynthesis is often represented by the following generalized, very simple equation:

$$CO_2 + 2\,H_2O \text{ light/chlorophyll} \rightarrow (CH_2O) + O_2 + H_2O$$

where CH_2O represents carbohydrates (Kramer and Kozlowski, 1979).

Carbon dioxide enters through stomata, primarily on leaf surfaces, in the presence of sunlight. Inward diffusion of carbon dioxide is regulated by flux between internal and external concentrations, illustrated in Box 4.1.

Mesophyll resistance slows the rate of diffusion and lowers the concentration of carbon dioxide ultimately available to chloroplasts for photosynthesis. Sun *et al.* (2014) determined that global carbon cycle models include only stomatal diffusion of carbon dioxide and not mesophyll diffusion. They developed a global mesophyll conductance (GMC) model which concluded that, by ignoring mesophyll diffusion, current global carbon cycle models overestimate the amount of carbon dioxide available for use in chloroplasts. This also appears to result in an underestimation of the effects of carbon dioxide on terrestrial biomass productivity (the CO_2 fertilization effect). Inclusion of mesophyll diffusion in the GMC model increased the modeled carbon dioxide fertilization effect for GPP. Resistance due to mesophyll diffusion is a barrier to carbon dioxide movement in leaves to chloroplasts. This implies that terrestrial vegetation is inherently carbon limited and therefore will absorb more carbon dioxide as carbon dioxide concentrations in air continue to increase, and this will result in increased rates of photosynthesis and gross primary productivity.

4.2.2 Woody Tissue Photosynthesis

Photosynthesis also occurs in many plant tissues that are not leaves: it can occur in stems, bark, flowers, fruits, and almost all vegetative and reproductive structures that contain chloroplasts. This can be viewed as additional opportunities for fixed carbon for plants (Aschan and Pfanz, 2003; Saveyn *et al.*, 2010). Woody tissue photosynthesis is common in trees (Teskey *et al.*, 2008). Saveyn *et al.* (2010) have suggested that photosynthesis in stems of woody plants and trees be termed "woody tissue photosynthesis." While woody tissue photosynthesis has long been known, it has been concluded that, in general, the amount of carbon fixed in tree stems did not contribute to significant carbon gain. With increasing awareness of the role of carbon fixation and storage by trees, and effects of accompanying diffusion and respiration of carbon dioxide on global warming and climate change, interest has increased in woody tissue photosynthesis.

Avila-Lovera (2014) have extensively examined and characterized stem photosynthesis in trees. Their cclusion is that it occurs mostly in the cortex of the stem. They divided stem photosynthesis into the following categories:

1. Stem net photosynthesis (SNP) in chlorenchyma below an epidermal layer containing stomates, allowing uptake of carbon dioxide from air.

2. Stem recycling photosynthesis (SRP) in chlorenchyma below a stomate-free well-developed periderm, using internally respired carbon dioxide from mitochondrial respiration. The obvious presence of chlorophyll-containing chlorenchyma below the protective periderm enables photosynthetic activity. This type of stem photosynthesis is also called bark photosynthesis (Aschan *et al.*, 2001).

Both SNP and SRP help to maintain physiological activity during stress periods, particularly in coping with drought. Trees in dry tropical areas that lose their leaves for most of the year use SRP with little water loss to provide carbon sources for refoliation before and during annual rainfall (Ávila-Lovera and Ezcurra, 2016). The palo verde tree (*Parkinsonia florida*) is a desert tree that has green bark tissues in branches and trunks ("green pole tree") most of the year. Stem photosynthesis enables annual refoliation when rains begin. The palo verde trees refoliate, flower, produce seed pods and defoliate, and the cycle continues. Aschan *et al.* (2001) found that the chlorophyll content of one-year-old twigs (stems) on trembling aspen trees (*Populus tremuloides*) approached that found in leaves. The chlorophyll content of aspen bark collenchyma in stems was found to be age-dependent. Aschan *et al.* concluded that refixation of internal carbon dioxide in chloroplasts in aspen bark collenchyma may contribute to the carbon budget of deciduous aspens when they are dormant and leafless. Bark photosynthesis is affected by high temperatures in summer and low temperatures in winter.

Saveyn *et al.* (2010) addressed the question of whether trunk bark photosynthesis could significantly affect plant growth and carbon balance. They investigated the influence of woody stem photosynthesis on chlorophyll concentration, radial stem growth, bud biomass, and composition of sugars in plant organs for three native evergreen tree species. Treatments consisted of light exclusion by covering 100% or 50% of the trunk, and a non-treated control. After initial radial measurements, all trees were defoliated, and later effects on bud formation and tissue sugars were determined. Complete exclusion of light reduced chlorophyll concentration, radial trunk growth, and bud mass. Complete light exclusion on defoliated trees resulted in increased ^{13}C in trunk and bud sugars. The contribution of woody stem photosynthesis to carbon accumulation and tree growth was clearly demonstrated in the results from this experiment.

Global warming and climate change appear to be increasing the incidence of drought stress in forests, which causes tree decline and often death. Vandegehuchte *et al.* (2015) have proposed that photosynthesis in woody bark tissue might result in enough carbohydrates to make up for loss from other sources due to disruption by drought. They conclude that this may be more likely for younger trees that may have greener shoot tissues and smaller bark layers.

4.3 BIOMASS GAIN FROM PHOTOSYNTHESIS

Carbon, primarily from leaf photosynthesis, is used to promote growth and development of tree buds, leaves, flowers, cones, seeds, shoots, branches, main stems (trunks), roots and associated mycorrhizae, which collectively can be considered as total biomass. Tree growth and biomass is often affected by multiple environmental stresses and disruptive events that can limit tree growth. These include light, carbon, water, and nitrogen. On a worldwide basis, water limitation is often the most limiting factor (Dickson, 1989). Tree growth seems to depend on maintaining a positive carbon balance while responding to one or more environmental stresses (Dickson, 1989). The rate of tree growth and biomass accumulation also varies with growth stages for trees. Dickson (1989) identified seedling, sapling, pole stage, mature flowering and fruiting, and senescence as growth stages for trees. Biomass gain is different at every growth stage and for every tree species. This is overlooked in most models that explain tree (summed as a generic term) response to environmental influences and climate change.

4.3.1 The Nature and Function of Trees and Photosynthesis

Wilson (1984) defines a tree as a simple system: "A tall single-stemmed woody plant with a branched crown and many leaves." He divides a tree into three basic components: leaves, shoot system, and root system. Leaves capture carbon in photosynthesis. Carbohydrates are used in construction of the mass of tree components. Stems and branches support leaves. In stems, phloem transports photosynthate within the tree, especially to the roots. Xylem moves water and nutrients, especially nitrogen, and auxins upward to leaves and meristems. Roots anchor the tree.

Wilson's purpose in writing his book was to "show how the great size and complexity of a tree is generated by relatively few processes, repeated over and over each year as the tree grows." How well these components function together will affect tree growth and biomass accumulation and carbon allocation within trees.

Patterns of bud expansion and shoot growth vary with seasons and tree species, and this influences growth and biomass production. Leaf development and expansion begins with bud expansion. Kramer and Kozlowski (1979) identified three general patterns of seasonal bud expansion and resulting shoot growth:

1. In determinate shoot growth, only one terminal bud expands on a shoot each year. Maximum leaf area occurs early in season. On some deciduous trees, two or more may form sequentially and expand in the same year. Examples include some species of pine, spruce, oak, and hickory.
2. In indeterminate shoot growth, the shoot tip bud may abort, allowing axillary buds to expand. New leaves may be added continuously. This is common in deciduous trees.
3. In intermittent growth, new shoots grow periodically in flushes. This is common in warm-climate pine species and in many tropical forest trees.

Dickson (1989) compared seasonal leaf production and function in deciduous and evergreen trees. Different strategies are used to gain, use, and store carbon obtained from photosynthesis.

In deciduous trees, growth is usually rapid, and large numbers of carbon-efficient leaves are produced annually. Defoliation at the end of the growing season is followed by rapid renewal of large numbers of leaves from bud expansion the following spring. This renewed spring growth requires large amounts of stored carbohydrates. After leaf expansion, much of the new fixed carbon is used for stem and root growth and storage.

Most conifers have narrow needle-like persistent leaves. Annual growth may be slower than for deciduous trees. The amount of new leaf produced in spring is small in relation to the existing persistent several-year leaf biomass. Depending on species and tree age, conifers may retain physiologically active leaves on stems for periods ranging from 2 to 7 years. Photosynthesis and carbon fixation are active in older leaves, declining with needle age. All ages of conifer leaves can be photosynthetically active in warm sunny early spring weather before budbreak and new leaf emergence. Some of this carbohydrate is stored in leaves, stems, and roots. When new leaf growth begins to emerge, some of this newly fixed carbohydrate is translocated to the new leaf growth. If carbon fixation in new leaves and all classes of older leaves is combined, total tree annual carbon gain for a conifer may be similar to that of a rapidly growing deciduous tree (Matyssek, 1986).

In addition to providing support for leaves on shoots and pathways for transport of water, minerals, carbohydrates, and auxins, the main stem and branches of trees are where radial growth and carbon sequestration occur, primarily in physiologically inactive wood. Radial growth occurs primarily from meristem growth in the vascular cambium located between bands of xylem on the inside and phloem outside in stems and branches. In temperate zone trees, cambium activity is suspended during winter. In spring, the cambium generates annual increments of new xylem on the inside and new phloem on the outside of the cambial layer. The new increments are formed between old layers of xylem and phloem, and this results in increases of stem and branch diameters (Kramer and Kozlowski, 1979).

Roots anchor trees and provide storage for carbohydrates and water and essential elements for shoot growth. Unlike leaves and shoots, it is difficult to visualize and determine the extent of tree root systems. There are a few examples where entire or partial tree root systems have been excavated and characterized, which provides some basis for generalizations about tree root systems (Kramer and Kozlowski, 1979; Pallardy, 2008). Life begins for a tree when a seed germinates under favorable conditions. The emerging root functions as a non-persistent tap root which later branches to begin the root stem. Wilson (1984) states that it is a myth that trees have persistent tap roots. Large perennial roots and smaller lateral roots anchor a tree. A very extensive network of fine roots extends well beyond the dripline of the tree crown. These are sometimes called "feeder roots" as they take up most of the water and nutrients for the tree. They are found typically in the upper 15 cm (6 inches) of soil (Wilson, 1984). Fine roots make up most of the root length, but only a small portion of total root weight. Rapid turnover of fine roots occurs, owing to surface disturbance, changes in soil temperature, and other environmental factors. Considering the extent of tree fine root systems, the death of fine roots may contribute to the soil carbon sink (Pallardy, 2008).

Fine roots also have symbiotic associations with nonpathogenic fungi that are called mycorrhizae. Root cells are invaded, and associations are established between the fungus and the root cell for mutual benefit. Two types of mycorrhizal associations that relate to trees are:

1. Endomycorrhizae (endotrophic). The fungus is entirely within the colonized cells. There is no change in the shape of the root cells or the external appearance of the root. Mycorrhizae of this type are found only in a few tree species such as *Acer*, *Liriodendron*, and *Liquidambar*.
2. Ectomycorrhizae (ectotrophic). The fungus is both inside root cells and outside the root, causing root cells to divide repeatedly to form external large multi-branched structures that increase uptake of water and minerals. This association is common in forest tree roots, and there are characteristic fungi associated with tree species. Part of the fungus life cycle is visible above ground in late summer or autumn as large fleshy growths called mushrooms. Some are edible and are avidly sought by people as food.

Trees provide carbohydrates and other nutrients to mycorrhizae. In turn, mycorrhizae increase uptake of nutrients and water and may protect roots from invasion by soilborne root pathogenic fungi (Pallardy, 2008).

4.3.2 Carbon Allocation and Biomass Estimation

Capture of carbon dioxide from the atmosphere, patterns of allocation of carbon from photosynthesis within trees, and its retention in tree tissues, primarily wood, are key components of how trees influence atmospheric temperatures. Carbon allocation in trees influences how much is invested in biomass, consisting of leaves, stems, and roots. The allocation varies between deciduous and evergreen trees and between tree species. General background about carbon allocation is presented here, together with invasive destructive and non-invasive methods for determining carbon allocation and biomass estimation.

4.3.2.1 Carbon Allocation

Several authors have posed the question, "Where does all the carbon go?" To understand this, it is essential to know and predict where and how assimilate from photosynthesis is allocated within trees (De Kauwe *et al.*, 2014). There is general consensus that most of the fixed global terrestrial carbon is found in trees and forests (Bonan, 2008). Klein and Hoch (2015) estimate that as much as 90% of fixed terrestrial global carbon resides in forest trees. Forest trees are estimated to contain approximately 650 billion tonnes of wood, which is the most important location within a tree for long-term storage of carbon obtained from the atmosphere via photosynthesis. The amount of carbon dioxide in the atmosphere (carbon source) is at present greatly elevated and exceeds the amount that trees can assimilate through photosynthesis. The response of trees to elevated carbon dioxide is determined not by atmospheric carbon dioxide (source) but by the extent of photosynthesis and resulting cambial growth (sink) possible to produce wood and other woody tissues. Cambial sink strength limits (controls) the mitigation potential of trees and forests by wood sequestration for global warming and resulting climate change (Sass-Klassen, 2015).

Kozlowski (1992) has provided an extensive review of carbon allocation in trees and woody plants. Carbon is assimilated during photosynthesis in chloroplasts in leaves. Some may be converted to starch and used for chloroplast growth and metabolism. The rest is converted primarily to sucrose and other carbohydrates, such as sorbitol, mannitol and some oligosaccharides, and transported by mass flow in phloem to other locations throughout the tree, depending on relative sink strengths (Holtta *et al.*, 2014; Ryan and Asao, 2014). Holtta *et al.* (2014) point out that while water transport from soil to leaves in xylem in trees is fairly well understood, system transport of carbohydrates in phloem in trees is less understood and more complicated, a view also shared by Lemoine *et al.* (2013) and Bruggemann *et al.* (2011).

Carbohydrates from photosynthesis are translocated to leaves, branches, stems, and roots of trees for growth, metabolism, storage, and respiration. Transfer in roots includes exudation to soil and mycorrhizal associations. Some is transformed into nonstructural carbohydrates, principally starch, but also lipids and fructans that are stored for use during periods of stress or lack of sufficient available carbohydrates from photosynthesis (Ericsson *et al.*, 1996; Sala *et al.*, 2012; Klein and Hoch, 2015).

Ericsson *et al.* (1996) proposed a general scheme for carbohydrate allocation, based on deciduous tree growth and maturity in a forest:

> In early stages of tree growth in a forest, much of the assimilate is used for leaf production and blade expansion. As tree growth continues, more assimilate is used for development of branches, stems, and roots.
>
> Assimilate production and rate of biomass increments increases and peaks at the time of canopy closure. Net carbon gain may begin to decline with tree age.
>
> After canopy closure, respiration continues to increase as the branches, stems, and large perennial roots continue to increase in size and accumulate carbon. Net carbon gain begins to decrease. Carbon dioxide fixation may not keep up with carbon costs for maintenance and respiration. The amount of carbon for branch, stem, and root growth may begin to decrease.

Klein and Hoch (2015) have proposed a sequential pathway scheme to describe tree allocation in response to atmospheric carbon dioxide. Their carbon budget scheme can be summarized as:

$$A = R + G + E + L + S = C$$

where A = assimilation, R = respiration, G = sequestration through growth, E = root exudation, L = carbon litter released, S = storage of non-structural carbohydrates, and C = complete carbon budget.

4.3.2.2 Measuring Carbon Allocation

Because of the size and complexity of underground root systems, it is difficult, if not impossible, to measure carbon allocation accurately. This causes problems as one way to accurately determine carbon allocation for a tree is to measure the size, extent, and weight of tree leaves, branches, stems, and roots. This has resulted in a number of methods to measure and estimate tree carbon allocation. Destructive harvest of smaller trees has been used to identify sinks and establish carbon budgets. Detailed systemic complete analyses of carbon allocation in trees are not numerous and rely on estimates as well as actual measurements, especially for roots (Hogberg *et al.*, 2002). Tracing labelled carbon molecules through trees has more appeal and is used to determine the path of the carbon.

4.3.3 Destructive Harvest Mass Balance

Agren *et al.* (1980) established the first complete annual carbon budget for a tree (a 14-year-old Scots pine, *Pinus sylvestris* L.), in a forest in Sweden, using actual measurements and estimates based on them. Their annual budget is in Box 4.2.

The accuracy of their estimates was variable. They concluded that they had used accurate estimations for stem respiration (10%), stem growth (9%), current needle growth (17%), and net photosynthesis (100%). While most of the tree carbon was found in fine roots, their estimates of fine root growth were less certain as their measurements were uncertain. With the exception of branch weights, the authors concluded that their carbon budget was balanced. Their

BOX 4.2 **First Complete Annual Carbon Budget for a Tree**

Actual measurements, and estimates based on them, for a 14-year-old Scots pine (*Pinus sylvestris* L.) in Sweden. Estimated annual photosynthetic production: 1,696 g carbon.

Respiration	173 g carbon	10%
Stem growth	145 g carbon	9%
Branch growth	132 g carbon	8%
Current needle growth	286 g carbon	17%
Fine root growth	960 g carbon	57%

Most carbon was estimated to be in the fine roots.

Source: Agren *et al.*, 1980

results illustrate that the difficulty of establishing a carbon budget for a tree lies in the methods of determining the extent and weight of roots of various sizes.

Helmisaari *et al.* (2002) identified beginning biomass and annual biomass production for a forest stand of sapling (15 years old), pole stage (35 years old), and mature (100 years old) Scots pine (*Pinus sylvestris* L.) trees in Finland. Fine root mass was determined by soil core sampling. Biomass and annual production values were obtained for needles, cones, stem wood, and coarse roots, and calculated for the whole stand using biomass components from felled tree samples. Their results are in Box 4.3. Annual fine root production predominated in biomass production. This suggests that fine roots are large sinks for carbohydrates. Respiration, death, and decomposition of fine roots could release considerable carbon into the soil.

Konôpka *et al.* (2010) evaluated young trees (first age class, 0–10 years old) of Scots pine (*Pinus sylvestris*), Norway spruce (*Picea abies*), European beech (*Fagus sylvatica*), and sessile oak (*Quercus petrae*) growing in regeneration areas of forests in Slovakia. For each species, basal diameter and height for up to a total of 175 trees was calculated.

BOX 4.3 **Initial and Annual Biomass by Tree Age for Scots Pines (*Pinus sylvestris*)**

Saplings (15 years), pole stage (35 years), and mature (100 years)

	Sapling	Pole	Mature
Beginning biomass			
Needles	9%	9%	4%
Stems, branches, cones	66%	69%	83%
Coarse roots	10%	15%	2%
Fine roots	15%	7%	2%
Annual biomass production			
Needles	15%	12%	14%
Stems, branches, cones	39%	26%	18%
Coarse roots	3%	3%	8%
Fine roots	43%	59%	60%

Source: Helmisaari *et al.*, 2002

Some were then excavated and the biomass of foliage, branches, stems, leaves, and roots was determined. Allometric equations were used to determine biomass allocation patterns, termed biomass allocation coefficients (BAC). They also calculated stem biomass increment per unit of foliage area or foliage biomass, termed growth efficiency (GE). They found that there were large differences in BAC and GE between the evergreen and deciduous trees; and also differences between beech and oak, and between Scots pine and Norway spruce. Their conclusion was that forest growth models should include all tree species and age classes, not just older more mature trees, to more accurately predict forest biomass and stored carbon.

4.3.4 Non-invasive Isotopic Analysis

The destructive harvest or mass balance approach to determining carbon allocation within trees relies on implications from physical measurements. Non-destructive tracing of assimilate using labelled carbon allows more precise determination of carbon allocation from photosynthesis in living plants. Isotopic forms of carbon, principally ^{13}C (carbon 13) or radioactive ^{14}C or ^{11}C can be applied as short or continuous pulses to trace assimilate from source to pathway in the plant to exudation to soil microbes to respiration (Bruggemann *et al.*, 2011; Dietz *et al.* 2014). Allocation to sinks for assimilate can be estimated by the amount and persistence of labelled assimilate and loss through respiration, root exudation, and emissions of BVOCs (Epron *et al.*, 2012). Extensive reviews of isotopic analysis and the use of isotopes to determine carbon allocation can be found in Bruggemann *et al.* (2011) and Epron *et al.* (2012).

Hogberg *et al.* (2008) used pulse-labelled $^{13}CO_2$ to trace assimilate from the canopy of 4 m tall Scots pines (*Pinus sylvestris*) through the tree to roots, soil and soil microorganisms, and back to the atmosphere via soil respiratory efflux. They found labelled carbon in phloem after 24 hours, in soil respiratory efflux after 2–4 days, in ectomycorrhizal roots after 4–7 days, and in soil microbial cytoplasm after 2–4 days. From their results, they concluded that ectomycorrhizal roots were the strongest sinks for the labelled assimilate.

4.3.5 Leaf Area Index

The extent of tree leaf area, and how long the leaves persist, are important determinatives for GPP. Leaf area is affected by available soil moisture and nutrients. Leaf persistence is governed by temperature and soil moisture availability (Duursma *et al.*, 2009). Both leaf area and persistence vary with tree species, age, and location. This can complicate efforts to use leaf area in general predictive models.

Leaves have the most active living cells of any part of a tree. Leaves in a tree canopy are the place where carbon dioxide uptake, transpiration, light interception and reflection (albedo), photosynthesis, and assimilate formation occur. Leaves are the key energy source and atmospheric exchange site for the biogeochemical cycle in trees (Bartelink, 1997; Breda, 2003). Anything that affects tree leaves will have an effect on leaf function and atmospheric exchange, and thus on the contribution that trees make to cooling or warming the atmosphere (Breda, 2003).

Actual or estimated tree leaf canopy areas are used in predictive models of tree cover and change; gas exchange and function; and carbon accounting. Accuracy in measuring and estimating tree leaf canopy are essential to the validity and application of models. Determining canopy size and number of leaves for herbaceous plants and small trees can be accomplished by counting them and obtaining dry weights. This can be done on a limited scale when young trees are destructively harvested to determine carbon allocation. This provides data for the time of harvest, but does not allow for continuing assessment, unless a continuing cycle of destructive harvest is established. Indirect estimation methods are necessary for larger trees. One method of estimation for canopy leaf area for larger trees in forests is called leaf area index (LAI), defined as: the total one-sided area of leaf tissue per unit of ground surface area, the area of ground surface covered by leaves of the canopy (Breda, 2003; Zhao and Popescue, 2009). LAI is a useful metric, as it has been concluded that there can be good correlation between LAI and GPP and NPP (gross and net primary production) (Duursma *et al.*, 2009).

LAI can be measured in many direct and indirect ways. Results from direct methods seem to be more accurate than those from indirect methods (Breda, 2003). The index is easier to calculate for deciduous trees than for conifers. A labor-intensive and time-consuming traditional direct method for determining LAI for deciduous forest trees involves collecting leaves from traps placed beneath canopies at 2-week intervals during leaf fall. Collected leaves are dried and weighed to determine weight per square meter. Results from collection dates are converted to leaf area. LAI is expressed as accumulated leaf area during the total leaf-fall period (Breda, 2003). Indirect methods include monitoring daily and seasonal light transmission through canopies. LAI is determined by measuring the transmission. A number of commercial analyzers can also be used to measure radiation transmission (Breda, 2003). Zhao and Popescue (2009) used pulsed laser energy from airborne LiDAR (light detecting and ranging) to determine LAI for a pine forest area in East Texas. They compared their results with those for LAI from moderate-resolution satellite results and concluded that their results were superior for mapping LAI at local and regional scales.

4.3.6 Biomass

Estimation of above-ground forest biomass (leaves, branches, and stems) is essential to determine the extent and condition of available sinks for atmospheric carbon dioxide and how this data can be incorporated into existent and predicted global climate change models. Like LAI, there are many ways to do this. Destructive and invasive methods give the most accurate results, but are expensive, consume large amounts of time, and are not appropriate for large or large numbers of trees. Non-invasive methods are less accurate but are more efficient and less expensive.

Dittmann *et al.* (2017) have provided an extensive review of non-invasive methods for estimating tree biomass:

Allometric Equations Biomass estimation from measurements obtained from non-invasive methods, such as diameter at root collar, diameter at breast height (dbh; 1.3 m above ground), tree height, crown width, and height above stem, are used to formulate regression equations. This is appropriate for small areas and uses low grade technical methods.

Bartelink (1997) used measurements of 38 beech (*Fagus sylvatica*) trees, ranging from 8 to 59 years old, to establish allometric relationships for stem, crown characteristics, biomass, and leaf area. These relationships increased with tree age and increases in stem diameter. He concluded that above-ground biomass ranged from 6 to 167 tonnes per hectare, increasing with tree age. Nowak (1996) collected data on dbh, tree height, height to base of live crown, and crown width for urban trees. He used regression equations to predict leaf area and leaf biomass based on dbh and crown characteristics. Combining dbh with crown parameters provided better results with a stronger relationship than dbh alone.

Optical Imaging Passive remote sensing, using visible and infrared wavelengths, of large mostly homogeneous forest stands, can be obtained from airplanes or satellites. Muukkonen and Heiskanen (2005) used optical ASTER satellite data to estimate stands of boreal forests, together with National Forest Inventory of Finland data. They found that their estimates were close to the forest inventory data.

Radar and Laser Technology Airplane and satellite radar can be used on large scales. It is most effective over large areas with re-growing or spare stands.

Laser technology has proven much more effective and useful than radar. Popescue (2007) used airborne LiDAR to measure form and biomass of individual loblolly pine trees (*Pinus taeda*). LiDAR-measured parameters such as tree height and crown diameter were used in regression models. The above-ground biomass and component biomass were then determined. Kankare *et al.* (2013) used terrestrial laser scanning (TLS) to estimate tree biomass. Dense clouds from TLS measurements allowed features that describe biomass to be estimated from stem form and canopy measurements.

Computer Vision Dandois and Ellis (2010) applied computer vision algorithms to digital photographs and were able to demonstrate high-resolution three-dimensional measurements of the structure of vegetation.

4.3.7 Respiration

During photosynthesis, it is known that trees obtain carbon from carbon dioxide in the atmosphere via stomatal conductance and release oxygen. Carbohydrates, principally glucose and stored starch, accumulate for use within the tree. Energy is required to maintain the integrity of the tree and to promote growth. In all living cells throughout a tree, an autotrophic oxidation process in mitochondria called respiration provides the energy. Carbohydrates, often glucose, are substrates for the respiratory process. Unlike photosynthesis, oxygen is used in respiration, and carbon dioxide and water are released. Respiration occurs primarily at night. A brief example of a complicated and complex process, using glucose as a substrate, is given below:

$$C_6H_{12}O_6 + 6\,O_2 \rightarrow 6\,CO_2 + 6\,H_2O + \text{est. 686 calories/mole}$$

(Kramer and Kozlowski, 1979; Pallardy, 2008).

Saveyn *et al.* (2008) divide respiration in trees into two components:

Growth respiration: synthesis of material for new structures (assimilation);
Maintenance respiration: maintaining existing cellular contents and structure.

They conclude that maintenance respiration strongly depends on temperature, as it involves enzymatic processes. As for photosynthesis, the effects of ambient air temperatures on respiration are well known. Respiration is expected to increase as temperatures increase, while photosynthetic rate will decline when temperatures exceed an optimal temperature range. An exponential equation involving Q_{10} (relative increase in basal reference respiration rate at temperature T_1 to an increase of 10 °C in air temperature) can be used to calculate an increased respiration rate at the new temperature (T_2) (Turnbull *et al.*, 2001; Saveyn *et al.*, 2008).

Tree maintenance and growth depend on the availability of the fixed carbon products, primarily carbohydrates, from photosynthesis. Griffin and Prager (2017) conclude that the amount of carbon dioxide removed from the atmosphere each year by vegetation is almost balanced by the amount of carbon dioxide returned to the atmosphere through respiration by vegetation. Estimates of losses of fixed carbon from photosynthesis due to autotrophic respiration range from 40% to 60% for deciduous forests, to as much as 90% for tropical forests (Ryan *et al.*, 1997; Turnbull *et al.*, 2001; Saveyn *et al.*, 2008). In deciduous trees, approximately half of the carbon fixed on one day is estimated to be lost through respiration the next night. What is left can be used for maintenance and growth (Turnbull *et al.*, 2001). The difference between photosynthesis gain and respiration loss determines carbon balance of the forest (Hogberg *et al.*, 2002). Gains from photosynthesis are expressed in GPP. When losses from respiration are subtracted, NPP remains. NPP rates determine forest tree growth and carbon allocation (Ryan *et al.*, 1997; Turnbull *et al.*, 2001).

4.3.8 Respiration Loss by Trees

Leaves Leaves are the site of most photosynthesis and also where the respiration rate is the highest, as most of the tissues and cells in leaves are alive and functional. Leaf respiration changes with leaf age and location on the tree, with respiration rates higher in leaves in the tops of canopies (Pallardy, 2008). Turnbull *et al.* (2001) investigated leaf respiration rates for three species of deciduous trees in the field in relation to temperature and available soil moisture. Gas exchange measurements were used to determine rates of dark respiration for red maple (*Acer rubrum* L.), red oak (*Quercus rubra* L.) and chestnut oak (*Quercus prinus*) leaves at ambient and increasing temperatures. Respiration rates for all species were similar at ambient temperatures. Values for all species were lower at the wet site than the higher drier site. There were significant differences between species in respiration rates in response to warming. The smallest increases in respiration occurred in leaves of *A. rubrum*. The Q_{10} value for *A. rubrum* was 1.5 and 2.1 for *Q. prinus*. The variable rate of leaf respiration by different common deciduous forest tree species, in response to air warming and soil moisture, is a factor to consider when estimating or modeling future rates of respiration from tree leaves.

Stems It is assumed that carbon dioxide from cellular respiration in tree stems can readily diffuse outward into the atmosphere. Teskey *et al.* (2008) challenged this assumption and concluded that internal barriers may slow and reduce release of internally generated carbon dioxide. Some may be used for photosynthesis by internal cells, or dissolve in xylem and be transported to leaves. Based on their findings, they proposed that less carbon dioxide diffuses into the atmosphere than is commonly thought, and that carbon dioxide concentrations in tree stems may exceed 20%. They proposed rethinking carbon dioxide fluxes in tree stems and suggested that this would help to increase understanding of tree stem emissions of internally generated carbon dioxide.

Fan *et al.* (2017) investigated the effects of stem size on stem respiration and flux components in yellow poplar (*Liriodendron tulipifera* L.) trees with different basal diameters. For the smallest tree (20 cm diameter), they determined that 86% of the internally produced carbon dioxide diffused to the atmosphere, while only 46% diffused from the largest tree (60 cm diameter) More internal carbon dioxide remained in the xylem sap as the trees increased in diameter.

Ryan *et al.* (1995) conducted a large field experiment at four geographic sites, with a relevant conifer species at each site, to estimate baseline maintenance respiration for boles (stems) of each species. Measurement of carbon dioxide efflux for estimating maintenance respiration was done in autumn, when respiration from growth or construction was low or non-detectable. Ponderosa pine (*Pinus ponderosa*) represented a southwest region of the United States, slash pine (*Pinus elliotti*) represented the southeast region, red pine (*Pinus resinosa*) represented the northeast region and western hemlock (*Tsuga heterophylla*) represented the northwest region. They estimated that autumnal maintenance respiration of the conifer species used 5–13% of annual net carbon assimilation. This increased as temperatures increased at the sites.

Roots and Soil Respiration Measuring respiration from leaves and stems can be accomplished fairly accurately. Measuring respiration from roots is more difficult as they are not readily available for use. Root respiration may be confounded when soil microbial respiration is also a factor, and it is difficult to separate the two forms of respiration. Soil respiration, then, is meant to include both types of respiration.

Hogberg *et al.* (2002) and Chen *et al.* (2014) divide soil respiration into two parts. Root respiration includes respiration from coarse and fine roots, and their mycorrhizae, and carbon dioxide from root exudates directly driven by photosynthesis. Heterotrophic respiration is from microbial decomposition of above- and below-ground soil organic matter from leaves, roots, and plant debris indirectly driven by photosynthesis.

Hogberg *et al.* (2002) estimate that 75% of carbon allocation to roots is respired and only 25% is used for growth. Pallardy (2008) concludes that root respiration may be up to 50% of the carbon dioxide released from soils, with much of it coming from fine roots near the surface and their mycorrhizal associations. Bloemen *et al.* (2016), however, believe that much of the root-respired carbon dioxide remains in the root system and is transported to the shoot in xylem sap. This controversy remains to be resolved.

Soil respiration has been proposed as the second largest flux of carbon dioxide between the terrestrial ecosystem and the atmosphere. It has been estimated that soil respiration releases 78–98 billion tonnes (GT) of carbon to the atmosphere annually, a larger emission of carbon dioxide than from fossil fuel combustion (Chen *et al.*, 2014).

Respiration Acclimation Photosynthesis and accompanying respiration both respond to air temperature. Both increase with temperature and are thus expected to increase with global warming. Warmer temperatures, due to increasing atmospheric carbon dioxide, will increase uptake of carbon dioxide, resulting in increased photosynthesis and carbon sequestration. Respiration, however, also increases as temperatures increase. This means that as the rate of photosynthesis increases, the rate of respiration, and release of carbon dioxide, will also proportionally increase. With increasing temperatures, the approximate 50:50 ratio of photosynthesis to respiration may change in the direction of respiration (Aschan *et al.*, 2001). The concern is that increased temperatures may increase respiration and release of carbon dioxide, changing the carbon content of forests and increasing global warming (Turnbull *et al.*, 2001; Reich *et al.*, 2016; Griffin and Prager, 2017).

It was found, however, that rates of respiration can adjust or acclimate to increasing temperatures. This would result in decreased emissions of carbon dioxide in response to rising temperatures. This has been determined primarily in controlled experiments and field experiments of varying lengths. The rationale for this is uncertain, and it has been ascribed to changes in respiration responses to temperature. There is a suggestion that predictions of increased carbon dioxide emissions due to respiration may not be completely accurate (Griffin and Prager, 2017).

Reich *et al.* (2016) concluded that, while there was some evidence of acclimation of respiration to warming under controlled conditions, there was no long-term evidence of acclimation of respiration to warming temperatures in the field. They established a multiple-year study of the effects of increasing temperature by 3.4 °C above ambient on leaf respiration for young juvenile plants of 10 North American tree species under forest conditions. When comparisons were made to control plants that were not exposed to an increased temperature of 3.4 °C, they found that, on average, leaf respiration increased by 5%. They predicted that without respiration acclimation, the increase would have been 23%. Acclimation eliminated 80% of the expected increase in respiration. They concluded that if respiratory acclimation is a common response to temperature increase, then respiration rates from plants may not increase as much as predicted, and this contribution to global warming may be less than expected. Achieving similar results with older trees could prove to be difficult. More needs to be done to determine the extent and importance of acclimation of respiration to increasing temperatures.

4.4 FACTORS AFFECTING PHOTOSYNTHESIS, GROWTH, AND CARBON STORAGE

Trees use photosynthesis to fix carbon from carbon dioxide and either use it for growth or store it in sinks in stems, branches, and roots. It has been widely assumed and proposed that increasing levels of anthropogenic carbon dioxide will greatly stimulate photosynthesis in trees and other terrestrial vegetation, resulting in increased growth and carbon storage. Results from satellite scans conclude that it is likely that there is an extensive human-induced global greening or carbon dioxide fertilization effect in progress (Mao *et al.*, 2016). Results from ground-based empirical research, however, may not completely support this conclusion.

Unlike animals including humans, trees and other plants must adapt or acclimate to changes in their immediate above-ground and below-ground environments. Their own inherent characteristics and requirements influence how effectively they can acclimate. This variability is not included in large predictive models or satellite scans, especially in relation to elevated carbon dioxide and photosynthesis. In these approaches, trees are often used as a generic term.

Photosynthesis is essential for tree growth. Trees and forests often occur in areas where essential conditions for tree growth and photosynthesis are limiting (Oren *et al.*, 2001). Atmospheric limiting factors include stomatal function, light, temperature, and carbon dioxide (Cieslik *et al.*, 2009; Rennenberg and Schmidt, 2010; Royal Society of Chemistry). Soil factors include available soil water and nutrients. Tree species, stage of plant development, age, canopy structure, leaf area, leaf age and longevity, and phenology are among inherent factors that affect photosynthesis. Inclusion of limiting factors in calculations or assessments of tree photosynthetic and growth responses to elevated carbon dioxide results in more relevant and realistic appraisals.

4.4.1 The Law of Limiting Factors

F. F. Blackmann is credited with formulating the law of limiting factors in 1905. He developed it while studying factors affecting the rate of photosynthesis. "The law states that the rate of a physiological process will be limited by the factor which is in the shortest supply. Any change in the level of a limiting factor will affect the rate of reaction." Based on his investigations, he concluded that the law of limiting factors determines the rate of photosynthesis (Royal Society of Chemistry). In a warming world, light intensity, temperature, carbon dioxide, soil water, and soil nutrients are likely major limiting factors for photosynthesis.

4.4.2 Stomatal Function

Opening and closing of stomata regulates intake of carbon dioxide and water loss through transpiration. When enough carbon dioxide is present in the intercellular air spaces for photosynthesis, stomata close to conserve water. During transpiration via open stomata, evaporation of water cools surrounding air. Stomata also open to regulate internal leaf temperature to prevent overheating from exposure to strong sunlight. Stomata close during drought to save water (Cieslik *et al.*, 2009).

4.4.3 Light

Light in the photosynthetically active radiation (PAR) range of 400 to 700 nanometers is required for photosynthesis. The amount and intensity of ambient light depends on the weather, the season of the year, and the time of day. Light intensity typically peaks at noon in warm summer months that coincide with the growing season for plants. Photosynthesis may peak in the late afternoon and declines with darkness. Chlorophyll molecules respond to the light intensity they receive, and this affects generation of ATP and NADPH. Light-dependent reactions such as these are not temperature-dependent. In general, light intensity increases increase the rate of photosynthesis, unless limited by another factor (Royal Society of Chemistry).

The canopy structure of trees affects light availability. The light intensity diminishes within canopy depth. Light availability within the canopy regulates leaf area, leaf energy balance, water use, and photosynthesis (Ellsworth and Reich, 1993). Leaves at the top of the canopy, exposed to bright sunlight, may be light-saturated (Perry *et al.*, 2008). This reduces the efficiency of their use of light for photosynthesis. Leaves within the canopy receive less light but are more efficient in using it in photosynthesis. With clouds, atmospheric aerosols from pollution, or BVOCs from trees, light intensity is reduced but is more uniformly distributed to and within tree canopies. Resulting reductions in overall PAR may reduce photosynthesis, but this may be balanced by the effectiveness of increased PAR at the top and within canopies in increasing photosynthesis. Until 1999, PAR in the global atmosphere was diminished (global dimming) by pollution aerosols. It has been estimated that the reduction and more uniform distribution of PAR increased global land carbon sinks from 1960 to 1999 by 25% (Mercado *et al.*, 2009). Rap *et al.* (2018) have recently proposed the term "diffuse radiation fertilization" to describe the effect of BVOC aerosol particles that reduce direct sunlight and increase light distribution within tree and plant canopies, resulting in increased well-distributed photosynthesis and increased biomass productivity.

Seasonal rainfall and cloud cover may influence photosynthesis in evergreen tropical forests. With adequate rainfall and available soil water, photosynthesis is maintained and has increased during the dry winter season in tropical evergreen forests. Guan *et al.* (2015) are concerned that increasing cloud cover during the wet season will reduce PAR available for photosynthesis.

4.4.4 Temperature

Trees and plants are affected by air temperatures in their immediate environment. Optimal temperatures for survival, photosynthesis, growth, and reproduction vary widely with species. Temperature also regulates the activity of enzymes that govern light-independent reactions of photosynthesis (Royal Society of Chemistry). Markings (2017) has detailed the response of these enzymes to low, medium, and high temperatures.

- Low temperatures: 32–50 °F (0–10 °C)
  Enzymes are not efficient. Reduction in glucose production may stunt growth.
  The limiting factor here is inefficient enzyme activity.
- Medium temperatures: 50–68 °F (10–20 °C)

Enzymes function at their optimal level. Photosynthesis rate is high and optimal.
The limiting factor here is the rate of stomatal diffusion into leaves.

- High temperatures: above 68 °F (20 °C) and 104 °F (40 °C)
  Above 68 °F (20 °C), enzymes begin to be adversely affected by temperature and the rate of photosynthesis begins to decrease, even as increased diffusion of carbon dioxide into leaves may increase.
  At 104 °F (40 °C), enzymes lose shape and become denatured and ineffective. Even with optimal light and water, photosynthesis declines.
  The limiting factor here is warming temperature effects on enzyme activity.

Lin *et al.* (2012) describe some processes that control the relationship of photosynthesis to temperature. The general assumption is that photosynthesis is limited by either the maximum rubisco (ribulose-1,5-phosphate carboxylase/oxygenase) carboxylation rate or the maximum regeneration rate of RUBP (ribulose-1,5-biphosphate). Both of these processes are temperature-dependent. The sensitivity of plant species and growth stage responses of photosynthesis to temperature vary in the comparative role played by these two biochemical processes.

4.4.5 Thermal Acclimation of Photosynthesis to Temperature

With increasing ambient temperatures from global warming, there is interest in determining whether photosynthesis can acclimate to warming temperatures. Dillway and Kruger (2010) tested this in a large field experiment. They established a 900-km transect in Eastern North America crossing seven degrees of latitude with a 12 °C difference in temperature from low to high transect end. At intervals along the transect, they planted two boreal tree species (trembling aspen, *Populus tremuloides*, and paper birch, *Betula papyrifera*) and two temperate tree species (Eastern cottonwood, *Populus deltoides*, and sweetgum, *Liquidambar styraciflua*). Leaf photosynthetic metabolism was assessed, focusing on maximum rate of RUBP carboxylation and regeneration. Little evidence of photosynthesis acclimation by location was found for all species. Three tropical tree species were grown over a range of air temperatures, and carbon dioxide uptake and photosynthesis responses were determined. All species showed some indications of acclimation to increasing temperature. The conclusion was that photosynthesis of the tropical tree seedlings could probably acclimate to moderate temperature warming, but that carbon gain would decrease with warming (Slot and Winter, 2017).

4.4.6 Stomatal Regulation

Stomatal regulation of internal carbon dioxide is affected by air temperature. Stomata respond to temperature and also to increases in vapor pressure deficit (the difference between water vapor pressure and saturation water vapor pressure at a given temperature) that occurs as temperatures rise. Vapor pressure deficit regulates stomatal aperture and conductance. It has been shown to increase with air temperature in experiments. The response of photosynthesis to temperature is affected by vapor pressure deficit effects on stomatal conductance.

4.4.7 Water

Trees obtain most of their water from soil. Water must be available in soil to be absorbed by roots and then transferred via xylem, with nitrogen and other nutrients, to leaves where photosynthesis takes place. Transpiration of water vapor occurs whenever stomata are open. During gas exchange, water vapor diffuses outward, and carbon dioxide diffuses inward. Water is also necessary to maintain turgor pressure and protoplasm hydration (Kramer and Kozlowski, 1979; Larcher, 2003). Stomatal apertures narrow during water deficiency, and this reduces gas exchange, carbon dioxide diffusion, and photosynthesis. Protoplasm hydration is also affected, as are chloroplasts (Larcher, 2003). The extent of water stress depends on how the rate of water absorption from soil affects transpiration rate from leaves (Kramer and Kozlowski, 1979).

Predictions for the future include a warmer drier world. Drought is becoming more widespread, as is drought stress in trees. During drought stress, stomata close. Photosynthesis slows down or may stop, as little new carbon dioxide is available, and transpiration has stopped. Trees face a no-win situation when temperatures are elevated and drought occurs. Cieslik *et al.* (2009) describe two possible strategies by trees to cope with high temperature and drought: stomata open to provide leaf cooling, or stomata close to reduce water loss. Leaves overheat without transpirational cooling. If overheating continues, leaves may burn, discolor, and die. Cornic (2000) conclude that mild drought stress decreased stomatal aperture, and this was the cause of inhibition of photosynthesis.

4.4.8 Nitrogen and Mineral Elements

Trees obtain nitrogen, phosphorus, and mineral elements from soil via the flow of water from soil to leaves in the transpirational stream. Trees growing in soils with sufficient available water, nitrogen, phosphorus, and other elements, under appropriate light and temperature conditions, exhibit a high rate of photosynthesis and water-use efficiency that allow them to approach their genetic potential. Many forests, especially in remote northern forests, do not exist under these ideal conditions and are deficient in nitrogen and other elements (Oren *et al.* 2001; Perry *et al.*, 2008). Fernandez-Martinez *et al.* (2014) analyzed how nutrient availability affected GPP and NPP. They concluded that forests in high-nutrient soils have high GPP and NPP. Forests growing in low-nutrient or nutrient-poor soils lose much of their GPP to respiration (Figures 4.1 and 4.2).

Craine *et al.* (2018) examined trends in foliar nitrogen concentrations over a 37-year period and concluded that foliar concentrations of nitrogen declined by 9%. This suggested that the amount of available nitrogen in relation to plant requirements is declining. This is a

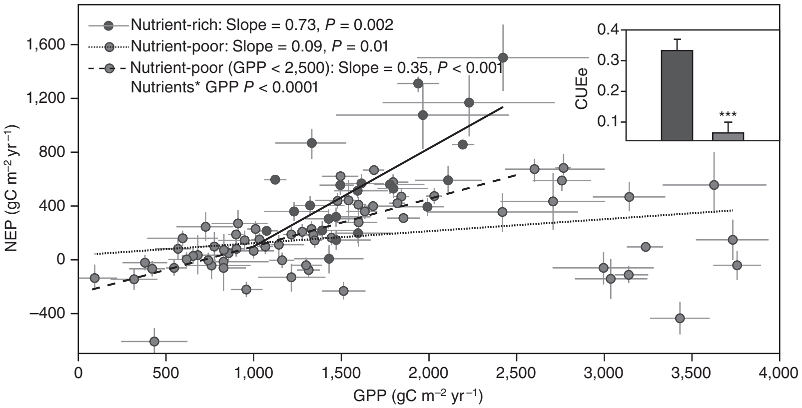

FIGURE 4.1 Only nutrient-rich forests substantially increase carbon sequestration with increasing carbon uptake.

The bar chart inside the main graph shows that carbon-use efficiency at the ecosystem level (CUEe, which is the ratio of net ecosystem production to gross primary production, NEP/GPP) in nutrient-rich forests (red) is more than five times as high as in nutrient-poor forests (blue). We also present results for forests with GPP $< 2{,}500$ gC m^{-2} yr^{-1}, because values of GPP $> 2{,}500$ gC m^{-2} yr^{-1} were available only for nutrient-poor forests. When considering only forests with GPP $< 2{,}500$ gC m^{-2} yr^{-1}, the Nutrient*GPP (where Nutrient = nutrient availability) interaction (where * indicates an interaction) is significant at the 0.006 level. In the bar chart, error bars indicate the s.e.m. and *** indicates significant differences at the $P < 0.001$ level.

(A black and white version of this figure will appear in some formats. For the color version, please refer to the plate section.)

Adapted by permission from Springer Nature: Springer Nature Ltd, *Nature Climate Change*, Nutrient availability as the key regulator of global forest carbon balance, M. Fernández-Martínez *et al.* © (2014)

particular problem for trees now experiencing longer growing seasons and might affect growth, uptake, and sequestration of anthropogenic carbon dioxide.

Deficiencies in mineral elements can adversely affect chlorophyll and chloroplasts. Deficiencies in magnesium or iron can cause reduction in leaf chlorophyll and a yellow coloration called chlorosis. This slows uptake of carbon dioxide and reduces photosynthesis (Larcher, 2003). Wang *et al.* (2012) consider soil water and nitrogen to be major limiting factors for photosynthesis.

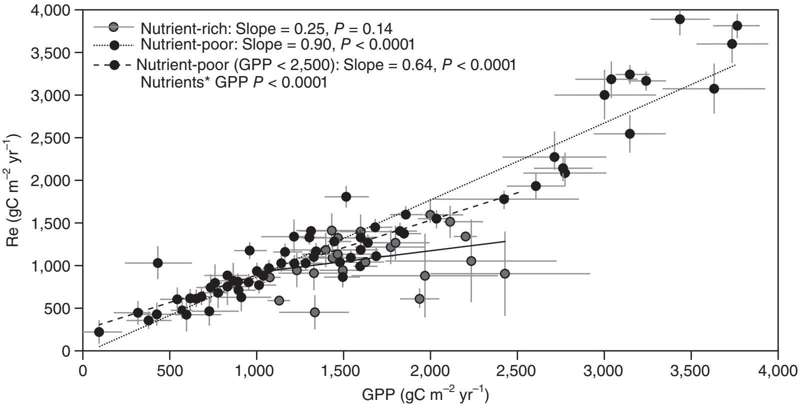

FIGURE 4.2 The coupling between ecosystem respiration (Re) and gross primary productivity (GPP) is weak in nutrient-rich forests and very strong in nutrient-poor forests.
Nutrient-rich forests decouple Re from GPP, resulting in an increase in carbon accumulation with increasing GPP. When considering only forests with GPP $< 2{,}500$ gC m^{-2} yr^{-1}, the Nutrient*GPP interaction (where * indicates an interaction and "Nutrient" = nutrient availability) is significant at the 0.005 level. Error bars indicate the uncertainty of the estimate on both the *x* and *y* axes (s.e.m.).
(A black and white version of this figure will appear in some formats. For the color version, please refer to the plate section.)
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4.4.9 *Nitrogen*

Trees, like many other plants, require more available nitrogen than any of the other 16 elements required for plant growth (Perry *et al.*, 2008). Nitrogen in leaves is used in synthesis of chlorophyll, regulatory proteins, and enzymes. Nitrogen-containing enzymes in chloroplasts, which function in photosynthesis, contain approximately 75% of available foliar nitrogen. Rubisco, the primary enzyme in carbon fixation from carbon dioxide, contains approximately 20% of available foliar nitrogen. Nitrogen deficiency affects enzyme formation and chlorophyll synthesis and reduces photosynthesis. Leaf chlorophyll and nitrogen content correlate well (Kramer and Kozlowski, 1979; Larcher, 2003; Perry *et al.*, 2008).

4.4.9.1 Nitrogen Deposition

It has been widely assumed and proposed that atmospheric deposition of nitrogen will stimulate primary plant productivity in nitrogen-limited areas, which will increase sequestration of carbon from anthropogenic carbon dioxide. This would be accomplished by increased photosynthesis. Evidence for this from field experiments and models is controversial.

Most atmospheric nitrogen originates from combustion, primarily from vehicles. Atmospheric nitrogen is deposited in dry or wet modes. Dry deposition includes gases such as nitrogen dioxide (NO_2), from combustion and ammonia (NH_3) from animal agriculture (Reay *et al.*, 2008). Some NO_2 can also diffuse into substomatal cavities with carbon dioxide during gas exchange for photosynthesis. Nitrogen from NO_2 can be used as a nutrient promoting growth. In wet deposition, nitrogen compounds are captured in water droplets which are deposited on leaves, stems, or soil where they can be used for plant growth. Janssens and Luyssaert (2009), however, consider that much of the wet atmospheric nitrogen deposition is lost to groundwater, evaporates back to the atmosphere, or becomes part of temporary tissues such as leaves and twigs that end up as litter on the ground. Nadelhoffer *et al.* (1999) concluded from ^{15}N tracer studies in temperate forests that nitrogen deposition would not be a major contribution to increased tree growth and carbon storage.

4.4.9.2 Nitrogen and Phosphorus Addition to Forest Soils

Trees growing under high or adequate nutrient conditions allocate more resources to biomass growth than to roots (Sara *et al.*, 2012). Forest soils are often deficient in nitrogen and phosphorus, especially phosphorus in tropical soils, which limits net primary productivity (Wieder *et al.*, 2015; Ellsworth *et al.*, 2017; Schulte-Uebbing and de Vries, 2017; Jiang *et al.*, 2018). Trees growing under nitrogen and phosphorus soil deficiencies allocate more resources to root development than shoot development, especially to large networks of fine roots to find soil nitrogen (Rennenberg and Schmidt, 2010). Concern has been raised about the impact of nitrogen and phosphorus limitations on carbon dioxide uptake, biomass formation, and carbon sequestration in relation to global warming predictions (Wieder *et al.*, 2015). Many experiments have been conducted on the growth response of forest trees to additions of nitrogen to forest soils. They were designed to simulate the effects of atmospheric nitrogen deposition to forest soils on tree growth. Schulte-Uebbing and de Vries (2017) conducted a meta-analysis of tree responses to soil nitrogen. They concluded that temperate and boreal forest trees responded with increased growth and carbon fixation. Tropical forest trees did not show significant increases in growth and carbon fixation. Low soil phosphorus levels in tropical soils have been assumed to be a limiting factor for tropical tree growth responses to nitrogen added to soils. Addition of phosphorus to soils amended with nitrogen did not, however, result in significant increases in tropical tree growth and carbon fixation.

Thomas *et al.* (2009) concluded that the results from small plot studies and models regarding the nitrogen deposition and its effects on carbon sequestration were inconclusive and controversial. He used forest inventory data to determine that growth response of 24 temperate deciduous trees to nitrogen deposition varied considerably by species. Growth was enhanced for only 11 species. The role of mycorrhizal fungi was important in determining tree growth benefit from nitrogen added to soil. Trees with VA mycorrhizae, caused by obligate vesicular arbuscular (VA) fungi, had enhanced growth as they were unable to enzymatically break down added soil nitrogen and were able to use it.

Only a few forest trees have VA mycorrhizae. *Acer rubrum*, *A. saccharum*, *Liriodendron tulipifera*, and *Prunus serotina* are common trees with VA mycorrhizae. Most forest trees have ectomycorrhizal associations. They produce enzymes that break down added soil nitrogen and do not benefit as much from soil nitrogen deposition.

Many experiments with nitrogen deposition find that the response of trees to nitrogen deposition may be inconclusive, so sometimes phosphorus is included as well. Schulte-Uebbing and de Vries (2017) conducted a meta-analysis of tree responses to nitrogen addition. They concluded that there was good growth response by young temperate-zone trees. Tropical forests did not show positive growth responses to nitrogen deposition. Phosphorus was considered as a limiting factor, but phosphorus additions did not elicit significant growth responses.

Jiang *et al.* (2018) investigated the role of nitrogen and phosphorus additions on tree growth response in a tropical montane forest in Hainan Island, China, for a 5-year period. Nitrogen additions alone did not result in significant growth responses. Phosphorus additions alone resulted in enhanced growth of only small trees. Results from combined additions of nitrogen and phosphorus were not significantly different from those obtained with nitrogen application alone. Their results suggest that phosphorus regulates (or limits) tree growth in tropical forests. Ellsworth *et al.* (2017) found that adding phosphorus to a phosphorus-limited soil increased growth of trees in a broadleaved evergreen eucalyptus forest in Australia. Wieder *et al.* (2015) feel that projected estimates of future increases in NPP may be too high and may not be supported by adequate amounts of nitrogen, phosphorus, and other elements necessary to achieve the projected increases. They included limitations for nitrogen and phosphorus in projections for estimates of increased NPP by the end of the twenty-first century. They concluded that nitrogen limitations would decrease NPP by 19%. Phosphorus limitations decreased NPP by 25%. Taken together, these limitations would turn the terrestrial ecosystem into a net source of carbon dioxide.

4.4.10 Seasonal Changes in Leaves and Photosynthesis

On a global scale, photosynthesis is constrained by the seasons of the year. Keeling *et al.* (1996) found that carbon dioxide levels were higher in winter and lower in summer in the Northern Hemisphere. This implied that photosynthesis was lower in winter than in summer and that this affected carbon dioxide levels. Wenzel *et al.* (2016) confirm that the lack of photosynthesis, fuel combustion for heating, and organic matter decomposition in winter constrain the influence of photosynthesis on global warming. Guan *et al.* (2015) used satellite imagery to determine how seasonal rainfall affected photosynthesis of evergreen tropical forests during the dry season. Canopy photosynthesis of some tropical forests declines during the dry season, while in others it continues as if they were in the wet season. They concluded that the extent of seasonal rainfall could be a threshold for forest function. They proposed that a rainfall threshold value of 2,000 mm yr^{-1} would allow the evergreen state of forests to be maintained during the dry season. Wu *et al.* (2016) proposed that not seasonal climate, but seasonal leaf phenology, was responsible for seasonality of photosynthesis in tropical evergreen forests. During the dry season, older leaves fall and are replaced by younger, more photosynthetically active leaves in the canopy.

Photosynthesis changes in leaves as they age throughout the growing season. The patterns and extent of change vary with environment and with species of deciduous and evergreen (conifer) trees. Jurik (1986) determined that carbon dioxide exchange rates for *Populus grandidentata*, *Betula papyrifera*, *Quercus rubra*, *Acer rubrum* and *Fagus grandiflora* increased in June and reached a maximum at full leaf expansion. This continued until mid-September and then declined until leaves died. Seasonal changes in canopy leaves of *Quercus crispula* were highest from June to August in summer and decreased in September (Hirosaka *et al.*, 2007). Wilson *et al.* (2001) determined seasonal leaf development patterns, photosynthetic capacity, and senescence rates for leaves of *Q. alba*, *Q. prinus*, *A. rubrum*, *A. saccharum*, and *Nyssa sylvatica*. They compared their results to those from a model (CANOAK). The model used the maximum early season value for photosynthetic capacity for the entire growing season. They determined that the model overestimated seasonal carbon uptake by 50%. When allowances were made for mid- to late summer changes in leaf development and photosynthetic capacity, the model overestimation was 25%. Unlike deciduous trees, conifers produce new leaves (needles) annually and can retain older cohorts of needles for as long as 5 years. Needle age affects photosynthetic capacity. Jensen *et al.* (2015) found that needle cohorts of *Picea mariana* varied by age for photosynthetic activity. New youngest needles (Y0) had the lowest activity, followed by year one (Y1) and then year two (Y2).

4.4.11 Tree Age

It has been proposed that mature trees and old-growth forests continue to grow and serve as continually expanding large sinks for carbon from photosynthesis and biomass production. They are not just neutral reservoirs of carbon conserved in wood. This has proven to be controversial and has led to differing conclusions (Bond, 2000; Luyssaert *et al.*, 2008). Given the role often given to mature trees and old-growth forests in reducing anthropogenic carbon dioxide via photosynthesis, it is important to examine this issue. A few examples of many reports about this are given here.

The reference that supports the proposal that is most often cited is Luyssaert *et al.* (2008). Given favorable climate and nitrogen, old-growth forests store carbon in tree biomass, litter, and soil, and serve as global carbon sinks. Luyssaert *et al.* conducted a literature and database review for carbon flux estimates and NEP (net carbon balance of forest and soil). NEP was usually positive for forests ranging in age from 15 to 800 years old. They concluded that old-growth forests are important carbon sinks and therefore are not carbon-neutral or carbon sources. Stephenson *et al.* (2014) examined whether growth and biomass production in trees increases, remains constant, or declines with tree age and size. They evaluated actual measurements and observations for 403 global tropical and temperate tree species. In most cases, biomass growth increased with tree size. Compared to smaller trees, they concluded that large older trees continue to sequester large amounts of carbon via photosynthesis. The rationale for continuing carbon fixation by older trees was that continuing increase in total leaf area compensated for declining activity per leaf area unit.

Bond (2000), however, concluded from her review that changes in stomatal conductance and photosynthesis in trees and woody plants are age-related. Net photosynthesis declines with age.

Most of the carbon fixed by photosynthesis is stored in wood. Sillett *et al.* (2010) note that wood production increases with tree size and age and then typically declines as the tree reaches maturity at an age where wood production rate declines when one or more factors becomes limiting. The decline varies with tree species and environmental conditions. They compared wood production in relation to longevity in two very tall trees: *Eucalyptus regens* in Australia and *Sequoia sempervirens* in California. *E. regens* grows rapidly to great height but declines fairly quickly owing to fire and disease. *S. sempervirens* grows more slowly, sometimes for 1000 years or more, and continues to produce resistant heartwood.

Relating leaf age and level of function and photosynthesis to tree age has been the subject of many experiments. Thomas (2010) conducted an extensive field experiment to determine the course of gas exchange and leaf level photosynthesis, leaf area, size, mass, and nitrogen content in the upper canopy, and related these to tree age and dbh. Seedlings, saplings, pole-sized, intermediate, mature, and very old trees of *Acer saccharum*, *Betula alleghaniensis*, and *Tilia americana* were evaluated in a single uneven-sized forest. Photosynthetic capacity peaked at intermediate tree size and correlated with dbh. Bassow and Bazzaz (1998) measured gas exchange in relation to tree species in a mixed 60–70-year-old forest. Measurements at canopy tops and interiors indicated that gas exchange rate was highest for *Quercus rubra*, followed by *Betula papyrifera*, *B. alleghaniensis*, and *A. rubrum*. Yoder *et al.* (1994) compared net rates of photosynthesis per unit area for 1-year-old needles from mature *Pinus ponderosa* and *P. contorta* trees that had either stopped growing or had ceased growth. Net photosynthetic rates for needles on actively growing trees were 14–30% lower than for needles on trees that had stopped growing.

NPP has been observed to decline in trees and forests with age. This has been attributed to decline in photosynthesis and GPP. It has also been noted that water may become more limiting with tree age. Drake *et al.* (2010) proposed that hydraulic conductance rates of water from soil to leaves may limit photosynthesis due to extent of stomatal closure. Tang *et al.* (2014) examined traditional views that NPP declines with age in forests because rates of photosynthesis and GPP are stable but autotrophic respiration increases. They concluded that in ageing boreal and temperate forests, both GPP and respiration decline, with GPP declining more rapidly than dark respiration.

4.4.12 Elevated Carbon Dioxide

Stomatal conductance determines the diffusion rate of carbon dioxide from ambient air into the substomatal cavity of a leaf. The rate of mesophyll conductance or resistance governs further internal diffusion to intercellular air spaces and eventually to chloroplasts and rubisco. Changes in stomatal conductance due to changes in stomatal aperture and mesophyll resistance affect the rates of this process (Niinemets *et al.*, 2010; Long, 2012). Guard cells of stomates, which control the extent of stomatal aperture opening, respond to a number of environmental factors, such as light, humidity, and carbon dioxide (Morrison, 1998). Concentrations of carbon dioxide that are much higher than ambient are well known to decrease stomatal conduction, which can increase or stimulate photosynthesis (Long, 2012). Partial stomatal closure caused by elevated carbon dioxide increases resistance to water loss by transpiration, while maintaining a constant internal concentration of carbon dioxide for photosynthesis (Perry *et al.*, 2008; Keenan *et al.*, 2013).

When global brightening gradually began to replace global dimming in the 1980s, global warming became more evident, as did continuing increases in atmospheric carbon dioxide. Carbon dioxide was determined to be the most persistent of the reradiative gases and most likely the major cause of global warming. Numerous models began and have continued to predict that carbon dioxide in the future would increase considerably and could be as much as 100% higher than at present. Assumptions were made about the possible role of terrestrial plants, especially trees, in reducing increased levels of carbon dioxide through photosynthesis and storage of fixed carbon in wood and soil. How effective trees and forests might be in utilizing above ambient concentrations of carbon dioxide became the subject of hundreds if not a thousand or more experiments, beginning in the 1980s.

Given the size, complexity, and cultural requirements, trees are not typical of plants used in replicated experiments. The first experiments were short-term and done with potted tree seedlings in growth chambers or greenhouse compartments containing ambient carbon dioxide (then 370 ppm) or carbon dioxide as high as 800 ppm. Trees also respond differently at different growth stages, so it was realized that larger trees should be used in longer-term experiments under natural conditions. Branch chambers were used on older trees, large open-top chambers allowed use of saplings, and FACE (free air carbon dioxide exposure) systems could be used for up to 12 years. Three things became evident from all these experiments. First, there were many instances where elevated carbon dioxide stimulated tree growth. Second, there were differences between and within tree species regarding degree of incidence of growth stimulation. Third, after an initial period of stimulation of photosynthesis and growth, the stimulation levelled off or declined, indicating additional requirements for continued growth stimulation.

Forests often either occur naturally or are related to areas with low soil fertility (Oren *et al.*, 2001). Plants grow well when nutrients, especially nitrogen, and water and light are readily available (Kramer and Kozlowski, 1979; Korner, 2003; Ainsworth and Rogers, 2007; de Dios *et al.*, 2016). It was also known that low plant tissue levels of nitrogen could reduce the response of trees to elevated carbon dioxide (Cotrufo *et al.*, 1998; Korner, 2003). This led to numerous field experiments on the effects of nitrogen and phosphorus on the response of trees to elevated carbon dioxide. An early conclusive experiment was conducted at the Duke Forest in FACE experiments with 550 ppm carbon dioxide exposure and maturing loblolly pines growing in place. Trees in a poor soil site did not respond to elevated carbon dioxide. Trees at a moderate-fertility site responded positively, but only for 3 years. When nitrogen fertilizer was added to the sites, large long-term increases in photosynthesis and growth were obtained in response to elevated carbon dioxide at 550 ppm (Figure 4.3). In a 12-year FACE experiment at Oak Ridge National Laboratory, Warren *et al.* (2014) found that sweetgum trees initially experienced increases in photosynthesis and biomass due to exposure to elevated carbon dioxide, but this was not sustained. Availability of soil nitrogen declined, and lack of nitrogen as well as acclimation to elevated carbon dioxide may have curtailed the rate of photosynthesis. Decreased soil nitrogen availability in trees was concluded to be due to a decrease in transpiration of soil water into roots and transport of less nitrogen and other elements to leaves because of partial stomatal closure on exposure to elevated carbon dioxide (McDonald *et al.*, 2002; Taub and Wang, 2008). A decline in net carbon dioxide uptake and growth stimulation in response to continued exposure to elevated carbon dioxide reduces tissue nitrogen availability. This reduces maximum carboxylate (V_{cmax}) velocity of rubisco and RuBP generation capacity (Jach and Ceulemans, 2000; Rogers and Humphries, 2000; Ainsworth and Rogers, 2007). Rogers and Humphries (2000) concluded that decline of initial growth stimulation of net carbon dioxide uptake is almost entirely due to decline in V_{cmax} of rubisco.

Phosphorus soil levels can be low in eucalyptus forests in Australia. Ellsworth *et al.* (2017) compared the growth and rates of photosynthesis of plots in an evergreen eucalyptus forest to elevated carbon dioxide, with and without phosphorus addition to soil for 3 years. Trees in the low-phosphorus soil did not increase growth in response to elevated carbon dioxide. Photosynthesis, however, increased by 19%. Trees in soil amended with phosphorus increased growth by

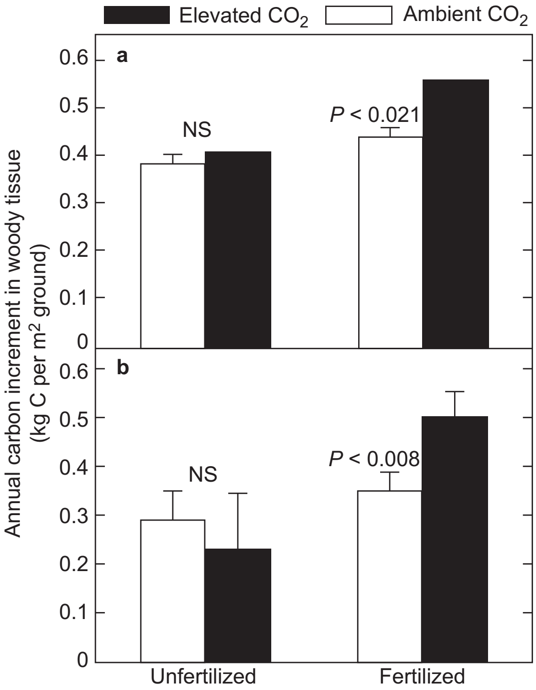

FIGURE 4.3 **a**, A moderate-fertility Duke Forest site (averaged for 1999 and 2000); **b**, an infertile SETRES site (1997 and 1998). *P* values represent test results between ambient and elevated CO_2 in each fertility level. In both sites, elevating only CO_2 had no significant effect (in **a**, data without nutrient addition are the mean of the past 2 years); fertilizing in ambient CO_2 had a significant effect; and fertilizing under elevated CO_2 had significantly higher effects than the sum of the single CO_2 and N effects. NS, not significant.

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35% with elevated carbon dioxide (Figure 4.4) Phosphorus availability in soils may determine positive effects of elevated carbon dioxide.

Tree response to elevated carbon dioxide varies between and within species. de Dios *et al.* (2016) conducted a meta-analysis search for elevated carbon dioxide effects on growth responses of trees within species, focusing on young trees, mostly in the genus *Populus*. They found variation in height, stem growth, stem biomass, stem volume, and photosynthesis. Growth responses, however, were not correlated

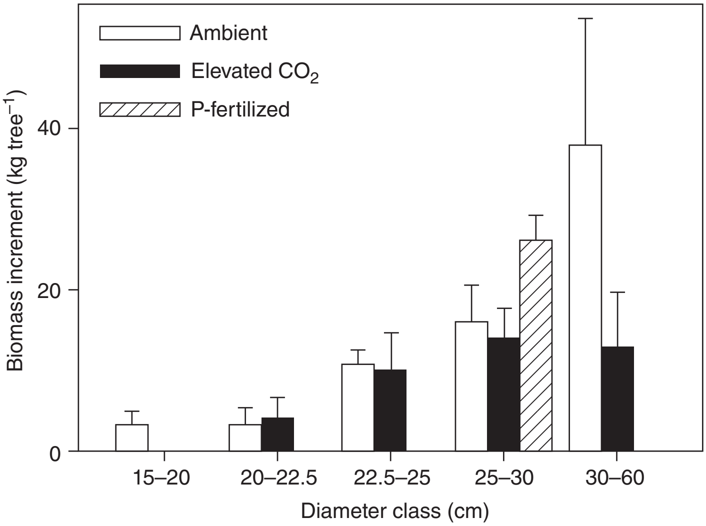

FIGURE 4.4 Shown is the biomass increment over 4 years from December 2011 to December 2015 within each size class for trees grown in ambient (open bars, mean ± s.e.m.) and elevated CO_2 (dark bars, mean ± s.e.m.), and for ambient-grown trees with 4 years of P-fertilization (striped bar, mean ± s.e.m.). Diameter classes are defined as the diameter in December 2011 before the start of treatments. The biomass increment for elevated-CO_2 trees in the first size class (15–20 cm) was not different from zero. Each combination of tree diameter class and treatment contained nine unsuppressed trees on average ($N = 5$ trees for P-fertilized). Bars are means +1 s.e.m. within each size class. The P-fertilized tree increment is significantly different from the ambient tree increment for the appropriate size class ($P = 0.031$; one-tailed t-test).

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with photosynthetic response. It was recommended that superior genotypes be selected for tree breeding and reforestation. Zhou *et al.* (2011) exposed *Pinus korainensis* and *P. sylvestriformis* to ambient (370 ppm) and elevated (500 ppm) carbon dioxide in open-top chambers for 8–9 years. They measured photosynthesis and specific leaf area on current and 1-year-old needles. Photosynthesis increased for both, but varied with needle age and pine species. Slow-growing *P. korainensis* did not acclimate to elevated carbon dioxide, but fast-growing *P. sylvestriformis* did.

Ghannoum *et al.* (2010) grew well-watered and well-fertilized faster-growing *Eucalyptus saligna* and slower-growing *E. sideroxylon* trees in glasshouse chambers with 290, 400, and 650 ppm carbon dioxide, and examined the effect of air temperature on response to carbon dioxide concentration. At ambient temperatures, elevated carbon dioxide did not stimulate eucalypt growth above that at the pre-industrial level of 290 ppm. Warming increased growth at elevated carbon dioxide, but not photosynthesis. Complete results are found in Figures 4.5 and 4.6.

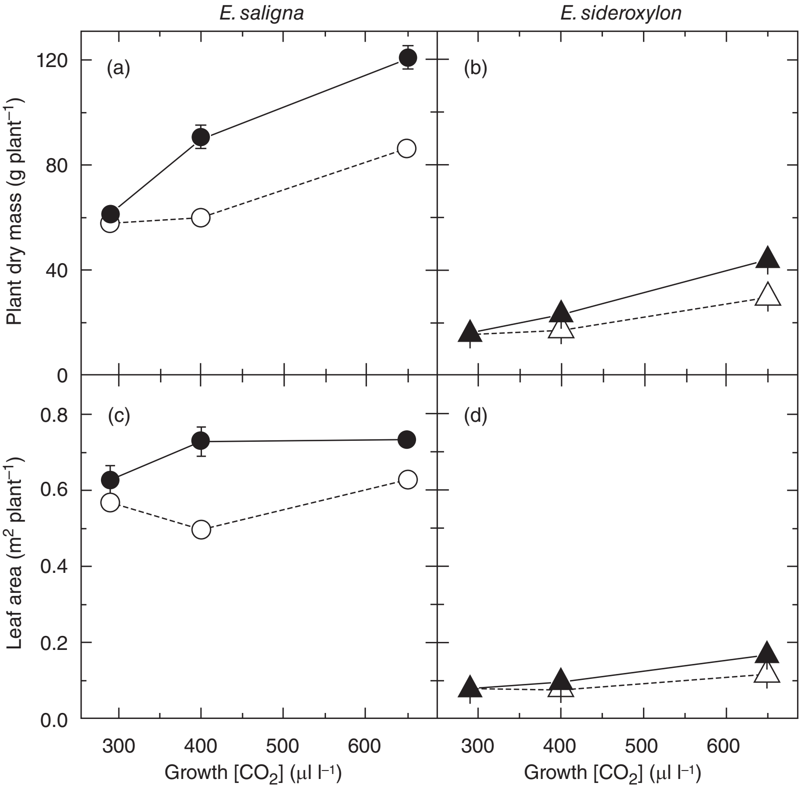

FIGURE 4.5 Total plant dry mass (**a** and **b**) and leaf area (**c** and **d**) of *E. saligna* (**a** and **c**) and *E. sideroxylon* (**b** and **d**) grown at three values of atmospheric [CO$_2$] with day averages of 290, 400, or 650 μl l^{-1}, and two air temperatures (ambient (△○●) or high (ambient +4 °C, ○●▲)). Plants were harvested 150 days after planting. Values represent means ± SE.

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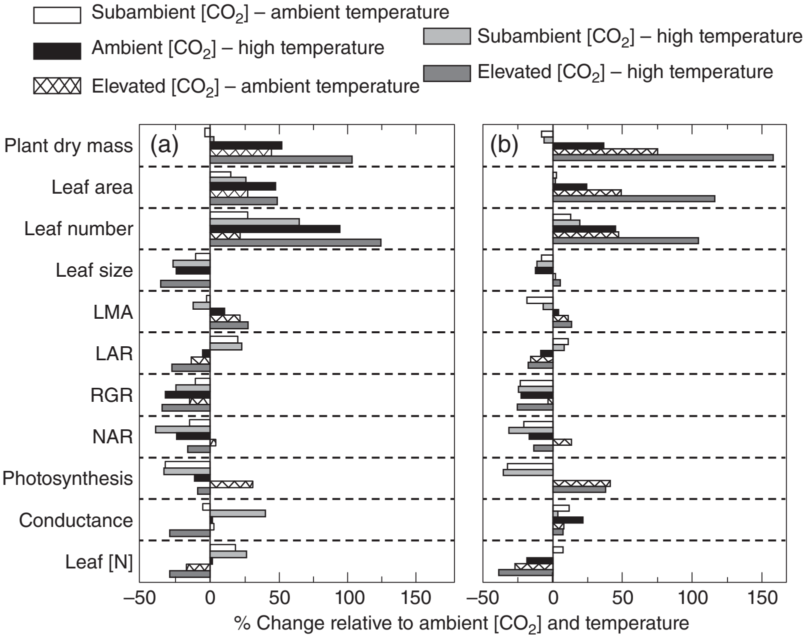

FIGURE 4.6 Percentage change of key physiological parameters of *E. saligna* (**a**) and *E. sideroxylon* (**b**) relative to current ambient conditions of CO_2 and temperature. Five different scenarios of CO_2 and temperature: subambient CO_2 and ambient temperature (white bars); subambient CO_2 and high temperature (light grey bars); ambient CO_2 and high temperature (black bars); elevated CO_2 and ambient temperature (checked bars); and elevated CO_2 and high temperature (dark grey bars). LAR, leaf area ratio; LMA, leaf mass/area; RGR, relative growth rate; NAR, net assimilation rate.

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4.4.13 Leaf Age and Photosynthesis

Leaf age and longevity affect the response of leaves to elevated carbon dioxide. If leaf age is a factor, and leaf senescence is delayed by elevated carbon dioxide, in a longer autumn, this would affect tree carbon gain in a growing season (Herrick and Thomas, 2003). Jach and Ceulemans (2000) investigated the effect of leaf age and elevated carbon dioxide (ambient + 400 ppm) on photosynthesis in current and 1-year-old Scots pines (*Pinus sylvestris*) in open-top chambers for 2 years. Elevated carbon dioxide reduced photosynthesis in both current and 1-year-old needles by 18% and 23%. Herrick and Thomas (2003) investigated senescence and photosynthesis in sweetgum (*Liquidambar styraciflua*) leaves on trees exposed to elevated carbon dioxide in the Duke Forest FACE program. They found that elevated carbon dioxide increased photosynthesis until early November. Taylor *et al.* (2007) found that elevated carbon dioxide at 550 ppm in FACE exposures (AspenFACE USA and PopFACE Italy) delayed fall leaf color and leaf senescence for clonal *Populus euroamericana*. Leaf level photosynthesis and carbon uptake was increased by elevated carbon dioxide.

4.5 BIOGENIC VOLATILE ORGANIC COMPOUNDS (BVOCS)

The atmosphere contains numerous volatile organic non-methane small hydrocarbon compounds. Anthropogenic volatile organic compounds (AVOCs) originate primarily from incomplete combustion fuels. BVOCs are naturally released from plants, especially trees. The concentration of BVOCs in the atmosphere is at least 10 times greater than that of AVOCs, and, other than methane, they are the most frequently emitted small organic molecules (Unger, 2014b; Zhao *et al.*, 2017). Dicke and Loreto (2010) estimate that more than 1,700 volatile compounds can be released by plants. Tropical forests in the Amazon are major emmiters of BVOCs, mainly isoprene (Greenberg *et al.*, 2004). Isoprene and monoterpenes are the main BVOCs and are well known to influence many aspects of plant physiology and function, including leaf temperature, insect infestations, and drought response. Penuelas and Staudt (2009) have published a detailed review linking BVOCs to global climate change.

Diurnal patterns of temperature and light regulate synthesis and emissions of BVOCs (Wang *et al.*, 2017). Emissions also play a role in formation of ozone, secondary aerosols, and cloud formation. Emissions strongly influence local atmospheric cooling and warming (Jokinen *et al.*, 2015).

4.5.1 Isoprene

Isoprene (C_3H_8 2-methyl-1,3-butadiene) is commonly associated with leaves of deciduous trees. Isoprene is not constitutive in leaves and is synthesized when needed. Synthesis requires carbon fixed in photosynthesis. Emission rates can be determined, as isoprene is emitted as soon as it is formed. Light and temperature control its synthesis and release. Emission does not occur in the dark or below 20 °C. Isoprene emission helps to reduce high temperatures of leaves exposed to full sunlight (Cieslik *et al.*, 2009). Isoprene levels may be very high when the sun is shining, air temperature is high, and winds are calm. This could increase its role in the photochemical oxidant cycle with oxides of nitrogen that forms ozone (Chameides *et al.*, 1988; Sharkey and Singaas, 1995; Dicke and Loreto, 2010). Increasing air temperatures may cause larger tree canopies in the future, which could result in increased emission of isoprene (Sharkey and Monson, 2014). Elevated carbon dioxide levels may promote growth and larger tree canopies, which could increase emissions of isoprene (Kumala *et al.*, 2004). Sun *et al.* (2013) exposed hybrid poplars (*Populus tremula* × *P. tremuloides*) to 380 and 780 ppm carbon dioxide. Trees in elevated carbon dioxide had greater leaf area and greater emission rates of isoprene.

Trees naturally emit isoprene in varying amounts that differs by tree species and type. Considering its roles in ozone formation, secondary aerosol formation, and cloud formation, interest has developed in determining isoprene emission rates for common tree species. Suitable tree species, with lower natural emission rates for isoprene, could lower ozone levels and be appropriate for use in large-scale afforestation/reforestation programs. Benjamin *et al.* (1996). tested 124 native trees and shrubs for isoprene and monoterpene emission rates with the idea that species with high isoprene emission rates should not be included in new native plantings. Donovan *et al.* (2005) modeled scenarios for isoprene emissions from 30 tree species in the Midlands region of the United Kingdom with the aim of identifying low-emission species to recommend to reduce incidence of elevated photochemical oxidant events. They developed Urban Tree

Air Quality Scores (UTAQS) for trees based on their potential to increase ozone formation. Pine, larch, and silver birch had positive effects on air quality, while oak, willows, and poplar had negative effects. A Tree BVOC Index was developed to identify low-emitting trees for use in future tree planting schemes (Simpson and McPherson, 2011). Aydin *et al.* (2014) determined BVOCs in emissions from 38 tree species (18 conifers and 20 broadleaved), growing in natural forests in Turkey. Isoprene was the major BVOC from broadleaved species with interspecies variability in oak species. Monoterpenes predominated in emissions from conifers.

4.5.2 Monoterpenes

Monoterpenes ($C_{10}H_{16}$) are 10-carbon small-chain terpenes that contain two isoprene units. They are commonly found in leaves of conifers, including boreal black spruce (*Picea mariana*) and jack pine (*Pinus banksiana*) (Lerdau *et al.* 1997). Monoterpenes can either be directly emitted or stored in resin ducts or glands. Unlike isoprene, synthesis is not required for emissions of monoterpenes (Loreto *et al.*, 1996). Drought stress, excessive heat, mechanical injury, and insect activity can affect monoterpene emissions (Wang *et al.*, 2017). Monoterpene emissions from leaves are controlled by the vapor pressure (VP) of monoterpenes in leaves, which is controlled by air temperature and monoterpene concentration within the leaves. High VP of monoterpenes results in volatilization from leaves (Lerdau *et al.* 1997). Wang *et al.* (2017) monitored summer BVOC emissions from 118-year-old Norway spruce (*Picea abies*) trees with branch chambers. High temperatures in August induced maximum seasonal emission of BVOCs. Monoterpenes dominated, with only small levels of isoprene.

BVOCs are readily oxidized by ozone and OH (the hydroxyl radical). Low volatile organic compounds (LVOCs) can either form new particles or become part of existing particles, both of which enhance concentrations of secondary organic aerosols (SOAs) and formation of cloud condensation nuclei (Jokinen *et al.*, 2015; Scott *et al.*, 2018). The formation of cloud condensation nuclei is closely linked to oxidation of BVOCs from vegetation. Monoterpene oxidation produces large quantities of LVOCs, while oxidation of isoprene results in low concentrations of LVOCs. LVOCs from monoterpenes increase new particle formation, increase the size of existing particles, and produce more cloud condensation nuclei (Jokinen *et al.*, 2015; Scott *et al.*, 2018). Monoterpene emissions in boreal forests in Europe have been directly linked to SOA formation (Tunved *et al.*, 2006). The size and composition of SOAs is affected by a number of environmental factors. Zhao *et al.* (2017) investigated the effects of temperature and aphid feeding on monoterpene emissions from boreal trees. They found that aphid feeding resulted in release of sesquiterpenes rather than only monoterpenes. This modified the composition of SOA and CCN activity. Temperature alone affected cloud condensation nuclei through an increase in size of SOA particles (Figure 4.7).

SOA particles in the size range of 100 nanometers can act as cloud condensation nuclei to form cloud droplets. Cloud condensation nuclei here also include AVOCs (Topping *et al.*, 2013). Cloud brightness and duration depends on the number of cloud droplets. Depending on elevation and nature, clouds could provide negative climate radiative forcing (Scott *et al.*, 2018). Low clouds could also slow the return of infrared radiation to space and increase night warming. There is observational evidence for increased cloud cover over forests in Western Europe. The cloud cover has a higher albedo than the darker forests, so it may reflect more light back to space and have a cooling effect (Topping *et al.*, 2013). The future of this kind of negative forcing effect for clouds is questioned by Unger (2014a) and Hantson *et al.* (2017). Deforestation has changed the forest cover of the Earth by 50%. Continuing deforestation will reduce BVOC emissions and secondary aerosols. A warmer climate may lead to lower emissions of monoterpenes if conifers are reduced or eliminated from reforestation or new forest plantings.

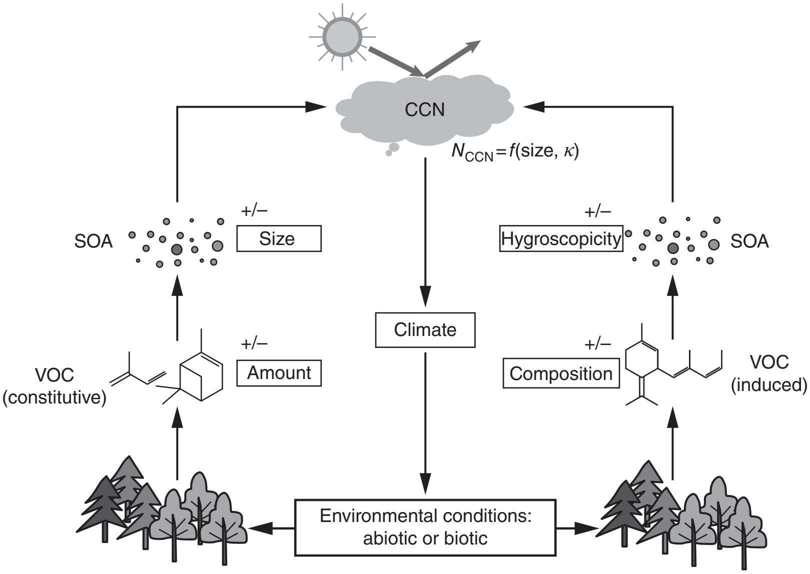

FIGURE 4.7 The schematic shows the interactions of environmental conditions, plant volatile organic compound (VOC) emissions, secondary organic aerosol (SOA), cloud formation, and climate. In unstressed conditions, plants emit constitutive VOC (black arrows on the left path), which on oxidation form SOA that act as cloud condensation nuclei (CCN) and can affect cloud formation and climate. Unfavorable environmental conditions (stresses) can induce VOC emissions (red arrows on the right path). Climatic changes and the resulting environmental conditions can affect the amount of constitutive VOC emissions and/or induce VOC emissions that modify the VOC composition. Such alterations in VOC emissions will be reflected in the particle size and/or particle composition. The latter determines the hygroscopicity parameter (κ) of the SOA, which is a measure of CCN activity at a given particle size. Both particle size and κ determine the number concentration of CCN (N_{CCN}), and thus affect cloud formation and climate. +/– indicates the changes of parameters.
(A black and white version of this figure will appear in some formats. For the color version, please refer to the plate section.)
Adapted from Zhao *et al.* (2017).

4.6 BIOGEOPHYSICAL FACTORS

Biogeochemical and biogeophysical factors together affect tree growth and function and how they affect global warming and cooling. For convenience, they are considered separately in this chapter.

Biogeophysical factors, such as albedo and evapotranspiration, have received considerable attention. They are key physical components that influence climate and integral parts of many climate change models. Biogeochemical factors, such as photosynthesis and BVOCs, have received less attention. Ozone is included in both categories. Its formation at above-background levels involves VOCs and BVOCs, and it is a physical factor affecting carbon dioxide uptake, evapotranspiration, and plant growth and development.

4.6.1 Albedo

Sunlight provides energy for the Earth, and this determines its temperature, general climate, and weather. Sunlight enters at the top of the Earth's atmosphere and moves downward to the surface of the Earth (NASA, 2011; Farmer and Cook, 2013; Climate Data Information, 2010–2015). NASA (2011) has calculated that a planetary average for energy from the sun is 340 watts per square meter. Approximately one-third is reflected back to space, leaving 240 watts per square meter to be absorbed or reflected by the atmosphere, land, and the ocean. How much of incident sunlight is absorbed or reflected by substances and surfaces depends on their exposure, color, and texture. Smooth light-colored surfaces will reflect more light than rougher or darker surfaces.

The degree of light reflection from a surface, without absorption, is called albedo (Farmer and Cook, 2013). Complete reflection has been assigned the number 1.0. Climate Data Information (2010–2015) has presented some albedo values of interest. Fresh clean snow has albedo from 0.80 to 0.90, declining to 0.40 with melting and age. The difference between snow cover and bare ground is approximately 0.50. Grassland albedo values may average 0.25, with deciduous trees at 0.15–0.18 and conifers at 0.08–0.15. The average albedo for the Earth is 0.30–0.31, but is affected by many factors, including deforestation, land cover changes, cloud cover, and secondary aerosols (NASA, 2011; Climate Data Information, 2010–2015).

Deciduous forests generally have higher albedo values than coniferous forests owing to the darker color of coniferous trees (Betts, 2000; Bonan, 2008; Naudts *et al.*, 2016; Cherubini *et al.*, 2017). Forests that reflect less light could absorb more solar radiation, warming the forests and surrounding areas (Mykleby *et al.*, 2017). Low albedo values for forests, especially dark coniferous boreal forests, can cause positive radiative climate forcing (Betts, 2000; Bonan, 2008). Results from a simulation study suggested that in some boreal forests, positive forcing from low albedo values might offset negative forcing from carbon sequestration (Betts, 2000).

4.6.1.1 Determinants for Forest Albedo

Kuusinen *et al.* (2015) propose that albedo values for forests are determined by structure, which affects light transmission into the forest, and the relative reflection by the components of biomass. Structure includes size and density of the trees, branches, and leaves. Biomass components include leaves, stems, branches, understory vegetation, or bare soil. Both structure and biomass vary considerably between tree species and locations. They used measurement data from 1,005 field plots in forests in central Finland together with airborne laser scanning data and high-resolution satellite albedo retrievals (Landsat) to investigate factors affecting albedo in summer. Albedo here was influenced by forest structure, tree species, and the composition of understory vegetation. Albedo decreased as the trees increased in size. Deciduous trees (*Betula* and *Populus*) had the highest albedo. Norway spruce (*Picea abies*) had the lowest albedo, with Scots pine (*Pinus sylvestris*) at an intermediate value.

4.6.1.2 Deforestation, Afforestation, and Reforestation

Large-scale deforestation has considerable influence on albedo. Deforestation in boreal areas allows for more snow cover and higher albedo values, and decreases the warming influence from lower conifer albedo. In tropical regions, surface albedo is increased by deforestation. The cooling effect is decreased, however, by reduced transpiration and lower cloud albedo (Bonan, 1992, 2008; Betts, 2000).

Afforestation and reforestation are widely recommended to lower atmospheric carbon dioxide and reduce radiative forcing, resulting in a cooling effect. Restoring or increasing forest cover, particularly with conifers, means lower albedo levels than the previous grass or pasture areas. More radiation is absorbed by the forests, and this can lead to an increase in radiative forcing and a warming effect. Kirschbaum *et al.* (2011) conclude from this that decreased albedo and carbon storage are opposing processes, with the net effect on radiative forcing depending on the size of each. Extensive cumulative measurements of albedo and biomass data, from a developing *Pinus radiata* forest in New Zealand, were used to estimate net change in radiative forcing as the newly planted forest grew. By the end of the forest rotation, it was estimated that, although carbon storage increased, changes in albedo reduced the benefits from carbon storage by 17–24%. de Wit *et al.* (2014) concluded that natural expansion of the range of mountain birch into high-latitude non-forested areas would increase carbon sequestration and cooling, but would reduce albedo, which could cause warming. They modeled mountain birch expansion from 2000 to 2100. Forest canopy increased by 12–27% with an increase in biomass and carbon storage of 59%. Albedo in the new forested area went from 0.46 to 0.30. They estimated that the warming caused by the lower albedo in the new forest was 10–17 times greater than any cooling effect.

Mykleby *et al.* (2017) concluded that changes in albedo brought about by afforestation could affect net absorbed radiation. They simulated a comparison of the effects of differences in net radiation from afforestation in mid and high latitudes in North America on mitigation of global warming. They drew a boundary line across North America: south of the line, they projected cooling due to a positive equivalent carbon balance; north of the line, they projected negative equivalent carbon balance and warming, except for snow-covered areas.

Forests in Europe are largely planted and managed, often planted with single tree species with selected genotypes. Naudts *et al.* (2016)

conducted an extensive review of forest management in Europe from 1750 to 1850. Deforestation was common, followed later by extensive replacement with new trees. Native deciduous trees were replaced with conifers, mainly Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*), chosen as good sources of useful wood that grew faster than deciduous trees. Conifers are darker in color and thus have lower albedo and absorb more solar radiation. Naudts *et al.* (2016) conclude that conifer forests in Europe warm the air, with a possible increase of 0.12 °C. Well-managed forests today store less carbon than forests in 1750. Large-scale use of conifers for reforestation or afforestation is not an effective strategy to reduce global warming. Tree species selection is essential for reforestation or afforestation. Hovi *et al.* (2016) conclude that increasing incidence of broadleaved (deciduous) trees in coniferous boreal forests has potential to raise forest albedo values.

4.6.2 Evapotranspiration

In the forest hydrological cycle, water enters as rainfall, fog, cloud droplets, or snow. Fog and cloud droplets can be directly absorbed by leaves, especially at high elevations. When snow melts, some water is absorbed into soil and some evaporates. Rainfall is the most common form of water, especially in the tropics. In direct throughfall, some rain lands on the forest soil. A small part runs down stems and is known as stemflow. Some of the water on the leaf canopy drips to the ground or is evaporated in place. Soil water is taken up by plant roots and returned to the atmosphere via transpiration. It is estimated that 10% of water vapor in the air originates from transpiration, with the rest from the oceans, lakes, rivers, and streams. Remaining soil water may run off or contribute to soil water recharge, groundwater, and streamflow (Roberts, 2009; USGS, 2016; Ellison *et al.*, 2017).

Evapotranspiration includes water returned to the atmosphere as water vapor from water on or in soil or forest litter, and water vapor from groundwater released from plants via stomata during transpiration (Schlesinger and Jasechko, 2014; USGS, 2016). Evaporation of water on leaves from rainfall, especially for trees with large canopies or high LAI, is usually not included, especially in models (Liu *et al.*, 2017). Evapotranspiration is thus a collective term that includes evaporation from two related but very different water sources. Both can be measured separately and the contribution of each determined. This is most likely to occur in long-term field studies, where the use of the term is appropriate. Transpiration is the appropriate term for experiments involving stomatal conductance and release of water vapor. Schlesinger and Jasechko (2014) evaluated 81 ecosystem-scale field experiments in which evapotranspiration was divided into evaporation and transpiration. They concluded that 61% of evapotranspiration was attributable to transpiration alone. Jasechko *et al.* (2013) used isotopic effects to separate the contribution of evaporation and transpiration in evapotranspiration. They concluded that transpiration was the largest global water flux, and that transpiration was 80–90% of terrestrial evapotranspiration. In view of these findings, only transpiration will be considered here.

Transpiration is the process of outward diffusion of water vapor into the air surrounding a leaf through open stomata. This regulates leaf temperature. Heat is used in the internal cellular evaporative process, and diffusion of water vapor cools the air around and near the leaf. Diffusion of water vapor into the air also causes movement of more water and soluble nutrients from soil into the plant (Pallardy, 2008; Perry *et al.*, 2008; Cieslik *et al.* 2009). Most of the water in trees that is obtained from soil is released via stomatal diffusion to the air (Pallardy, 2008). Sunlight increases leaf temperatures, and trees can lose large volumes of water each day (Ellison *et al.*, 2017). Larcher (2003) estimated that, in general, temperate trees could lose 200–350 liters of water for every kilogram of biomass, while release from tropical trees could be as high as 600–900 liters. Atmospheric conditions near a leaf, such as temperature, relative humidity, wind speed, sunlight and resulting linked leaf warming, as well as carbon dioxide and ozone concentrations, can affect stomatal opening. Lack of available soil water and differing water demands by tree species are key factors regulating stomatal opening (Pallardy, 2008; Cieslik *et al.*, 2009; US Geological Survey, 2016). Partial or complete stomatal closure reduces demand for water from soil.

Perry *et al.* (2008) consider transpiration to be essential to the gas exchange process that leads to photosynthesis. Water vapor diffuses outward, and carbon dioxide diffuses inward, through open stomata. The water vapor diffuses more rapidly outward than carbon dioxide inward (Larcher, 2003). Water evaporation diffusion rates depend on the degree of opening (aperture) of the regulating stomatal guard cells. High leaf temperatures and/or optimal internal concentrations of carbon dioxide for photosynthesis can cause stomata to close to save water and thus reduce transpiration, soil water demand, and nearby air cooling (Pallardy, 2008; Cieslik *et al.*, 2009; Holtum and Winter, 2010).

Photosynthesis requires water loss through transpiration. Water-use efficiency (WUE) relates water loss from transpiration to carbon gain in photosynthesis (Keenan *et al.*, 2013; van der Sleen *et al.*, 2015). Increased WUE is key to the concept that increasing carbon dioxide will cause corresponding partial stomatal closure, resulting in increased WUE due to lower transpiration. This will allow sufficient internal carbon dioxide concentrations to maintain a high level of photosynthesis, resulting in increased biomass. On a global scale this is known as Earth greening, global greening, carbon dioxide fertilization effect, or other descriptors (Keenan *et al.*, 2013; Zeng *et al.*, 2017). Increased WUE in Northern Hemisphere temperate and boreal forests for the past two decades appeared to be a result of the carbon dioxide fertilization effect. Increases in WUE were related to increasing rates of photosynthesis and carbon sequestration and decreased evapotranspiration (Keenan *et al.*, 2013). Zeng *et al.* (2017) conducted an extensive review of the role of increased LAI and decrease in global albedo in Earth greening and global cooling. They concluded that LAI increase over a 30-year period caused a 0.09 °C decrease in global air temperature. Evapotranspiration was responsible for 70% and albedo for 6%. Increased LAI caused cooling in

Eurasia, India, Northwest Amazonia, and the Sahel, but not in North America and East Asia. All things considered, they concluded that global land warming had been reduced by 12% for the past 30 years. Increased growth in tropical forests has been attributed to stimulation by elevated carbon dioxide. Holtum and Winter (2010) concluded that increased growth in tropical forests may not be due to the effects of carbon-dioxide-caused increases alone, but also to carbon-dioxide-caused decreases in transpiration and increased soil water content. Van der Sleen *et al.* (2015) measured stable carbon isotopes and annual growth rings in 1,100 understory and canopy trees in tropical forests in Bolivia, Cameroon, and Thailand. WUE increased over the past 150 years for all trees measured, as carbon dioxide levels were also increasing. Analysis of tree growth rings did not reveal an increase in tree growth in relation to increasing carbon dioxide. They questioned the common assumption that elevated levels of carbon dioxide alone will stimulate the growth of tropical trees.

Transpiration from forests plays a major role in the world's hydrological cycles from atmospheric cooling to atmospheric recharge, rainfall, soil infiltration, plant water uptake and transpiration, groundwater recharge, and surface runoff. As much as 40% of rainfall over land may be attributable to water evaporation. Forests and hydrological cycles may be more effective in global cooling than photosynthesis and carbon sequestration (Ellison *et al.*, 2017). Water from rainfall that does not infiltrate soil instead runs off and may affect streams and rivers. Gedney *et al.* (2006) identified increases in water runoff on a continental basis in the twentieth century. Using a model to evaluate causes such as deforestation, global dimming, climate change, and elevated carbon dioxide, they concluded that the most likely cause was reduction of plant transpiration due to partial or complete stomatal closure caused by increasingly elevated carbon.

4.6.3 Ozone

Ozone is a secondary molecule that forms episodically in the atmosphere when the conditions are right for interactions of nitrogen dioxide (NO_2) and ultraviolet light in sunlight at warm temperatures. Ultraviolet light dissociates NO_2 to NO and an oxygen atom. The oxygen atom combines with an oxygen molecule (O_2) to form O_3, an unstable trivalent molecule which back reacts with NO and breaks down to reform NO_2 and O_2. Ozone cycles between formation and breakdown, and does not reach concentrations high enough to injure plants. This is background ozone, which may be 35–50 ppb in North America and Europe (Ainsworth *et al.*, 2012). Introduction of AVOCs and BVOCs into the cycle, especially isoprene from tree leaves, interferes with the extent of O_3 breakdown by NO, allowing more O_3 to rise to concentrations that can cause plant injury. Ozone now is an air pollutant. It occurs primarily during warm summer months, which unfortunately coincides with the growing season for trees. Ozone concentrations are often highest in late afternoons, especially if long-range transport from urban areas is a factor (Ainsworth *et al.*, 2012).

Ozone can be removed from the atmosphere by rain or by deposition to soil surfaces (Unger, 2012). Ozone can also make direct contact with leaf surfaces. Reactions can occur with surface cuticles and waxes over time, especially with persistent conifer leaves, resulting in changes in integrity that lead to leaking of cations and other soluble compounds, and possible foliar injury symptoms. Ozone makes contact with moist mesophyll cells in the substomatal cavity of a leaf, following inward stomatal diffusion during gas exchange. It elicits the formation of highly reactive oxygen species that cause cell injury. Ozone does not directly cause cell injury.

While diffusive conductances vary, stomata do not discriminate against inward diffusion of atmospheric gases. Ozone and carbon dioxide can both diffuse inward through stomata, while water vapor diffuses outward during transpiration. Stomatal aperture regulates diffusive conductance (Ainsworth *et al.*, 2012). Reich (1987) concluded that differences in innate leaf diffusive conductance rates could be used to quantitatively predict ozone uptake by stomata and resulting effects on plant growth and carbon assimilation. He predicted that in a growing season, agricultural crops would be most sensitive to ozone, followed by hardwood trees and conifers. Jolivet *et al.* (2016) proposed that combination of atmospheric ozone concentrations with estimated stomatal conductance rates would allow good estimates of the amount of ozone uptake by a plant. This would allow for more accurate determination of a dose/response function. In many experiments, dose/response for plant exposure to ozone has been determined by measuring plant effects in response to the concentration of ozone used multiplied by the duration of the exposure, which was considered to be the effective ozone dose, without determining diffusive conductance for ozone.

As a toxicant, ozone can reduce tree growth, net primary productivity, and carbon storage. Long-term or chronic exposure can result in priority for assimilate accumulation and use in leaves, buds, and stems, and reduction of allocation to stems and roots. Roots serve as storage areas for assimilate to be used for annual renewal of aboveground shoot growth, and reduction in root storage could initiate tree decline (Cooley and Manning, 1987).

To be an effective toxicant, ozone must diffuse into the substomatal cavity of a leaf to cause formation of reactive oxygen species at a high enough concentration to cause cell injury and affect tree growth, function, and carbon storage. Ozone diffuses via stomata to the substomatal cavity. Depending on inherent genetic tree constitution, stomatal aperture, ozone concentration, and rate and duration of diffusion, reactive oxygen species are induced, which can injure or kill membranes, cells, and enzymes like rubisco. Limitation of injury can be accomplished by defensive compounds like constitutive reductive apoplastic ascorbate and others, such as superoxide dismutase, glutathione, and phenolics. The entering ozone concentrations may be too high for complete prevention of toxic effects of reactive oxygen species by defense compounds, resulting in cell damage (Ainsworth *et al.* 2012; Jolivet *et al.*, 2016). In addition to foliar damage to leaves, photosynthesis, starch, and sucrose metabolism may be affected. On a

FIGURE 4.8 Black punctate stipple and chlorosis on older leaves of common milkweed (*Asclepias syriacus*), Sheffield, Massachusetts.
(A black and white version of this figure will appear in some formats. For the color version, please refer to the plate section.)

whole tree level, biomass, leaf area, and senescence may be affected. In a forest community, NPP may be reduced, and ozone-sensitive species may decline or be eliminated (Felser *et al.*, 2007; Ainsworth *et al.*, 2012).

Foliar ozone injury usually appears on leaves in mid to late summer. For deciduous tree leaves, it is evident first on the upper surface of older leaves. Injured areas do not cross veins. Injury symptoms can be considered to be acute or chronic. Acute injury results from periodic high ozone concentrations for a short time. Cell contents leak, and areas of epidermal cells may die, or individual or small groups of palisade parenchyma cells remain white or fill with black to red-brown pigments, creating a symptom called stipple, illustrated on leaves of milkweed (*Asclepias*) (Figure 4.8). Exposure to fluctuating low concentrations of ozone over time decreases photosynthesis by affecting chloroplasts, causing leaf chlorosis, illustrated on a leaf of Morning Glory (*Ipomea*) (Figure 4.9). Leaf bronzing from accumulation of phenolics and red-brown anthocyanins often results in premature senescence, illustrated on leaves of *Gaylussacia* (Figure 4.10).

FIGURE 4.9 Chlorosis on older morning glory leaves (*Ipomea purpurea* cv. Heavenly Blue), Amherst, Massachusetts.
(A black and white version of this figure will appear in some formats. For the color version, please refer to the plate section.)

FIGURE 4.10 Red-brown phenolic leaf pigmentation on leaves of black huckleberry (*Gaylussacia* spp.), Quabbin Reservoir, Massachusetts.
(A black and white version of this figure will appear in some formats. For the color version, please refer to the plate section.)

Given the episodic nature of ozone concentrations, it is possible to find both acute and chronic ozone injury symptoms on the same leaf. Chlorotic mottle on first-year and older leaves on conifers, especially pines, is a common symptom of ozone injury. Extensive injury may result in defoliation (Manning and Feder, 1980; Krupa and Manning, 1988).

4.6.3.1 Ozone and Trees

In the aftermath of World War II, there was a huge global upsurge in industrial development, power plant construction, new housing, trucks for commercial use, and personal cars. Inexpensive fossil fuels became readily available for power plants, home and commercial heating and cooling, and to power vehicles. Increased fuel consumption released oxides of nitrogen and AVOCs in ever-larger concentrations. The photochemical oxidant cycle began to form ozone at levels not experienced before. While it was suspected that human health was affected by ozone, it became obvious early on that trees were being affected by something. Ponderosa and Jeffrey pines in forests in the San Bernadino mountains in southern California were developing chlorotic mottling on needles that eventually led to extensive senescence by 1- to 2-year-old needles. Individual trees varied in the extent of chlorotic mottle and needle loss, with a few appearing unaffected (as illustrated in Figure 4.11). Chlorotic mottle was determined to be caused by high levels of ozone, transported there from Los Angeles, where it had formed. In addition to the effects of needle loss, affected trees became more susceptible to bark beetle infestations and root disease fungi, and began to die (Richards *et al.*, 1968; Miller *et al.*, 1997). This is the classic case of ozone-mediated forest decline (Figure 4.11). Significant ozone-influenced forest declines in other locations are described in Sanderman *et al.* (1997).

Later, ozone injury became apparent on forest trees in the eastern United States. This prompted numerous and continuing surveys of trees in regional areas for foliar ozone injury symptoms. Felzer *et al.* (2007) summarized results from surveys in the Southern Appalachian Mountains and the Mid-Atlantic Region. Conclusions were that black cherry and yellow poplar were the most sensitive, with red maple, loblolly pine, and northern red oak being intermediate, and red spruce the most tolerant. Results from surveys are useful indicators of air

FIGURE 4.11 Variation in ozone tree sensitivity in Ponderosa pine (*Pinus ponderosa*) and Jeffrey pine (*Pinus jeffreyi*) forest in the San Bernadino forest above the Los Angeles Basin, Southern California. (A black and white version of this figure will appear in some formats. For the color version, please refer to the plate section.)

quality for ozone. Correlations of foliar ozone injury symptoms with reductions in growth and carbon storage in a few instances for trees such as yellow poplar and loblolly pine have been reported, but this has not generally been the case (Felzer *et al.*, 2007).

Ozone injury occurs on leaves of trees in forests wherever conditions are appropriate for its formation. Symptoms occur on trees in central and southern Europe, often on tree species originally imported for forestry from the United States. Ozone injury on as many as 19 tree species occurs in Beijing (Wan *et al.*, 2014). Ozone injury on trees in remnants of the Southern Brazil Tropical Atlantic Forest, downwind of San Paulo, Brazil, is increasing (Moura *et al.*, 2018). The potential for ozone injury of trees in the Amazon Basin is indicated from aircraft measurements of ozone from 40 ppb to 60 ppb in the east and south during the dry–wet season. Precursors from biomass burning may be a contributing factor (Bela *et al.*, 2015).

Given the size, complexity, and climatic requirements of trees, there have been very few determinations of ambient ozone effects, under completely ambient conditions, on growth and carbon assimilation and storage in large, in situ trees. In their place, hundreds of short- and long-term experiments on predictive ozone effects on trees have been done with tree seedlings and saplings under varying degrees of controlled reductionist conditions, in indoor and outdoor chambers of various kinds, or in FACE systems. Extrapolation of results to ambient conditions and scaling up results to forest level may pose a challenge.

White pine (*Pinus strobus*) is native to much of the Eastern United States. Genetic differences in needle response to ambient ozone can be identified in natural stands. McLaughlin *et al.* (1982) used needle symptom conditions of 25-year-old white pine trees to select ozone-sensitive, intermediate, and tolerant trees for study near Oak Ridge, Tennessee. Growth ring analysis indicated a steady decline for the sensitive trees of 70% over 15 years, while the other categories were similar to each other. Respiration rate compared to photosynthesis was higher in sensitive trees. Photosynthate accumulated preferentially in foliage and branches, with less going to stems and roots, as determined by tracking ^{14}C. Decline of sensitive trees was explained by needle loss, increased respiration, and altered translocation induced by ozone.

Bartholomay *et al.* (1997) examined radial growth rates for eight stands of white pine in Acadia National Park in Maine. Negative associations between ozone and tree core results were found for seven of the eight stands. Associations with tree core results were stronger for ozone than for associations with climate. Twenty-eight mature loblolly pines (*Pinus taeda*) were used for 5 years by McLaughlin and Downing (1995) to investigate interactive effects of ozone (40 ppb), low soil moisture, and high air temperatures on short-term stem expansion, using dendrochronometer bands. They concluded that annual radial growth was inversely related to low soil moisture and ozone.

4.6.3.2 Present and Future Ozone

There is considerable interest in determining present ozone levels and predicting future levels. Conclusions from a meta-analysis indicate that present ozone concentrations ranging from 20 ppb to 65 ppb, with an average of 40 ppb, are found in the Northern Hemisphere. These ozone levels have been concluded to be likely to reduce the current forest carbon sink, and higher future ozone levels will increase this effect (Wittig *et al.*, 2009). Reduction in precursors nitrogen dioxide and AVOCs has reduced the number of episodic high ozone concentration events. More frequent current lower ozone levels cause more chronic than acute ozone injury. Models predict, however, that if precursor levels increase, ozone could increase to 68–70 ppb (Sanderson *et al.*, 2007; Sitch *et al.*, 2007; Wittig *et al.*, 2009; Klingberg *et al.*, 2011). Long-range transport of ozone and ozone precursors from Asia, particularly China, affects ozone levels in the United States and Europe (Wittig *et al.*, 2009).

Models predicting ozone effects on carbon sequestration by forests assume a certain level of uniformity in terms of genetic composition of species, size, age, and sensitivity to ozone. Wang *et al.* (2016) feel that this can lead to misleading results and conclusions, especially for deciduous forests. They propose that there are ozone-sensitive and ozone-tolerant individuals within the tree species that constitute the forest community. A possible example of differential responses of ponderosa pines (*Pinus ponderosa*) and Jeffrey pines (*P. jeffreyi*) to ozone in a forest in the San Bernadino mountains in Souhern California is shown in Figure 4.11. Ozone may select for ozone-tolerant trees and diminish ozone-sensitive trees. Their results suggest that the ozone-tolerant trees may not be negatively affected by ozone, and if they dominate the forest, ozone may not reduce the capacity of the forest to assimilate and sequester carbon from carbon dioxide. This may, however, result in increased isoprene emissions from trees that may tolerate ozone exposure better. This could result in an increase in atmospheric ozone, which would constitute a positive feedback from the forest.

4.6.4 Ozone and Carbon Dioxide Interactions

Ozone and carbon dioxide can occur together in the atmosphere. Diffusion into stomata depends on external concentrations. Elevated concentrations of each can reduce stomatal aperture or close stomata completely, reducing or eliminating uptake and photosynthesis or cellular ozone injury. Stomatal closure induced by elevated carbon dioxide can prevent ozone diffusion (Sitch *et al.*, 2007). As a result, ozone levels might stay the same or decrease in central and southern Europe (Klingberg *et al.*, 2011). If extensive ozone diffusion is successful, ozone-caused reduction of NPP in forests may result in an increase in carbon dioxide in the atmosphere that could result in indirect radiative forcing (Unger, 2012).

It is widely assumed that continuing rising levels of carbon dioxide will reduce the effects of ozone on plants by reducing stomatal aperture or closing stomata. This was tested most extensively in the field in the world's largest experiment on elevated carbon dioxide and ozone on growth and productivity of young forest trees, an 11-year-long experiment in the AspenFACE facility near Rhinelander, Wisconsin, USA. Uddling *et al.* (2010) determined stomatal flux rates for canopy and sun leaves of aspen and birch during long-term exposure to ambient and elevated concentrations of ozone, carbon dioxide, or both. Accumulated stomatal flux data indicated that stomatal flux was not reduced by elevated carbon dioxide. Stomatal flux rates were higher for aspen than for birch.

In long-term experiments with ambient and elevated ozone and carbon dioxide and combined exposures in the AspenFACE facility, ozone as low as 1.5 times ambient offset or moderated elevated carbon-dioxide-induced growth in aspen, aspen/birch, and aspen/maple plots. Ozone completely offset growth enhancement for both ozone-sensitive and ozone-tolerant aspen clones (Karnosky *et al.*, 2003). Later evaluation of the aspen, aspen/birch, and aspen/maple FACE plots indicated differences in the effects of elevated carbon dioxide, elevated ozone, and a combination of both on tree biomass.

Elevated carbon dioxide increased biomass by 25% for aspen, 45% for aspen/birch, and 60% for aspen/maple. Elevated ozone reduced biomass by 24% for aspen, 13% for aspen/birch, and 14% for aspen/maple. Elevated carbon dioxide and elevated ozone reduced biomass for aspen by 7.8%, increased biomass for aspen/birch by 8.4%, and increased biomass for aspen/maple by 24.3% (King *et al.*, 2005). These results indicate that under these circumstances, elevated carbon dioxide effects on reducing ozone injury are species-specific and range from incomplete to partial. The role of elevated carbon dioxide in reducing ozone effects on trees in a forest requires further investigation.

4.7 SUMMARY AND TRANSITION

Biogeochemical and biophysical factors were considered separately here. How they interact affects physiology, growth, biomass accumulation, and carbon storage by trees. How trees grow and function determines how effective they can be in cooling the atmosphere. Fixing carbon from carbon dioxide in photosynthesis provides removal, storage, and potential cooling. This is a negative climate forcing process. Photosynthesis is affected by light intensity, air temperature, carbon dioxide, soil water and nutrients, and vapor pressure deficit. Carbon gain in photosynthesis is offset by respiration. Light reflection (albedo) by darker-colored forests, especially conifers, is low, resulting in a warming effect. Transpiration and photosynthesis occur together. Transpiration from a forest can cool the air. Partial stomatal closure by elevated carbon dioxide reduces soil water uptake and transpiration, and is largely responsible for increased biomass. Decreased transpiration results in reduced air cooling, which can be a positive climate forcing process, increasing air temperature. Trees emit isoprene and other BVOCs. Together with AVOCs from combustion, these can increase production of ozone in the photochemical oxidant cycle. Ozone can reduce tree growth and carbon storage. It is also a reradiative or greenhouse gas, contributing to air warming.

BVOCs and AVOCs also influence cloud formation and aerosol formation, which can result in either air warming or cooling.

Tree responses to a continually warming world is considered in the next chapter. Warmer days and nights, and drought, are affecting the ways that trees and forests function. Phenology, leaf longevity, photosynthesis, respiration, and evapotranspiration are affected. Forest fires are increasing as are incidences of insect pests and diseases. Deforestation continues at a record rate.

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5 Trees in a Warming World

> Based on our projected densities, we estimate that over 15 billion trees are cut down each year, and the global number of trees has fallen by approximately 46% since the start of human civilization.
>
> Crowther *et al.*, 2015

> Deforestation in the tropics is not only responsible for direct carbon emissions but also extends the forest edge where trees suffer increased mortality. Fragmentation substantially augments carbon emissions from tropical forests.
>
> Brinck *et al.*, 2017

5.1 INTRODUCTION

In Chapter 4, interactive biogeochemical and biophysical factors that affect tree function in relation to atmospheric cooling and warming were considered. Biogeochemical factors include photosynthesis and biogenic hydrocarbons. Biophysical factors include albedo, evapotranspiration, and ozone. How growth, photosynthesis, transpiration, and ozone affect trees due to increasing changes in atmospheric temperature and composition will be considered here.

Trees establish and exist in place. Their success is determined by how well they continually adapt to their variable immediate environment through morphological and physiological changes. The environment changes the expression of the tree's genotype, which makes appropriate changes possible. This inherent ability is called phenotypic plasticity (Bradshaw, 1965). Adaptation lies within ranges for factors such as light, carbon dioxide, temperature, water, nutrition, ozone, and herbivory. A warmer, drier environment may make further adaptation difficult and result in genetic maladaptation (Frank *et al.*, 2017). The climate is getting warmer and affecting the adaptation of trees to their environment. The growing season is getting longer and warmer (Linderholm *et al.*, 2006; Penuelas *et al.*, 2009); spring is coming sooner and winter starting later. Warmer temperatures and a longer growing season are often accompanied by increasing aridity, which is affecting adaptation of forests worldwide. Tree declines, caused by warmer temperatures and drought, with secondary stressors such as wildfires, insects, pathogens, and ozone, are increasing (Allen *et al.*, 2015; Trumbore *et al.*, 2015; Clark *et al.*, 2016; Li *et al.*, 2017). This is reducing carbon dioxide sequestration, transpiration, and air cooling, and affecting the hydrological cycle. Deforestation for land clearing for agriculture, industry, and housing is accelerating to meet the needs of an ever-increasing world population (Hansen *et al.*, 2013; Crowther *et al.*, 2015; Lewis *et al.*, 2015). In addition to removing trees that fix carbon, burning, logging and land clearing of biomass and debris, and decomposition of plant remains result in substantial releases of carbon dioxide to the atmosphere (van der Werf *et al.*, 2009).

5.2 FOREST DECLINE AND LOSS

Keeling *et al.* (1996) concluded that increased summer concentrations of carbon dioxide in the Northern Hemisphere caused increased vegetative growth, indicating an increased sink for carbon dioxide. Since then, many satellite observations, forest inventory data, and models have been used to estimate increased GPP (global greening) for all vegetation (Pan *et al.*, 2011; Zhu *et al.*, 2016; Campbell *et al.*, 2017) and trees (Fang *et al.*, 2014). Zhu *et al.* (2016) used global satellite observations and models to determine growing-season increases in greening (LAI) for 25– 50% of all global vegetation areas. Less than 4% of all global vegetation surveyed showed as "browning," a decrease in LAI. The massive amounts of global deforestation and dead and dying trees that have been occurring, and continue to occur, did not seem to appear in their results. Hansen *et al.* (2013), however, were able to use high-resolution satellite imagery to construct maps to show where worldwide forest losses were occurring.

5.2.1 Deforestation

Using 429,775 ground measurements of tree density and generated regression models, Crowther *et al.* (2015) completed the first complete global map of the density of the world's forests. They estimate that there are 3.04 trillion trees in the world. Approximately 1.30 trillion are in tropical and subtropical forests, 0.74 trillion in boreal-region forests and 0.61 trillion in temperate-region forests. The total number of global trees has been reduced by approximately 46% since the beginning of human civilization. They estimate that from the total of 3.04 trillion trees worldwide, 15 billion trees are removed each year. Hansen *et al.* (2013) used high-resolution satellite data to map global forest loss for the Earth from 2000 to 2012. They estimated a loss of 2.3 million square kilometers and a gain of 0.8 million square kilometers. In the tropics, loss was increasing by 2,101 km^2 per year. Forest loss is increasing in Indonesia, Malayasia, Paraguay, Bolivia, Zambia, and Angola. Some reduction in the rate of rainforest clearing in Brazil was noted. The highest loss to gain ratio (where "gain" means reforestation), due to land-use change and forest harvest, was observed in subtropical areas. In the temperate domain, increased fires, beetles, disease, and logging resulted in high loss. Logging and fire and slow tree regrowth are very significant factors in deforestation in boreal forests. Loss to gain can be high, especially in Russia.

Land-use changes can make reforestation difficult or impossible. Lewis *et al.* (2015) examined land-use changes in tropical forest areas (an example of a newly cleared area in Brazil is shown in Figure 5.1). Forests are being converted to agricultural land to grow crops and pasture to graze beef cattle. From 1960 to 2012, approximately 100 million hectares of tropical forests were deforested for agriculture, especially for soybeans, corn, avocados, bananas, citrus, and palm trees for oil. Selective logging also occurs for valuable wood, such as teak. They assessed the condition of tropical forests as being 24% intact, 46% fragmented, and 30% generally degraded. The World Wildlife Fund (Schwartz, 2015) has identified 11 regions where the greatest forest losses can be expected by 2030. A 25% loss in forests in the Amazon is predicted as clearing progresses for agriculture and cattle pasture. Only 33% of forests in Borneo will remain, owing

FIGURE 5.1 Deforestation and edge effects, Amazon, Brazil.
(A black and white version of this figure will appear in some formats. For the color version, please refer to the plate section.)
Credit: luoman / E+ / Getty Images

primarily to clearing for palm oil production. Forests in the Cerrado region of Brazil will be cleared for soybean culture and cattle pasture. Forest clearing for power lines, mining, oil production, and roads will reduce forests in the Pacific Northwest of South America. East African forests will continue to be removed for cash crops for export and livestock. Land converted from forest in Eastern Australia will be changed to pasture for livestock. In the Greater Mekong, forests are removed for rice, sugar, rubber, and biofuels culture. Forest loss for agriculture continues in New Guinea. Land clearing for palm oil plantations continues in Sumatra. Harvesting wood and biomass, from natural and plantation forests, for firewood and wood pellet production in the United States and elsewhere, for domestic use and export, is expanding dramatically. Much has been written promoting this as a carbon-neutral fuel source, but the energy used to harvest, process, and transport firewood and pellets negates this neutrality. Fixed carbon is lost in combustion and from harvest debris. New

FIGURE 5.2 Deforestation, Amazon, Brazil.
(A black and white version of this figure will appear in some formats. For the color version, please refer to the plate section.)
Credit: luoman / E+ / Getty Images

replacement seedlings or saplings will take many years to replace woody biomass. Purpose-planted plantation trees store less carbon than natural forest trees (Schlesinger, 2018). In Africa, South America, and parts of Asia, rapidly increasing production of charcoal for cooking is widely degrading forests, with increasing populations driving demand. Even trees in reserved areas are being cut and burned (Sedano *et al.*, 2016). Burning wood for charcoal releases carbon dioxide and toxic compounds from incomplete combustion. Forest deforestation for many reasons is increasing and will continue to decrease the carbon sink capacity of the world's forests.

5.2.2 Forest Fragmentation

Intact forests all over the world, especially in the tropics, are being fragmented as part of global deforestation. Loss of tree biomass during fragment and edge formation results in additional release of carbon dioxide and reduction in transpiration. Creation of an edge effect is illustrated in Figure 5.2. Using remote sensing, Taubert *et al.* (2018) found that there are 130 million forest fragments distributed over three continents. They suggest that the rate of fragmentation will increase in the future.

Brinck *et al.* (2017) used high-resolution satellite maps to examine the condition of tropical forests. They estimated that there are 50 million forest fragments, and that across all tropical forests, 19% of intact forests were 100 m from a forest edge. Edge effects were concluded to cause 31% of estimated annual carbon dioxide release from deforestation of tropical forests. Trees along edges are exposed to a different environment than when they were in forests. Increased tree mortality may be due to increased wind speed, changes in vapor pressure deficit, and greater exposure to human contact and disturbances (Brinck *et al.*, 2017). Tree mortality is higher along forest edges. More large trees die, opening space for rapidly growing species that are not long-lived (Laurance *et al.*, 2000). Putz *et al.* (2014), using remote sensing analysis, investigated long-term carbon loss from fragmentation and resulting forest edges for neotropical forests within the next 10 years (2014–2024). They estimated a loss of 69 Tg (1 teragram =1 million metric tonnes CO_2 equivalents) for Brazilian Atlantic Forest and 599 Tg for the Amazon, as a result of forest fragmentation alone. Estimates of emissions for all tropical forests were 0.2 Pg (petagram or gigatonne = 1 billion metric tonnes CO_2 equivalents) per year, or 9–24% of annual carbon loss from deforestation.

5.2.3 Forest Growth Decline

Forest growth declines are becoming evident in several parts of the world. Decreasing forest growth is considered to be caused by various physical and biotic stress factors that lead to reduction in forest tree canopy and cover, and that may result in an increase in tree decline and mortality. Mortality rates that occur exceed those that are considered typical for an area (Cohen *et al.*, 2016).

An example of this was the sudden and widespread decline of aspen (*Populus tremuloides*) that began in southwestern Colorado in 2004. Tree crowns died back, or trees died. Warming temperature and water shortage appeared to be the cause (Worrall *et al.*, 2010). Slow growth declines that do not result in mortality also occur. These are often determined by evaluating measurements of trees in forests or comparisons with past forest inventory data.

Zimmermann *et al.* (2015) used tree ring analysis (dendrochronology) to determine radial growth of European beech (*Fagus sylvatica*), sycamore maple (*Acer pseudoplatanus*), Norway maple (*A. platanoides*), sessile oak (*Quercus petrae*), and European ash (*Fraxinus excelsior*) growing along a precipitation gradient in three mixed forests. Radial growth was reduced in the driest stand for *F. sylvatica* since approximately 1980, but not for the other four species. Using forest survey data in California, McIntire *et al.* (2015) found that between the 1930s and 2000s, tree density increased by 30%. Basal area, however, was reduced by 19%. This was due to a decline in larger trees and greater incidence of smaller trees, especially in drier areas. Forest composition also changed during that period, with oak (*Quercus*) species increasing and dominating, and pine (*Pinus*) species declining. Nabuurs *et al.* (2013) examined stem volume increment data for all of Europe between 2005 and 2010. He concluded that total stem volume had decreased and that this could be an early indication of a decrease in the forest tree carbon sink for Europe. Cohen *et al.* (2016) used Landsat data to determine forest disturbance and decline in forests in the United States from 1985 to 2012. They concluded that forest decline increased extensively in forests in the Mountain West and lowland west, attributing this to large increases in climate-related stress and secondary stress (insects, pathogens, fire). Liu *et al.* (2013) reported extensive tree decline in semi-arid forests in inner Asia since 1994, due to warmer temperatures, a longer growing season, and increasing water stress. Brienen *et al.* (2015) evaluated tree growth measurements for three decades obtained from 321 long-term plots in the Amazon. A long-term one-third decline in carbon sequestration was identified since the 1990s. Growth rates are levelling off and mortality is increasing, possibly owing to shortened tree longevity related to climate variability.

5.2.4 Case Study of a Forest Decline due to Disease

It is evident that forest growth declines do not have a single cause. Reductionist approaches that consider only a primary environmental factor, without inclusion of what are often considered secondary or interacting biotic factors, such as insect herbivory, plant disease, and fire, will not present a clear or complete causal result. There are examples where an inclusive analysis was done, and one is presented here. Wong and Daniels (2017) have analyzed the findings from their study of the long-term decline of whitebark pine (*Pinus albicaulis*) in the southern Canadian Rocky Mountains. They used tree ring analysis to determine rates of long-term tree growth. Prior to the 1940s, tree growth was limited by cool temperatures. They found that tree decline began in the late 1940s. Between 1947 and 1976, drought limited the growth of healthy trees. During this time, drought stress may have enabled a non-native blister rust fungus (*Cronartium ribicola*) to infect trees. Later, declining snowpack, resulting warming temperatures, and blister rust infections may have weakened tree resistance to bark beetles (*Dendroctonus ponderosae* and *Ips* species). The trees were killed by a combination of climate, blister rust, and bark beetles.

5.2.5 Endangered Species

A number of tree species appear to be at risk for survival under forest conditions. Habitat degradation, deforestation, warming, drought, herbivory, and disease and other factors can lead to decline and eventual extinction. The International Union for Conservation of Nature (IUCN) is an international organization that determines the endangered status of species, including trees. They publish Red Lists from time to time (Newton and Oldfield, 2008). They list trees as: critically endangered – extremely high risk of extinction in the wild; endangered – very high risk of extinction; and vulnerable – high risk of extinction. Forest trees on the Red List include: ash (four to five species of *Fraxinus*), coast redwood (*Sequoia sempervirens*), Fraser fir (*Abies fraseri*), giant redwood (*Sequoiadendron giganteum*), longleaf pine (*Pinus palustris*), Port Orford cedar (*Chamaecyparis lawsoniana*), and Serbian spruce (*Picea omorika*). Using IUCN Red List criteria for determination of endangered species, ter Steege *et al.* (2015) evaluated 15,000 species and concluded that at least 36% and possibly as many as 57% of all of the tree species in the Amazon were endangered. Some species will likely persist in protected forest areas and some in areas where indigenous people live and there is less forest disturbance.

5.2.6 Invasive Species

Insects and pathogens have co-evolved with forest trees and are associated with them. Understory plants are also characteristic of different forest types. As world commerce and travel increased, non-native insects, pathogens, and plants from other parts of the world were inadvertently introduced to forests. Lacking co-evolution with the local trees, and biological factors reducing their impact in their native locales, introduced or alien species can become invasive and cause extensive damage and decline of native forests. There are very many examples of the effects of introduced invasive species in forests. Some are given here.

Three non-native forest tree pathogens were introduced to North America in the early twentieth century. Introduction of the chestnut blight fungus (*Cryphonectria parasitica*) from Asia resulted in the elimination of a dominant forest tree, the American chestnut (*Castanea dentata*), from Eastern North American forests. *C. parasitica* is still present and active in forests, preventing any chestnut tree regeneration. Disseminated during beetle feeding, the Dutch Elm disease fungus (*Ophiostoma novo-ulmi*) eliminated most elm (*Ulmus americana*) trees in Europe and the United States. *O. novo-ulmi* is still present and reduces elm regeneration. The white pine blister rust fungus was imported from Europe to North America and remains a disease of white pine (*Pinus strobus*). The introduced fungal pathogen *Hymenoscyphus fraxinenses* was found causing leaf blight and branch dieback of European ash (*Fraxinus excelsior*) in Poland in the 1990s. It has rapidly spread throughout Europe and raised concern about possible extinction of European ash (Pautasso *et al.*, 2013). Movement of infected nursery stock between countries and regions aids in pathogen dissemination.

One of the oldest and most well-known and successful forest invading insects is the gypsy moth (*Lymantria dispar*) from Europe. Following accidental release, it spread rapidly and continues to cause periodic extensive outbreaks, especially on oak trees. The wooly adelgid (*Adelges tsugae*) was introduced from Japan and causes extensive losses to hemlock (*Tsuga canadensis*). Fraser fir (*Abies fraseri*) is on the IUCN Red List of endangered species because of susceptibility to *A. tsugae*. Mech *et al.* (2018) report that higher summer temperatures can reduce survival of the dormant stage of *A. tsugae*. The emerald ash borer (*Agrillus planipennis*) from Asia is active in Europe and more recently in the United States. It causes dieback and death of all ash species. The Asian longhorned beetle (*Anoplophora glabripennis*) recently arrived in the United States, primarily in New England and the Midwest. Hardwood deciduous trees, especially maples, are destroyed.

Insects move easily or can be moved easily from place to place by air currents, and especially in wood and wood products. It has been proposed that warming temperatures will increase insect activity and ranges.

Invasive trees, shrubs, and grasses can invade forests and colonize burned or denuded forest areas. Forest fragment edges and adjacent interiors and roadsides often serve as entry points for invasive species entry (Yates *et al.*, 2004). Some trees introduced to new areas for ornamental purposes or as potential new forest species can become invasive. Black cherry (*Prunus serotina*), a forest tree in North America, was imported into Europe as an ornamental tree and a potential addition to European forestry. It has become a common invader of European forests. It forms single-species stands and alters soil fertility to its advantage to exclude native tree species (Aerts *et al.*, 2017).

The shrubs multiflora rose (*Rosa multiflora*), honeysuckle (*Lonicera japonica*), and eleagnus (*Eleagnus umbellata*) are common invaders of forest edges and disturbed or new forest areas (Yates *et al.*, 2004; Meiners, 2007). Meiners (2007) found indirect effects of invasive multiflora rose and *Lonicera maackii*. Seed predators associated with the invasive species decreased tree seed germination and establishment of seedlings under invaders' canopies. Burned black spruce areas in Alaska were colonized by more non-native than local plants (Spellman *et al.*, 2014). While not alien or non-native species, aggressive perennial vines are invading open disturbed areas and developing young forests in tropical forests in the Amazon. Vines can reach the tops of tree canopies and reduce sunlight. Reduction in biomass and carbon content for trees colonized by vines may be as high as 20% (Schnitzer *et al.*, 2014; McDowell *et al.*, 2018). Alien vines, imported to North America as ornamental plants, have spread to forest areas where they pull down small trees and cover taller trees. In the northeast United States, oriental bittersweet (*Celastrus scandens*) and porcelain berry vine (*Ampelopsis pedunculata*) are rampant and widely invasive. Some forests in North America and Europe are being invaded by native and non-native perennial grass species. This alters soil fertility and soil carbon, and may affect tree seed germination and seedling success (Strickland *et al.*, 2010). The non-native grass *Microstegium vimineum* was able to colonize within closed canopies in shade (Huebner, 2010). Invasive plants that are shade-tolerant might be able to successfully invade interiors of closed canopy forests. Asner *et al.* (2008) used remote sensing to survey 221,875 hectares of Hawaiian rainforests. They concluded that non-native plant species were changing the structure of the forests. Native tree species were being replaced by five invasive species. With a warming climate, the role of non-native plant species invasions may be expected to increase in importance.

5.2.7 Tree Species Distribution and Range Shifts

A warming and often drier climate requires trees and forests to adapt to their local environmental conditions. Tree populations with specific requirements, and little genetic variation, may decline in growth and in seed formation and dispersal, in response to climatic changes, resulting in genetic maladaptation (Aitken *et al.*, 2007; Frank *et al.*, 2017). Representatives from 77–92 local populations of Norway spruce (*Picea abies*), silver fir (*Abies alba*) and European beech (*Fagus sylvatica*), from all over Switzerland, were grown in a common garden experiment. Cumulative data was obtained for growth rates, phenology, and genetic variation. The conclusion was that by the end of this century, genetic maladaptation may only affect beech and spruce (Frank *et al.*, 2017).

Numerous models predict extensive shifts in northern latitudinal range and tree species redistribution within this century (Aitken *et al.*, 2007; Coops and Waring, 2011; Boisvert-Marsh *et al.*, 2014; Fei *et al.*, 2017). Environmental factors include temperature, soil moisture, and photoperiod. Successful adaptation and migration develops along the northern edges of populations that may slowly shift northward (Aitken *et al.*, 2007; Boisvert-Marsh *et al.*, 2014; Fei *et al.*, 2017). The southern end of the ranges may contract. It has been suggested that in future, the species composition of New England forests will resemble those of current forests in Pennsylvania. Trees such as sugar maple (*Acer saccharum*) may shift to Quebec, Canada. The temperature increases from warming can be higher at high altitudes.

Boisvert-Marsh *et al.* (2014) used models to predict temperature effects on latitudinal shifts for 11 tree species from northern temperate and boreal forests from 1970 to 2002. Northern migration was by young trees on the leading northward edges of species ranges. Northern migration was noted for red maple (*Acer rubrum*), sugar maple (*A. saccharum*), white birch (*Betula papyrifera*), and aspen (*Populus tremuloides*). Southern migration occurred for balsam fir (*Abies balsamea*), white spruce (*Picea glauca*) and black spruce (*P. mariana*). Tree species may also shift range edges laterally as well as vertically. Examination of range edge changes for 86 tree species, during the last 30 years in the eastern United States, indicated that more tree species shifted westward than north (poleward). Most were deciduous species. Available soil moisture was considered to be more important than temperature (Fei *et al.*, 2017).

There is considerable interest in using models to predict tree vulnerability to climate warming. Coops and Waring (2011) used models to predict the vulnerability of 15 forest tree species within their ranges in the northwest United States. Their baseline for comparison was cool weather climate beween 1950 and 1975. Most models were run between 1976 and 2006. They defined and mapped the present distribution of each tree species based on how drought, day temperatures, high evaporation rates, and incidence and frequency of frost affected photosynthesis. This enabled them to determine areas that would remain suitable for each species and those where they would be vulnerable. They concluded that 70% of the species would remain in suitable areas, while 30% would be vulnerable. Vulnerable trees included grand fir (*Abies grandis*), noble fir (*A. procera*), lodgepole pine (*Pinus contorta*) and ponderosa pine (*P. ponderosa*). Using model predictions, Hamann and Wang (2006) predicted that trees at their northern range limits in British Columbia, Canada, would advance their range at approximately 100 km per decade. They expressed concern that important conifer species in sub-boreal and montane regions might disappear. Dyderski *et al.* (2017) used three climate change scenario models to predict future distribution and success for common European tree species from 2061–2080. Winners were considered to be mostly late successional species. They included: white fir (*A. alba*), beech (*Fagus sylvatica*), European ash (*Fraxinus sylvatica*), English oak (*Quercus robur*), and sessile oak (*Q. petrae*). Introduced alien species from North America were also considered to be winners. They included Douglas fir (*Pseudotsuga menziesii*), red oak (*Q. rubra*), and black locust (*Robinia pseudoacacia*). Losers were early pioneer species. They included: white birch (*Pendula pendula*), larch (*Larix decidua*), Norway spruce (*Picea abies*), and white pine (*Pinus strobus*), an alien from North America.

5.3 ENVIRONMENTAL AND BIOTIC FACTORS AFFECTING FOREST DECLINE AND LOSS

Many environmental and biotic factors, such as drought, bark beetles, and fires, cause forest disturbances and forest decline and loss. Increasing temperature in a warming climate is a key interacting or driving factor, and its influence continues to increase. Sommerfeld *et al.* (2018) concluded that increasing forest disturbance is caused by warming and drying conditions that exceed global averages. Warming interacts in various ways with and influences all of the forest decline factors given separately here. The following quote from Neumann *et al.* (2017) is appropriate here, as it summarizes the current state of knowledge about why trees die: "Tree death remains one of the least understood process of forest dynamics."

5.3.1 Drought

Drought, influenced by temperature, causes increasing, large-scale, unprecedented worldwide forest tree deaths (Adams *et al.*, 2009; Allen *et al.*, 2015; Doughty *et al.*, 2015; Greenwood *et al.*, 2017; Penuelas *et al.*, 2017). Warmer temperatures may not cause drought directly, but it is likely to occur faster and be more severe at higher temperatures (Trenberth *et al.*, 2014; Allen *et al.*, 2015). Tree mortality caused by drought, enhanced by warmer temperatures, reduces photosynthesis and the uptake and sequestration of carbon, reduces transpiration and air cooling, and affects the hydrological cycle (Bonan, 2008; Doughty *et al.*, 2015). Drought-caused tree mortality is continuing and is expected to increase worldwide (Peng *et al.*, 2011; Trenberth *et al.*, 2014; Bennett *et al.*, 2015; Neumann *et al.*, 2017). Peng *et al.* (2011) project future annual rates of mortality in Canadian boreal forests.

Drought occurs when transpiration rates exceed available soil water. Decreased rates of precipitation and the resulting decrease in available soil water, together with warming temperatures, can cause either chronic or sudden tree death. Neumann *et al.* (2017) concluded that warmer summers and variable rates of precipitation were causing tree mortality across Europe. Adams *et al.* (2009) proposed two mechanisms to explain the incidence of drought-caused tree mortality: carbon starvation in response to temperature and a period of prolonged water stress; or sudden death not affected by temperature, but due to rapid failure from extreme lack of water. They explored the effects of exposure of seedlings of pinyon shortened pine (*Pinus edulis*) seedlings to warmer temperature (4 °C above ambient) on drought-caused mortality. Time for drought mortality to occur was one-third faster than for the ambient control. Higher respiration rates over time for seedlings in the warming treatment indicated that carbon starvation was the cause of increased mortality. Large forest trees may be more susceptible to hydraulic water stress and drought than smaller trees. Bennett *et al.* (2015) consider that older trees play an important role in forest structure and function. Cieslik *et al.* (2009) proposed that leaves regulate their internal temperatures through transpiration by opening their stomates, which allows water vapor to diffuse outward. This promotes cooling, which protects leaves from high-temperature injury. Under moisture stress conditions and high air temperatures, stomata tend to close to prevent water loss. Internal leaf temperature may increase, and severe leaf injury and defoliation may result, hastening tree decline and death. Anderegg *et al.* (2018) found that differences in hydraulic conductance rates for trees in temperate and boreal forests affected the buffering of forest ecosystem response and resilience to drought. Specific leaf area and wood density were not predictors of drought response.

Tree mortality due to drought has been occurring with regularity over wide areas of the western United States. Deaths of conifers of all ages and types have doubled compared to past decades (van Mantgem *et al.*, 2009). A survey in 2016 revealed that more than a million trees had been killed by drought in California. Between 2010 and 2016, 7.7 million acres of forests were affected by drought. Millions more affected trees were expected to decline and die slowly. This increases the risk of wildfires considerably (US Forest Service, 2016).

There is much interest in the incidence and significance of drought in tropical forests in the Amazon Region. Drought occurs there periodically, but the effects of two huge droughts in 2005 and again in 2010 are of particular significance. Millions of trees were killed by both episodes. Extensive increases in release of carbon dioxide occurred after the 2005 drought. Tree mortality continued between the 2005 and 2010 droughts (Doughty *et al.*, 2015; Feldpausch *et al.*, 2016). Fires also burned 12% and 5% of trees in the southeast Amazon forests in 2005 and 2010, respectively (Brando *et al.*, 2014). Doughty *et al.* (2015) have observed that currently trees in the Amazon are growing and dying faster, with faster death than growth rates. They estimate that rate of carbon dioxide uptake is now less than it was in the 1990s. Fu *et al.* (2013) related the length of drying season in the South Amazon to increased risk for tree dieback and susceptibility to fire. They concluded that the longer the dry season, the greater the risk. Length of the wet season was not a factor.

Forest trees in temperate climate zones may experience low-level chronic water stress. The effects of this stress are not well known. In the United States, this is most likely to occur in deciduous forests in the eastern and midwest regions. Trees that are affected by chronic water stress are called mesophytic species (Brzostek *et al.*, 2014). Chronic water stress was estimated to reduce the carbon sink of a forest in Indiana by 17%. Wood and plant biomass production was reduced by 41%. Such reductions would reduce the ability of chronically water-stressed trees to reduce global warming and climate change. Zhang *et al.* (2018) examined forest tree inventories for the eastern United States from the 1980s to the 2000s and concluded that long-term soil water deficits reduced overall forest biomass and changed forest species composition by favoring establishment of drought-tolerant species with slower growth rates. Drought-tolerant trees usually store more carbon in fine root systems and less in leaves, branches, and wood. Slower growth rates result in lower uptake and storage of carbon. Abrams and Nowacki (2016) found considerable variability in 22 eastern North American tree genera in terms of temperature range, shade tolerance, drought tolerance, and longevity. High-level subalpine regions may experience periodic soil moisture deficits that may inhibit establishment of tree seedlings (Andrus *et al.*, 2018). This occurs in the United States in the Colorado Front Range of the Rocky Mountains. Snowpack has declined during the past 40 years, and summers have become drier. It has only been possible in 3 of the past 40 years for seedlings of Engelmann spruce to become established.

5.3.2 Warming

Increasing atmospheric warming and carbon dioxide may not continue to increase tree growth. Temperature interactions with other environmental and biotic factors might reduce biomass growth of forest trees, lower their carbon sink, and result in some negative climate feedback from forests. Acclimation to higher temperatures could reduce possible negative climate feedback. Determination of tree responses to higher temperatures will help to determine the extent of acclimation. Oren and Way (2010) examined data for tree growth (shoot height, stem diameter, and biomass) in relation to temperature from 63 reports in the literature, using a meta-analysis. They determined how trees responded to temperature in relation to functional groupings. They decided that growth responses were stronger for deciduous trees than for evergreen trees. Temperature increases affected tropical tree species more than temperate and boreal species. Adaptation to higher temperatures could be possible by respiration acclimation. Respiration acclimation was stronger than photosynthetic acclimation. High-altitude trees might benefit from warming. Boisvert-Marsh *et al.* (2014) indicated that warming at high altitudes is increasing, and that there is evidence of species adaptation and movement.

Aspinwall *et al.* (2016) investigated the role of temperature acclimation in the gum tree *Eucalyptus tereticornis* in whole-tree field chambers. Trees were exposed to either ambient air temperature or ambient plus 3 °C. Net photosynthesis and dark respiration both acclimated to warming. Pedlar and McKenney (2016) used data from provenance trials for black spruce (*Picea mariana*) and jack pine (*Pinus banksiana*), and data from other published trials for other conifers, to assess the potential responses from warming. Trees from cold areas are expected to benefit from warming, while those from warm areas might decline. Results indicated that both cold-origin and warm-origin trees grew well at temperatures typical of the southern parts of their ranges. The conclusion was that trees from the cold-origin areas might benefit from warming.

Global warming has caused increases in air temperature. Because of the reradiative (greenhouse) effect, night temperatures are increasing faster than daytime temperatures (Davy *et al.*, 2016). Turnbull *et al.* (2002, 2004) exposed *Populus deltoides* to different day and night temperature regimes, and determined the rates of photosynthesis and respiration. Elevated night temperature increased photosynthetic capacity in daylight in the following daytime. Their rationale was that dark respiration the night before increased respiration, leading to reduction in carbohydrate levels in leaves which stimulated photosynthesis the next morning. Similar experimentation with elevated carbon dioxide reached the same conclusions.

5.3.3 Wildfires

Wildfires that burn and consume forests are started by lightning strikes or accidentally and deliberately by humans. Half of the increases in wildfires are estimated to be caused by humans (Abatzoglou and Williams, 2016). Wildfires in forests are increasing all over the world and are expected to continue in the future. Huge fires have recently burned millions of hectares of forests in temperate, tropical, and boreal areas in Calfornia, Siberia, Alaska, Indonesia, Chile, and Portugal (Turetsky *et al.*, 2010). An example of a forest fire is shown in Figure 5.3. Fire is thought to be the major determinant of carbon balance now in many boreal forests (Bond-Lamberty *et al.*, 2007),

FIGURE 5.3 Fire in the forest, Yellowstone National Park, USA. (A black and white version of this figure will appear in some formats. For the color version, please refer to the plate section.)
Credit: Kip Evans / Design Pics / Getty Images

and future fires are predicted to eliminate as much as half of the boreal forests in Alberta, Canada (Stralberg *et al.*, 2018).

Warming temperatures are increasing evaporation from soil and litter, drying soils, and affecting tree growth. Earlier spring times, combined with earlier mountain snowpack melts in mountain areas, also dry soils (Westerling, 2016). Warmer temperatures increase insect activity and shorten reproductive cycle times, and this can result in large numbers of dead and dying trees to burn. A very long fire suppression policy has resulted in thick layers of accumulated combustible debris from trees on the forest floor (Abatzoglou and Williams, 2016).

A forest fire is incomplete combustion. Smoke, aerosols, and gases are emitted in very large quantities, influencing air quality. Ash is deposited on the ground. Much of the carbon in the biomass of the burned trees and organic debris on the forest floor is emitted as carbon dioxide from stored carbon. Methane and oxides of nitrogen are also released. Trees that are not completely burned slowly decompose over time, releasing carbon dioxide (American Forest Foundation).

Fires that burn the surface debris down to the underlying mineral soil layer make it extremely difficult for tree seeds to germinate and seedlings to grow to regenerate the forest. Ash from the fire may provide some initial elements to promote growth, but it may not be enough. Warmer conditions may cause soil drying and water deficits. Stevens-Rumann *et al.* (2017) consider that the success of forest restoration to a pre-fire condition, by a process called forest resilience, depends on enough tree regeneration. Regeneration after a fire may be slow and difficult.

5.3.4 Insects and Large Herbivores

In Section 5.2.6, the involvement of introduced invasive alien species of insects and pathogens in large-scale and persisting forest decline was considered. Native forest trees also have natural associations with a variety of insects and pathogens that, depending on temperature, moisture, and tree vigor, can cause periodic episodes of decline and mortality. Climate change might affect periodic episodes of native insects and pathogens. Climate change and increases in temperature and drought, now and in the future, may increase the incidence, duration, and extent of tree decline and mortality incited by insects and pathogens (Anderegg *et al.*, 2015; Katz, 2017). Temperature-limited insects and pathogens may expand into new areas (Lesk *et al.*, 2017). Continuing globalization may facilitate introduction of new insects and pathogens (Ramsfield *et al.*, 2016). The species composition of planted forests also influences the incidence and severity of insect- and pathogen-caused declines. Non-native species may avoid native insects and pathogens, but this may not last, or they may be affected by other different native insects and pathogens. A limited number of tree species is being used worldwide to establish large planted forests. Species in the genera *Picea*, *Pinus*, and *Populus* are frequently used in the Northern Hemisphere. Species in the genera

Acacia, *Eucalyptus*, and *Pinus* are frequently used in the Southern Hemisphere.

Bark beetles are commonly found in forests where they usually feed on trees weakened by high temperature and drought, leaf and root diseases, and foliar ozone injury and defoliation. As insects, their populations expand and contract with temperature. Cold winters may kill many overwintering larvae. Warm summers allow feeding activity and reproduction. Warming temperatures have changed bark beetle incidence and extent of tree destruction through reduction of winter kill of larvae, earlier emergence in spring, more frequent reproductive cycles, and range expansion. Increasing temperature has also increased heat stress and drought, predisposing the affected trees to beetle feeding. The result has been widespread massive incidence of numbers of beetles and beetle-killed trees on a scale never seen in history (Katz, 2017). An example of trees killed by bark beetles in Colorado is shown in Figure 5.4.

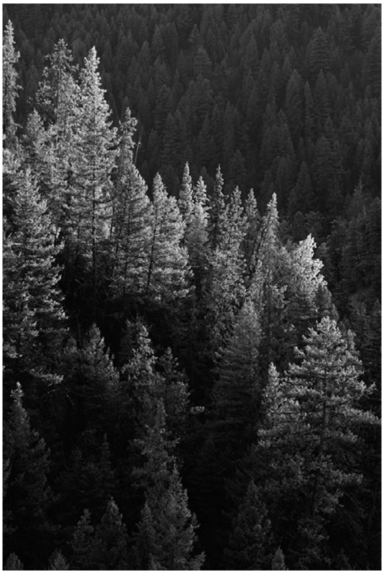

FIGURE 5.4 Beetle-killed pine trees. (A black and white version of this figure will appear in some formats. For the color version, please refer to the plate section.)

Credit: R_Koopmans / iStock / Getty Images Plus

The mountain pine beetle (*Dendroctonus ponderosae*) has caused massive destruction of lodgepole pine (*Pinus contorta*) and ponderosa pine (*Pinus ponderosa*) forests in the western United States and Canada. High-elevation spruce *(Picea engelmanni*) have been killed by the spruce beetle (*Dendroctonus rufipennis*). If warming continues, conditions will be appropriate for increases in both of these beetle species in western North America (Bentz *et al.*, 2010). Several species of beetles are killing Norway spruce (*Picea abies*) in Europe, and Serbian spruce (*Picea obovata*) in Siberia (Katz, 2017). Of major concern in eastern United States and Canada is the rapid range expansion northward by the southern pine beetle (*Dendroctonus frontalis*) into New York, New Jersey, and Connecticut, in response to warming temperatures. This poses a threat to northern pine forests (Lesk *et al.*, 2017).

Deer and other herbivores can also reduce forest regeneration by feeding on tree seeds, seedlings, and young trees. Deer populations in the United States have expanded as predators and hunting have decreased.

A very interesting and significant example of herbivory and forest regeneration has been documented in South Central Utah in the USA. An old and famous forest of trembling aspen (*Populus tremuloides*), known as "The Pando Clone", is under increasing herbivory pressure. This is a single-genotype forest, 43 ha in size, and includes approximately 47,000 genetically identical shoots. Some consider it to be the largest single organism on Earth. Regeneration involves emergence of new clonal shoots. Several large herbivores feed on these new shoots. The principal herbivore seems to be mule deer (*Odocoileus hemiionus*). Mule deer feeding is increasing, and there is concern for the successful regeneration of this ancient forest (Rogers *et al.*, 2018).

5.3.5 Forest Tree Diseases

In addition to the invasive pathogens previously presented, trees have foliar pathogens associated with them that may cause low-level disease with occasional increases. An example is anthracnose disease of American sycamore (*Platanus occidentalis*) caused by the fungus *Apiognomonia veneta*, which survives in twig cankers. As leaves of sycamore trees unfold in rainy weather, at temperatures below 50 °F, the fungus sporulates, and the spores germinate and cause leaf and twig blight. Defoliation can be dramatic and can be nearly complete. With warmer drier temperatures (above 60 °F), trees completely refoliate and grow, sometimes living to very old age. Earlier, warmer, drier spring weather could change this co-evolved tree/pathogen cycle. Red band needle blight of conifers is caused by the fungus *Dothistroma septosporum*. The fungus is widely found in both the Northern and Southern Hemispheres. It is considered to be a weak pathogen commonly associated with conifers, causing leaf symptoms that may result in some defoliation. Climate change is increasing temperature and precipitation, and this is increasing the incidence and severity of needle blight (Worrall *et al.*, 2010). Forest trees also experience root diseases that can slow them or kill them. Several species of the root rot fungus Armillaria are commonly associated with dying trees. Trees stressed by drought and insect defoliation are more susceptible to Armillaria (Moorman, 2017). Foliar pathogens require moist conditions/water for sporulation and spore germination and infection. Warmer and wet conditions should increase foliar diseases, while decreased precipitation should decrease disease. A drier, warmer climate might cause water stress in trees and increase root diseases.

5.3.6 Phenology and Growing Season

Phenology is the study of the occurrence and timing of biological events as affected by environment. For deciduous temperate-zone trees, the start of budburst and leaf unfolding in spring depends on having experienced a required number of winter chilling hours, enabling them to overcome environmentally imposed dormancy with increasing temperature and day length (Korner and Basler, 2010). Leaf senescence in fall can be delayed by warmer temperatures than usual. This may lengthen the growing season for some tree species. It has been confirmed that spring is occurring earlier and fall occurring later (Penuelas *et al.*, 2009) and that the growing season is increasing as a result (Linderholm, 2006; Schwartz *et al.*, 2006; Elmore *et al.*, 2016). Piao *et al.* (2008) suggest that this has happened in just the past few decades. Korner and Basler (2010) estimate that the growing season has increased at a rate of 2.5 days per year since 1971. Way (2011) concludes that the growing season has increased by 11 days since the 1960s. Linderholm (2006) estimated a 10–20 day increase in the growing season. The consensus is that the growing season is getting longer, and that this is important. A longer growing season is of great interest as it should affect rates of growth, photosynthesis, respiration, and carbon sequestration. An increase in growth and net carbon sequestration would provide stronger negative climate forcing for forests. This would be particularly important in boreal forests (Stinziano *et al.*, 2015). Piao *et al.* (2008) modeled temperature effects on photosynthesis and respiration in spring and autumn. They concluded that in autumn, the increase in respiration was greater than the increase in photosynthesis. Warming increased photosynthesis more than respiration in the spring. Reduction in uptake of carbon dioxide and sequestration in autumn was estimated to offset 90% of the carbon dioxide captured in spring. A longer growing season could increase requirements for soil water and nutrients, especially nitrogen which might reduce growth and carbon sequestration (Elmore *et al.*, 2016).

Shorter, warmer winters may lead to longer warmer growing-season effects on leaf growth and senescence. Trees require continued exposure to cold temperatures for a certain length of time in winter to complete dormancy requirements (Korner and Basler, 2010). Warmer temperatures in shorter winters could delay the timing of spring budburst and leaf unfolding, delay the start of the spring growing season, and reduce carbon sequestration (Piao *et al.*, 2008; Fu *et al.*, 2015). The importance of the timing of spring budburst for possible increases in carbon sequestration was determined by Keenan and Richardson (2015) who correlated its timing with the timing of autumn leaf senescence in the eastern United States.

5.3.7 *Ozone*

Ozone formation and some general effects were covered in Chapter 4. The emphasis here is on assessing current and predicted effects of ozone as a stress factor for trees and forests. Unlike carbon dioxide, ozone is present as background and periodic elevated events during the warm months of the year, coincident with the growing season for trees. With a warmer climate and longer growing seasons, the incidence of ozone concentrations that can cause tree injury may increase (Wittig *et al.*, 2009). Parrish *et al.* (2014) conclude that there is quantitative disagreement between ozone measurements and modeled determinations. Models significantly underestimated ozone changes in northern midlatitudes for the last 50–60 years. Future ozone levels may be higher than predicted by models.

Foliar ozone injury is likely to begin on deciduous tree leaves when they are approaching full expansion and progress from first-emerging to later-emerging leaves. Injury that occurs then may not appear as distinct visible symptoms on leaves until late summer (Manning and Godzik, 2004). Leaves of determinate tree species may stop growing as early as late June, and their reponse to ozone may be diminished as photosynthesis also declines with slowed leaf function and age. Other tree species may stop growing in early August. Leaf response to ozone depends on stomatal conductance during photosynthesis and is affected by water stress, drought, and high temperatures that affect photosynthesis. Tree also differ in their sensitivity to ozone with tree age and within and between species (Wang *et al.*, 2015).

Air quality regulations have reduced oxides of nitrogen and small hydrocarbons from combustion, and this has reduced the number of high-concentration incidents in Europe, the United States, and Canada that cause visible injury to leaves. Remaining chronic lower-level exposures, however, can cause less dramatic chlorosis and long-term growth reductions. Rapid expansion of industry and vehicles, with few regulations, in China, India, and other areas in Asia, has resulted in very high levels of ozone, with frequent high-concentration events. Ozone and its precursors move across the

Pacific Ocean to the west coast of the United States and across as far as Europe, increasing ozone there.

Abundant ambient air monitoring data imply possible adverse effects of ozone on trees. Exposure does not equal response. The effects need to be determined, and a causal relationship should be determined before the data have any biological significance for trees (Manning, 2003, 2005). Toxicologists do this with dose/response curves to determine the effects of a toxicant over time on growth, decline, and death of an organism under controlled conditions. Constructing a dose/response curve for ozone and trees under controlled conditions can be done by using small seedlings. Extrapolation of results to complex, variable, large trees in a forest under ambient conditions is impossible. The results are only relevant to the chamber environment and are only indicative of what might possibly occur. This has posed problems for research on ozone effects on trees. Trees are difficult organisms for experimentation. Cailleret *et al.* (2008) point out that we have a good understanding of ozone effects at the leaf level, but knowledge declines at the whole tree level. By necessity, movement has been away from small-chamber dose/response curves to the use of large growth chambers, a variety of field chambers, and open exposure (FACE) systems, resulting in ever-decreasing environmental control and greater variability (Manning, 2005). Hundreds of papers on ozone effects on trees have been published from the results of experiments using these methods. Such results are also used to model current and predicted ozone/tree risk. Some research has also been done under completely ambient conditions, and examples are presented here. More discussion of methods and results will be found in Chapter 7.

Wittig *et al.* (2009) used a meta-analysis of experiments on trees in chambers with ambient and elevated ozone. It was concluded that in most cases, ozone affected growth rates and biomass accumulation, accompanied by foliar injury symptoms, chlorosis, and leaf area reduction. Karnosky *et al.* (2005) led the world's largest and longest FACE experiment, AspenFACE. Sapling-stage trees were exposed to ozone and carbon dioxide. White birch (*Betula papyrifera*), aspen (*Populus tremuloides*), and sugar maple (*Acer saccharum*) growth was decreased by elevated ozone over time. Many models indicate current negative and predicted future effects of ozone on NPP. Cailleret *et al.* (2018) found them to be inaccurate in Europe, owing to the complexity of forests and confounding factors such as differing tree sizes, species, drought, soil nitrogen, tree acclimation, and growth compensation. Ozone effect data from chamber experiments were used in the models, and this led to overestimation of the negative effects of ozone. Some slight ozone effects may occur in European forests. Proietti *et al.* (2016) used data from 37 European forest sites from 2000 to 2010 to model ozone effects on GPP along a northwest European transect. Predictors for ozone effects at each site along the transect were soil water content and relative humidity. They found a negative ozone impact on GPP ranging from 0.04% to 30%. Ozone levels are high in China and most of Asia. Li *et al.* (2017) found that the AOT40 exposure standard for ozone was exceeded 65 times in 2015–2016. Ozone risk was estimated to be higher for northern temperate forests than southern subtropical and tropical forests. Subtropical evergreen broadleaved forests dominate in Chinese forests. They are less ozone-sensitive than temperate deciduous trees. Park *et al.* (2018) estimate that NPP of Korean forests has been reduced by 8.25%. Reductions of 8.47% to 10.55% are projected for the 2050s.

Dendrochronological methods can be used to correlate radial growth with ozone data (Manning, 2005). Braun *et al.* (2014) obtained stem diameter data from permanent plots of beech (*Fagus sylvatica*) and Norway spruce (*Picea abies*), established in 1984. A good ozone dose/response agreement was obtained for beech, but not spruce. Ozone injury was detected and confirmed on three tree species in remnants of the Tropical Atlantic Forest, influenced by proximity to Sao Paulo, Brazil (Moura *et al.*, 2018).

Trees can be adversely affected by ozone under experimental conditions, but the effects of ozone on carbon sequestration in large complex forests is more difficult to determine. People have proposed that ozone has either a small negative effect or no effect on carbon sequestration by forests. The size and complexity of forests makes determination of ozone effects difficult. Cailleret *et al.* (2018) suggest possible small negative effects. Wang *et al.* (2015) agree with Cailleret *et al.* (2018) and propose that ozone may not appreciably decrease the carbon sequestration capacity of forests. Their proposal is based on the premise that tree species in forests differ in sensitivity to ozone. Ozone could act as a selective agent for tree species that are less sensitive to ozone. Over time, the more susceptible trees would be replaced with tolerant trees, and ozone would not appreciably affect carbon sequestration. The ozone-tolerant trees, however, may emit more BVOCs than susceptible trees. Increased isoprene emissions could influence the photochemical oxidant cycle and lead to increased ozone. Ozone is an important greenhouse or reradiative gas.

5.3.8 Urban Trees and Forests

The definition of urban forest can be somewhat elastic, expanding and contracting without clear definition. "Urban" includes the well-defined densely settled and developed core of a city or town, but when urban expands to include outward gradations of less dense, poorly defined and diffuse suburban or periurban development, expanding outward and around the core city, the term then expands to the collective term "urban area". Urban here will refer to city cores. With this in mind, urban forests can be considered to be all the publicly and privately owned trees along streets and in parks and relic original forest areas in core cities. It has been estimated that, as of 2010, there were 3.8 billion trees in urban forests in America (Nowak *et al.*, 2010).

Large-scale tree planting is occurring in cities large and small all over America and in other countries. More than a million new trees are planned for New York and Los Angeles. Even the small town of Amherst, Massachusetts (population 33,000), is planting 2,000 new trees. The primary motivation for this is to do something to increase carbon sequestration and help to mitigate global warming. The slogan "Plant a Tree and Save the Planet" has strong motivational value.

Other benefits of urban trees include cooling from shade and transpiration, reduction in energy use, improvement in air quality, and reduction of storm water runoff. Aesthetic values include increased life quality (Nowak *et al.*, 2010). For many city people, trees are the only contact that they have with the natural world.

Nursery-grown trees used in city plantings, especially along streets, may have a very difficult period of adjustment and establishment. Root space may be limited, resulting in chronic water stress or drought affected by high air temperatures in the city. Many newly planted trees die from lack of care or from vandalism. Larger plantings of older trees may be affected by invasive plant species, such as English ivy (*Hedera helix*) and buckthorn (*Rhamnus cathartica*) (Nowak *et al.*, 2010). Temperature and water stress may predispose trees to insects and pathogens.

The most successful trees in cities are often widely occurring non-native invasive species. They do not need to be planted or receive care. The Tree of Heaven (*Ailanthus altissima*) will grow well anywhere in cities. It is scorned as a noxious weed tree and slated for eradication. The large numbers of *A. altissima* and other non-planted trees that occur in cities are not included in city tree inventories.

Tang *et al.* (2016) assessed tree growth and estimated carbon storage for street trees in Beijing, China, using tree growth measurements and statistical yearbooks. They estimated that Beijing street trees sequestered and stored about one-third to one-half of the carbon of similar trees in a forest. When total carbon sequestration was compared to carbon dioxide emissions from total energy consumption, they concluded that Beijing's street trees reduced only 0.2% of total emissions.

Pretzsch *et al.* (2017) used increment core sampling and tree ring analyses to determine radial growth of mature trees in ten very large world cities. They concluded that most trees had increased since 1960. An increase in tree growth of 35% was attributed to climate change (21%) and heat island effects (14%). This increased tree growth increased carbon sequestration. Meineke *et al.* (2013, 2016) identified areas of Raleigh, North Carolina, that had higher or lower temperatures due to the urban heat island, determined by the extent of paving and building infrastructure. They determined the effects of temperature in these areas on water stress and stomatal conductance and photosynthesis for willow oak (*Quercus phellos*) street trees. Photosynthesis was reduced in the warmest areas of the city. They estimated that this caused a 12% reduction in carbon sequestration by trees in the warmest areas. Incidence of scales and mites on leaves and small branches also occurred in the warmest areas, but their direct effect on carbon sequestration was considered not to be significant. Dale and Frank (2014) found that high heat areas in Raleigh, NC, were encouraging persistent infestations of scales and mites on red maple (*Acer rubrum*) street trees which were slowly causing the trees to decline and die. Unlike Pretzsch *et al.* (2017), Meineke *et al.* (2013, 2016) and Dale and Frank (2014) conclude that increasing temperatures in cities will result in reduction of the carbon sink of the urban forest.

5.4 SUMMARY

Trees grow in place, within ranges of environmental parameters and limitations. Continuous adaptation to a changing environment is necessary for growth and the realization of genetic potential. Inherent genetics and phenotypic plasticity facilitate adaptation to some changes. When maladaptation occurs, trees decline and may die. Trees and forests normally adapt to many environmental factors and co-evolved organisms. The impact and extent of these factors and organisms has increased hugely and is projected to increase more in the future.

Forest maladaptation is occurring widely on a global scale, due to global warming and other climate change factors. Forest cover is declining, and the trend will continue. Forests are being fragmented, especially in the Amazon, and this affects their function and opens them to invasive plant species and vines. Forest cover decline and fragmentation reduces carbon sequestration and the carbon sink value of forests.

Deforestation is increasing because of demand for wood, firewood and wood pellets, and land for agriculture for crops, high-value export foods and palm oil, grazing for cattle, housing, and other purposes. Trees and forests are in the way of the needs of a current very large human population, projected to increase by 2 billion or more people by 2050. Globalization and world trade have enabled the entry of highly destructive invasive insects, such as the wooly adelgid, which kills hemlock trees, and the emerald ash borer, which kills ash trees. One result is that hemlock, Fraser fir, ash, and several other forest tree species are listed as in danger of extinction.

Warming temperatures have increased incidence of chronic moisture stress and prolonged severe drought worldwide. Millions of trees have died in western America, and large numbers in the Amazon and other world regions. Water stress and drought cause increases in wildfires. Unprecedented numbers of bark beetles are killing water-stressed conifers. The generational time for beetles has been shortened due to warming. Longer growing seasons seem to have the potential to increase photosynthesis and carbon sequestration.

Ozone effects on growth of trees, under experimental conditions, are well documented, but ozone effects on forest growth and productivity are not clear, as variables such as tree age and diversity of tree species may negate any long-term effects on whole forest growth.

There is considerable interest in tree planting and urban forests. Trees in urban forests, especially street trees, are affected by heat island effects and water stress. Photosynthesis, tree growth, and carbon sequestration may be reduced by warming. Susceptibility to insects and pathogens may increase. The interacting physical and biological factors that affect tree growth and carbon sequestration, and tree responses to them, are not unique or unusual. What is unusual is the increased frequency and duration of occurrence, and the magnitude of lasting negative results.

Having explored factors that cause forest decline and loss in this chapter, we will examine in the next chapter the types of world forests and how their location, nature, condition, and future outlook would affect their contribution to cooling or warming.

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6 Forests of the World

Forests cover approximately 42 km^2 in tropical, temperate and boreal lands, approximately 30% of the land surface. Forests store approximately 45% of terrestrial carbon and contribute approximately 50% of terrestrial primary productivity. Complex and nonlinear forest–atmosphere interactions can dampen or amplify anthropogenic climate change.

Gordon B. Bonan, 2008

6.1 INTRODUCTION

In the previous chapter, environmental and biological factors that affect tree and forest health, vitality, growth, carbon sequestration, and survival were considered. How different types of forests respond to interactions of these factors depends on their composition and location. The nature of the world's natural and urban forests affects their function and role in carbon sequestration and in atmospheric cooling and warming. It seems appropriate to consider the nature, composition, function, and future of the forests of the world.

Most of the forested areas of the Earth are found in tropical areas and in the Northern Hemisphere, between 35° north and the Arctic. NPP in these regions constitutes the main land sink for carbon. Major differences between types of forests relate to extent of foliar biomass, determined by light, water, and nutrient availability, and growing season length (Perry *et al.*, 2008). Distance from the equator and rainfall are general criteria for distinguishing between forest types. A more detailed presentation of the nature and function of forests of the world was developed, using the following references for source material (Bonan *et al.*, 1992; University of California, Berkeley, Museum of Paleontology, 2006; Bonan, 2008; Perry *et al.*, 2008; Gauthier *et al.*, 2015; Baccini *et al.*, 2017).

6.2 FOREST TYPES BY LATITUDE

6.2.1 Tropical and Subtropical Forests

Tropical and subtropical forests are found between the Tropic of Cancer (23.5° north) and the Tropic of Capricorn (23.5° south). They occupy 7.55% of the Earth's land surface. High temperatures (average 27 °C), rainfall, and 12-hour day length affect tree growth. The temperature prevents winter, resulting in only wet and dry seasons. Their tree diversity is the most extensive of all forests. Many species are evergreen. Soils are acidic, nutrient-poor, often with low phosphorus, and easily leached. Fallen leaves and branches decompose quickly.

More than half of tropical forests have been lost since pre-industrial times. Drought and fires are increasing. Deforestation for logging and agriculture causes forest fragmentation and lowers the carbon sink. Destructive human influence is rapidly increasing (Lewis *et al.*, 2015).

An example of a tropical forest is shown in Figure 6.1.

Tropical and subtropical forests have been subdivided by seasonal rainfall and the length of wet and dry seasons. The evergreen rainforest has no dry season. Seasonal rainforest of evergreen trees is in a wet region with a short dry period. Semi-evergreen forest has a deciduous tree overstory and an evergreen understory, and occurs in a region with a longer dry season. In deciduous forests, the length of the dry season increases in relation to rainfall. The composition and function of these forest types is very different, but all are often considered to be tropical or semitropical forests.

6.2.1.1 Climate Forcing by Tropical Forests

Tropical forests have high rates of evapotranspiration. Transpiration from leaves especially cools the air in the vicinity of the leaves. It is usually assumed that transpiration from all tropical forests together is a negative force that cools the atmosphere, neutralizing the warming effect of trees with low albedo. Trees in tropical forests have been estimated to contain 25% of stored terrestrial carbon, further

FIGURE 6.1 Tropical forest, Brazil.
(A black and white version of this figure will appear in some formats. For the color version, please refer to the plate section.)
Credit: Jean-Yves Grospas / Biosphoto / Getty Images

providing negative forcing (Bonan, 2008). Tropical forests have generally been assumed to be large, reliable, expanding natural sinks for carbon from carbon dioxide and to partially mitigate global warming. This assumption is open to question.

Conditions in tropical forests have been changing rapidly, with widespread deforestation and extensive tree deaths (Hansen *et al.*, 2013). This has reduced carbon sequestration and transpirational cooling. Carbon dioxide is released from decomposing tree residues (from logging and land clearing) and fires. This suggests that tropical forests may be approaching net carbon-neutrality (Bonan, 2008) or becoming small net carbon sources (Grace *et al.*, 2014).

6.2.1.2 Methods of Assessment

The long-running question of whether tropical forests are effective carbon sinks, are net carbon-neutral, or are net carbon sources has not

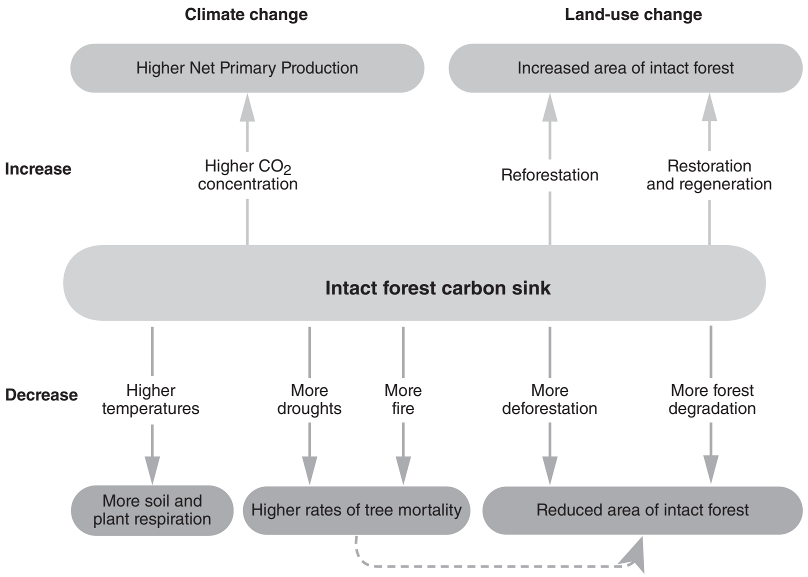

FIGURE 6.2 The effects of climate and land-use change on the intact forest carbon sink.
Potential contrasting effects of climate change and different trajectories of land-use change on the size of the intact forest carbon sink. Arrows pointing up show how climate change and policy could increase the magnitude of the sink, whereas arrows pointing down show how it will be reduced. All processes will occur to some extent, so predicting how the sink size will change is very difficult.
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had a conclusive answer. Assessment is usually indirect, and the various methods of assessment have produced different answers.

Mitchard (2018) looked at annual carbon fluxes in and out of tropical forests, comparing results from different methods of assessment, including forest inventory plots, remote sensing in an El Nino year or in an ordinary year, and combined methods (Figure 6.2). Except in the hot dry conditions of an El Nino year, Mitchard concludes that tropical forests, with carbon dioxide emissions from deforestation and degradation, are approximately carbon-neutral. Continuing forest loss and warmer drier conditions could result in tropical forests becoming sources of carbon dioxide.

Baccini *et al.* (2017) directly determined changes in above-ground carbon density (above-ground carbon) of live woody vegetation across tropical America, Africa, and Asia (between 23.45° N and 23.45° S), using a combination of LiDAR data and NASA MODIS satellite imagery, from 2003 to 2014. Forest growth provided carbon gains of 436.5 ± 31.0 Tg carbon per year (1 teragram = 1 million metric tonnes of carbon dioxide equivalents). Losses from deforestation (degradation and disturbance) were 861.7 ± 80.2 Tg C yr^{-1}. The net carbon source was 425.2 ± 92.0 Tg C yr^{-1}. Forest degradation and disturbance accounted for 68.9% of the overall forest carbon loss. Baccini *et al.* concluded that they had provided direct evidence that the world's tropical forests are a net carbon source. The future role of tropical forests as significant carbon sinks should not be automatically assumed. Tropical forests in the Amazon, and tropical forests in general, are at risk, as most of the 40,000 tropical tree species are threatened with decline or extinction (ter Steege *et al.*, 2015).

6.2.1.3 Effects of Agriculture and Deforestation on Climate Forcing by Tropical Forests

Mitchard (2018) has provided a schematic diagram (Figure 6.3) to indicate how the tropical forest sink might be affected by increase or reduction of forest size and the influence of climate and atmospheric carbon dioxide. Climate includes the influence of higher temperatures, fires, and drought. Mitchard concludes that integrating all these interacting factors and predicting their effects on the size of the tropical forest sink "is very difficult."

Rosa *et al.* (2016) reconstructed deforestation rates at 5-year intervals from 1950 to 2009 for tropical forests in the Amazon, southeast Asia, and the Congo Basin. They estimated that, during that time, approximately 2.27 million square kilometers were deforested (Figure 6.4). Cumulative emissions of carbon dioxide during this

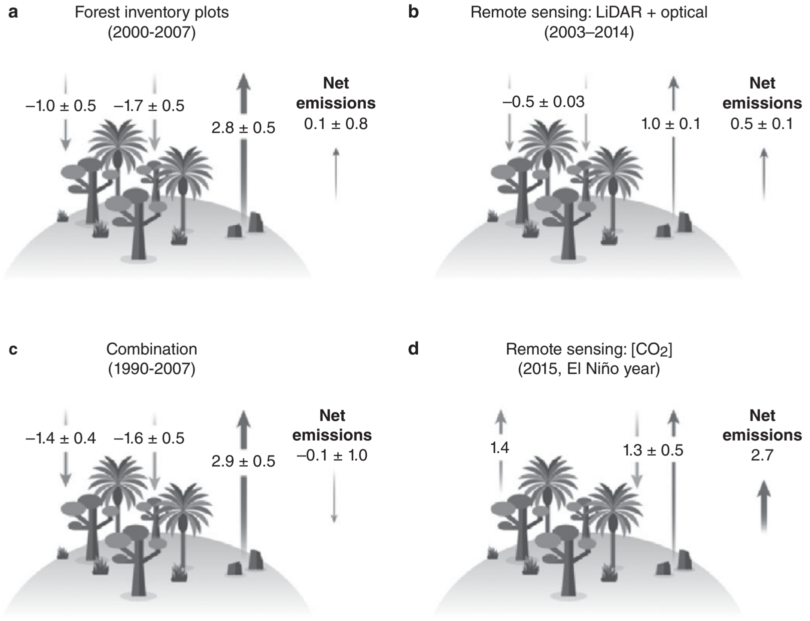

FIGURE 6.3 Annual fluxes into and out of tropical forests.
Fluxes (in Pg C yr^{-1}) are shown for different overlapping time periods (**a**–**c**) and for a recent El Niño year (**d**). The net intact forest flux is shown in turquoise, the net flux in regrowing forest is in orange, and the deforestation and forest degradation flux (including fire) is shown in pink. Panels **a**–**c** show that there is broad agreement that the tropics have made an approximately neutral contribution to atmospheric carbon stocks in the recent past, but **d** shows that intact forest can become a carbon source in hot and dry years, leading to considerable net emissions from the tropics. Data in **a** are from networks of forest inventory plots (see original paper for references), combined with forest area data from country surveys. In **b**, values are obtained from annual 463-m resolution optical satellite data, calibrated using LiDAR data and field plots from the mid-2000s. Intact and regrowth fluxes are not separated in this method. The figures in the study have been grossed up from biomass to total carbon stock change (that is, including dead wood, litter, soil). Data in **c** are derived from looking for overlap between atmospheric inversion, modeling and field-plot estimates. In **d**, data are obtained from satellites sensitive to atmospheric CO_2 concentrations for the 2015 El Niño year, which contrast sharply with the other estimates shown. Change in land use could not be divided into separate regrowth and loss fluxes in this method.
(A black and white version of this figure will appear in some formats. For the color version, please refer to the plate section.)

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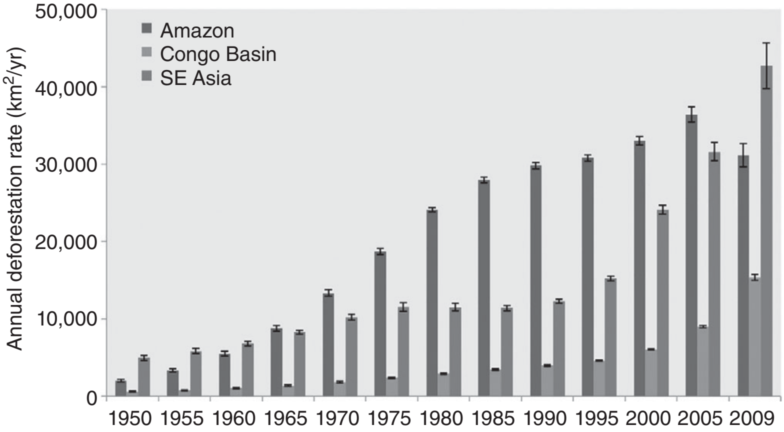

FIGURE 6.4 Modeled annual deforestation rates from 1950 to 2009 in five-year intervals.
Rates are shown in km^2/yr.
(A black and white version of this figure will appear in some formats. For the color version, please refer to the plate section.)
Reprinted from *Current Biology* **26**, 2161–2166, The environmental legacy of modern tropical deforestation, I. M. D. Rosa *et al.* © (2016), with permission from Elsevier

period were 28–66% for the Amazon, 25–60% for southeast Asia, and 9–14% for the Congo Basin.

6.2.2 Temperate Forests

Temperate forests occur between 25° and 50° N in eastern North America, northeast Asia, and western and central Europe. They are approximately 20% of the terrestrial land mass and contain about 10% of the stored terrestrial carbon. Seasons are well-defined and all occur. Precipitation (rain or snow) occurs in all seasons at 75–150 cm all year. Winter temperatures may be as low as −30 °C. Summer temperatures range to 30 °C and are increasing in southern regions. The forests have fertile soil with decomposing litter. The growing season is 140–200 days, with four to six frost-free months. Canopy density allows enough light penetration for understory vegetation development. Three or four species may dominate per square kilometer. Broadleaved deciduous trees may predominate: examples include oak, beech, maple, poplar, and hickory. Spruce, pine, hemlock, and fir are examples of conifers.

FIGURE 6.5 Temperate forest, Northeast United States.
(A black and white version of this figure will appear in some formats. For the color version, please refer to the plate section.)
Pixaby Pictures

Seasonal rainfall determines forest subdivisions as follows.

- Mixed moist conifer/deciduous forests: mild wet winters, dry summers.
- Dry conifer forests: higher elevations, low rainfall.
- Mediterranean forests: rain in winter only, less than 100 cm per year.
- Temperate coniferous: mild winters, rain greater than 200 cm per year.
- Temperate broadleaved rainforests: frost-free winter, even rainfall.

A typical deciduous temperate forest is shown in Figure 6.5.

6.2.2.1 Climate Forcing by Temperate Forests

Deforestation for agricultural crops and pastures can have two possible effects on climate forcing by temperate forests (Bonan, 2008).

1. Net climate effect: neutral or slight. Land clearing decreases sink strength for carbon dioxide, and emissions increase. Cleared land has higher albedo values than darker forested land. Albedo negates effects of carbon dioxide.

2. Net climate effect: cooling effect reduced. Land clearing decreases transpiration and shade from trees, decreasing atmospheric cooling.

Deforestation and commercial use of forests as sources for wood are increasing globally. This reduces carbon dioxide capture and sequestration in wood. Forest reduction decreases the sink capacity of forests.

European forests are often managed for wood production, and long-term data on tree growth and production are readily available. Using available forest growth data, Nabuurs *et al.* (2013) determined that long-term stem volume increments in European forests are declining. They considered this to be an early indication of signs of forest sink saturation in European forests.

Declines in forest carbon sinks for the United States have been projected by Wear and Coulston (2015). Forests in the northeast region will gradually decline over a 25-year period. Fire, insect infestations, and drought could cause more rapid forest decline in the Rocky Mountain region. In the cooler Pacific Northwest, forests might become stable.

6.2.3 *Boreal Forests*

These forests occur between 50° and 60° N and with difficulty to 70° N. Their distribution is circumpolar in Alaska, Canada, Siberia, and Scandinavia. A boreal forest area in the Yukon Territory of Canada is shown in Figure 6.6. Many are extensively managed for wood production. Winters are long and severe, and freezing temperatures are present for 8 months of the year. Snow is the principal form of precipitation (40–100 m annually). An example of a boreal forest area in winter is shown in Figure 6.6. The summer growing season is warm and short (130 days). Soils are acidic and nutrient-limited. Light penetration through canopies is low. Mixed forests include cold-tolerant conifers, such as spruce, pines, and fir, and cold-tolerant broadleaved deciduous trees, such as poplar, birch, and alder. Conifers may dominate at higher latitudes.

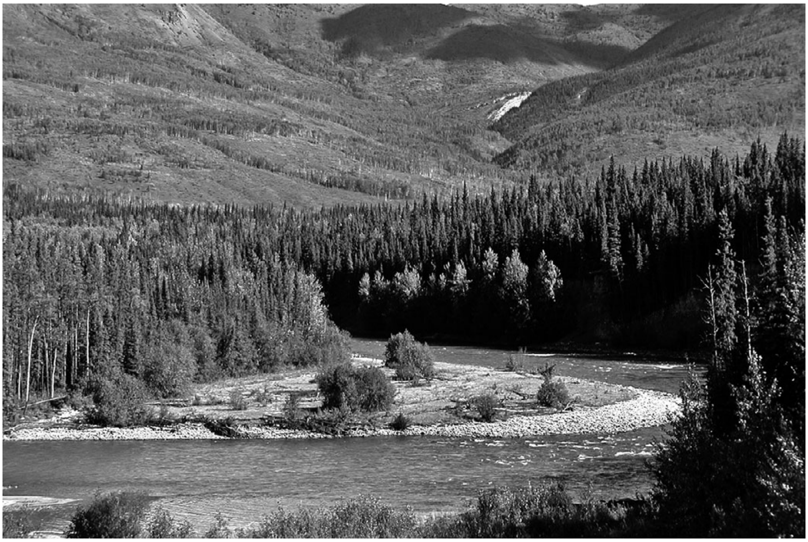

FIGURE 6.6 Boreal forest, Yukon Territory, Canada.
(A black and white version of this figure will appear in some formats. For the color version, please refer to the plate section.)
Good Free Photos

Despite a short growing season, boreal forest trees capture and sequester carbon in wood. Annual carbon gain by older, more mature trees, however, may be low (Bonan, 2008).

Fires are increasing in boreal forests. The extent of loss relates to forest composition in a given forest. Where conifers such as black spruce (*Picea mariana*) are dominant, loss from fires is more likely. Leaves of deciduous trees contain more moisture than conifer needles. When pure stands are compared, deciduous forests are 24 times less likely to burn than conifer forests (Astrup *et al.*, 2018).

6.2.3.1 Climate Forcing by Boreal Forests

Boreal forests constitute approximately 30% of all global forested land area. Given their large size and geographic distribution, there is considerable interest in their nature, how they function, and whether this will have warming or cooling effects on global climate. It has been suggested that boreal forests have the largest biophysical influence on average annual global temperatures (Bonan, 2008). Much has been published about their probable influence. Some of it is examined here, and a more extensive discussion is found in Chapters 7 and 9.

The discussion in the literature focuses on tree color and deforestation and their effects on surface albedo. Forests that are dominated by conifers, especially black spruce, are dark in color. They do not reflect light (radiant energy) well and have low albedo numbers. Deciduous trees and forests reflect somewhat more light and have higher albedo values (Astrup *et al.*, 2018). Clean fresh snow effectively reflects light and can have an albedo close to 1.00 (the highest value). This can be diminished by the low albedo values of dark forests, resulting in a small increase in air temperature during the long winter and more in summer (Bonan *et al.*, 1992). Deforestation, caused by humans, insects, and fires, results in areas of open ground that have higher albedo values than dark forests. This may result in atmospheric cooling (Bala *et al.*, 2007; Bonan, 2008). Much of what is known about albedo values and atmospheric warming or cooling in boreal forests has been obtained from results from models. Empirical ground-based data are much less available.

6.2.4 Urban Forests

As indicated in Chapter 5, the number and size of core cities and periurban areas is increasing dramatically worldwide. In some places, cities have become so large that accurate population data are not available. Interest in maintaining existing trees, in parks and along streets, and planting new trees in core cities is increasing correspondingly. Part of the rationale is to influence urban climate by reducing gaseous and particulate air pollution, and lowering air temperature by sequestering carbon, providing shade and transpirational cooling to alleviate urban heat-island effects. Trees also provide aesthetic value through their appearance, while introducing urban dwellers to some semblance of the natural world.

A city is an unnatural environment and a challenge for trees, especially for native species that grew there before the city was developed (Johnston *et al.*, 2011). Infrastructure, concentrated buildings of different sizes, streets, and development result in limited soil area for root growth, and soil water may be limited. Higher temperatures can inhibit or enhance growth. Microclimates are common, particularly involving temperature and light availability.

Except for any relic natural forest areas, all desired city trees must be planted. This is expensive, as nursery-grown trees, often specific selections or hybrids, are planted. At the same time, invasive tree species, such as Tree-of-Heaven (*Ailanthus altissima*) readily colonize almost any open area, grow quickly, and provide shade. *A. altissima* is considered to be a messy, undesirable tree that should be eradicated. Invasive plant species, however, are becoming the default flora of cities.

Traditionally, a small number of tree species have been used in cities – those that were available in nurseries and were well-liked. In the northeastern United States, oaks (*Quercus*), maples (*Acer*), ash (*Fraxinus*), and linden (*Tilia*), and in the past elm (*Ulmus*), were commonly used. They were planted in large single-species plantings, especially along streets. Then, as now, many newly planted trees from nurseries died within 2–3 years after planting from poor management: failure to establish, neglect, drought, and vandalism. Survival of replacement trees can be even less than that of originals (Gilbertson and Bradshaw, 2012). Tree planting on a large scale is expensive, and it became evident that perhaps different tree species might be more successful and provide new benefits. New tree species and clones, and hybrids of more common trees, better adapted to cities, have become available as a result.

In architecture, the original law was that form must follow function. This should also be applied to selection and use of trees for city plantings. Given the cost and effort needed to purchase, plant, and maintain city trees, it is essential that they function in ways that allow them to survive, grow to appropriate size, and enhance environmental quality. Aesthetic function is desirable, but it is not enough. A combination of environmental and aesthetic functions is ideal.

Databases for selection of appropriate trees for cities by categories are available. The City of New York developed a list of appropriate tree species (New York City Parks Approved Tree Species List, 2005) to plant in New York before embarking on a million-tree planting program. They used ultimate size and other criteria to select trees for specific locations, following the arboricultural dictum of "right tree in the right place". McPherson *et al.* (2016) established a similar urban tree database. Yang *et al.* (2015), however, conclude that despite interest in new tree species for cities, the tree composition of many cities worldwide remains remarkably homogeneous.

6.2.4.1 Climate Forcing by Urban Forests

Urban trees sequester carbon from carbon dioxide. Through the shade that they provide, they also reduce carbon emissions by reducing energy demand for cooling, and thus reducing power-plant generation of electricity (Nowak and Crane, 2002). One hundred common tree species were evaluated for size at maturity, life span, growth rate, and maintenance/care requirements, to determine which characteristics would be best for urban trees to function well in carbon capture and sequestration. Nowak and Crane concluded that long-lived, low-maintenance, moderate- to fast-growing, large-at-maturity, deciduous tree species would function well, provided they were in or were planted in appropriate sites that would promote their growth. Empirical evidence for carbon dioxide reduction by urban trees is not well developed.

Cities all over the world are characterized by higher ambient temperatures due to heat island effects and periodic heat waves. Tree populations in cities could provide some localized cooling, by shading or transpirational cooling. Large parks and relic forest areas might offer larger-scale localized cooling. Empirical evidence for air cooling is available only from observations and measurements from small groups of trees (Bowler *et al.*, 2010; Linden *et al.*, 2016).

Warmer city temperatures and other stresses increase emissions of the small hydrocarbon isoprene from leaves. Isoprene can increase the formation of ozone in the photochemical oxidant cycle in cities, affecting tree and human health, and global warming. In response to high temperatures, some species such as oaks, especially northern red oak (*Quercus rubra*), commonly used as city trees in temperate zones, emit large quantities of isoprene in summer, which is when ozone formation in cities occurs. Isoprene emissions should be considered when selecting tree species for planting in cities (Donovan *et al.*, 2005; Simpson and McPherson, 2011), and high-emitting species should not be planted there in large numbers.

6.3 SUMMARY

"Forest" is often used as a generic term in large process models to assess environmental effects on the present and future condition and extent of the forests of the world. The major forests of the world, however, differ widely in their location, composition, subdivisions, and functions, and should be assessed individually.

Forest area is decreasing worldwide, and this is decreasing the forest carbon sink. Deforestation for wood and agriculture, degradation, fires, insects, and drought are the major causes.

Deforestation in tropical forests increases carbon dioxide emissions and decreases transpirational cooling. Increased albedo in cleared land may partially mitigate the increased warming. Extensive deforestation may turn tropical forests from net carbon sinks to net carbon sources.

Deforestation in temperate forests may have only a slight negative effect on warming.

Vast boreal forests are dark in color and have low albedo values, resulting in warmer winter and summer temperatures. The high albedo value of snow for cooling can be reduced by low albedo values for trees. Deforestation by timber harvesting, fires, and insects opens up lighter-colored land surfaces to sunlight. Open surfaces have higher albedo than dark trees, and this may result in cooler air. It has been speculated that global climate might be cooler if there were no trees in the boreal regions.

Tree planting is increasing in cities to reduce carbon dioxide and urban temperatures. Shade and transpirational cooling can reduce air temperatures, but this may occur only in localized areas. More attention is being paid to selecting trees for cities that offer positive functions for environmental quality. Trees, such as oaks, that are high isoprene emitters should not be planted extensively.

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7 Knowledge Base for Forests in Cooling and Warming

> The only way to figure out what is happening to our planet is to measure it.
>
> Keeling, 2008

> While short-term leaf-level responses to CO_2 (such as A/Ci curves) are well understood, we have less data on longer-term CO_2 acclimation responses or responses at any time scale at larger spatial scales (such as stand level responses to CO_2 from Free Air CO_2 Enrichment (FACE) studies), and none that have run for decades or explored large-scale responses of forest stands to warming.
>
> Way *et al.*, 2015

7.1 INTRODUCTION

Previous chapters considered the nature and cause of global warming; the key role of carbon dioxide; the importance of the biogeochemical factors photosynthesis and BVOCs, and the biogeophysical factors albedo, evapotranspiration, and ozone; and how their interactions affect forests, atmospheric temperatures, and climate. Warming temperatures, forest fires, insect infestations, drought, deforestation and land-use change, latitudinal forest locations, and species composition all affect these interactions.

Recognition that carbon dioxide and ozone were increasing, and that atmospheric warming was occurring, resulted in extensive research on how this would affect trees and forests, now and in the future, and what effect this would have on atmospheric warming and cooling. Results from hundreds of experiments, extensive model simulations, and meta-analyses can be found in a wide variety of journals and books. This chapter will use some examples to focus on how the current knowledge base was determined. Emphasis will be on methods used, and how this affects the relevance of the results.

The devil is indeed in the details, and this is often overlooked when conclusions are drawn.

7.2 RESEARCH AND PERCEPTIONS OF REALITY

Research is the continuing search to identify and verify changing perceptions of reality. Verified perceptions constitute truth and in some cases facts. Truth is consistent with available relevant evidence and not contradicted by any important evidence (Ellis Cowling, North Carolina State University 1988, pers. comm.). Researchers often use declarative conclusive sentences that indicate the truth of their results from experiments or models as titles for their papers. In their abstracts and conclusions, however, their perceptions are often qualified by words such as estimate, likely, indicate, imply, suggest, or probably. This confirms the need for continuing research for perceptions of reality, but does detract from the surety of the titles and the conclusions.

Experimentation and modeling are used in a variety of ways to identify current conditions, and to predict how trees and forests will respond to, and be affected by, future carbon dioxide and ozone concentrations and warming temperatures, as influenced by other environmental and biological factors. Evaluation of the results involves connecting experimental variables and assumptions with results and conclusions, based on interactions and relationships. The extent and strength of the relationships indicates the degree of the new perceptions of reality or truth. Examples of some simple types of relationship are given below:

Association: A consistent relationship or association, ranging from weak to strong, is evident between variables. The significance of the relationship is not verified.

Correlation: A statistical procedure to determine the strength of linear regression relationships between two variables. An R^2 value (0–100%) determines the strength of the relationship. Statistically significant differences are calculated. Strong perceptions of new reality are possible.

Causation: A cause/effect relationship is established. Changes in what is considered to be the causal variable directly cause a corresponding effect in the other variable. Absent any confounding effects, this is proof of causation. Causation is the true perception of new reality or truth. Correlation is often incorrectly considered to be causation.

7.3 TREES AS EXPERIMENTAL PLANTS

Compared with annual plant species, trees are not ideal experimental plants. Slow growth, long life span, and large size preclude experimentation from seedling to maturity. Considerable variation also occurs within and between species.

Most trees result from germinated seeds. Seedling growth rates vary with species, and they may require 1–2 years or more of growth from seed germination to be useful. Older seedlings, young trees, and saplings are also used in experiments. Some trees are vegetatively propagated or cloned by rooting stem cuttings. These are fast-growing deciduous species and can be used for more rapid and more uniform growth responses. Species and hybrids of poplars (*Populus*) are usually propagated this way. For this reason, they are frequently used in experiments, especially in cooperative international research projects such as PopFACE and in the long-term AspenFACE experiment. Results from poplars are sometimes extended to relate to all tree species. "Tree" can be a generic term, especially in models.

Response to carbon dioxide, ozone, temperature, drought, and other factors varies considerably with tree age. Large trees function differently than seedlings or saplings. As seedlings progress to saplings and to mature trees, the amount of photosynthetically active tissue declines, and the amount of carbon stored in wood increases as cambial tissue increases. There are changes in uptake, transport, and distribution patterns of water and nutrients from soil. Developing canopies develop microclimates and differing light levels. This makes it difficult if not impossible for the responses of seedlings and younger trees used in experiments to be extrapolated directly (or scaled) to mature trees and forests (Pye, 1988). Samuelson and Kelly (2001) compared 63 examples of stomatal conductance of water vapor between younger and older trees and found considerable differences. They concluded that stomatal conductance rates for seedlings might underestimate ozone uptake by mature trees. Grulke and Miller (1994) found that seedlings of giant sequoia (*Sequoiadendron giganteum*) were ozone-sensitive until about 5 years old. After that, high water-use efficiency and compact leaf mesophyll tissues protected against ozone injury. Results from short-term experiments with tree seedlings or saplings and with elevated carbon dioxide and ozone do not predict well how mature trees will respond. Trees in nature adjust to changing temperatures and other environmental factors, site conditions and water availability, and changes that occur with age (Camarero *et al.*, 2015).

7.4 DETECTING TREE GROWTH

7.4.1 Tree Measurements

The influences of elevated carbon dioxide, ozone, temperature, drought, insect infestations, disease, and fires are reflected in tree growth and biomass development during the tree's life span. Tree biomass plays a key role in the global carbon and hydrological cycles. Assessing rates of tree growth and biomass development over time is essential to identify trends of environmental influence and to predict future growth and biomass in response to predicted environmental changes. Bowman *et al.* (2013) have provided an extensive and detailed review of detection of trends in tree growth.

Permanent sample plots provide long-term analysis of trends. Tree height and stem dbh (at 130 cm height) are common measures of tree growth (Bowman *et al.*, 2013). They are correlated with biomass and wood volume. The dbh can be measured for marked trees at regular intervals, and tree growth rates can be determined from the first sampling date. Long-term historical records of tree growth are available for retrospective analyses.

Nabuurs *et al.* (2013) used historical data on stem volume increments in Europe from 2005 to 2010 to detect slow-down in forest growth and indications of saturation of the forest carbon sink. Tang *et al.* (2016) used field surveys, tree growth measurements, and statistical records to estimate carbon sequestration capacity by trees in Beijing. They concluded that the "urban forest" of trees in Beijing sequestered one-third to one-half of the carbon sequestered by non-urban Chinese forests, and estimated that Beijing's trees sequestered 0.2% of the carbon dioxide emitted from energy production. Luyssaert and Cornelissen (2018) reviewed forest inventory data from the 1980s to 2000s to identify and characterize drought-tolerant trees, using tree diameters as an indication of biomass above the surface. More than 3 million trees were recorded by species and tree diameter. Drought-tolerant trees were identified on the basis of less reduction in growth caused by drought.

Dendrochronology, or tree ring analysis, can be used with trees that form clear annual growth rings in stem wood. It is a useful tool for retrospective investigations to evaluate past and current tree stem growth (Zhang, 2015). Annual growth-ring widths in cores from tree stems can be measured, and the rings counted and dated. Corrections are made for inherent tree age, size, and growth trends (Peters *et al.*, 2015). The ratio of ^{13}C to ^{12}C allows analyses of wood and wood metabolites from the present to millennia ago (Wieloch *et al.*, 2018). Dendrochronology methods are used to provide long-term data in temperate and boreal forests, with increasing use in tropical forests (Peters *et al.*, 2015). Bowman *et al.* (2013) state that tree diameter increment is widely used as a proxy for whole-tree growth.

Gazol *et al.* (2015) used tree ring data to assess and quantify growth trends, expressed as changes in basal area increment, for silver fir (*Abies alba*). Data were obtained from 1,300 trees at 111 sites in Spain, Italy, and Romania. Growth was limited in southern Europe by soil aridity. Increased warming in temperate northern Europe increased tree growth.

On-the-ground decadal forest monitoring studies in tropical forests have indicated decreasing rates of tree growth and biomass for some species, and increasing rates for others, in response to increasing carbon dioxide and temperature (Groenendijk *et al.*, 2015). They used tree ring analysis to examine growth trends for 13 specific tree species (approximately 1,300 trees) at a centennial scale in tropical forests in Bolivia, Cameroon, and Thailand. The aggregated trends indicated decreasing growth rates with time for eight to ten species, increasing growth rate for two species, and no trend for one species. These were not the growth patterns expected if elevated carbon dioxide had increased tree growth. The results suggested that not all tree species in tropical forests respond positively to elevated carbon dioxide. Van der Sleen *et al.* (2014) used tree ring analyses in the same areas as Groenendijk *et al.* (2015) to discern whether tree growth stimulation in undisturbed tropical areas was occurring. They measured stable carbon isotopes in wood growth rings in both understory and canopy trees, and concluded that water-use efficiency had increased by 30–35%. Analysis of the width of tree growth rings did not provide evidence of growth stimulation by carbon dioxide.

Cole *et al.* (2010), then followed by Peters *et al.* (2015), used several methods to determine how increasing carbon dioxide (over the past five decades) affected the growth of natural stands of clonal quaking aspen (*Populus tremuloides*) in Wisconsin. Tree rings were measured, and multivariate statistical analyses used to interpret results. Historical shifts in carbon dioxide and climate, and the age and genotype of clones were included. Growth of aspen increased on average 53% over the last 50 years. A 19.2% increase of carbon dioxide during that period was determined to be the likely cause. Soil moisture availability enhanced aspen growth.

7.4.2 *Soil Warming Experiments*

Increasing air temperatures will also increase soil temperatures. How this might affect tree growth and biomass under natural open-field ambient conditions has become an area of increasing interest. In experiments, a network of heating cables can be established in soil plots, and soil temperature can be increased. Plots without heating cables are used as ambient controls. Chung *et al.* (2013) reviewed open-field warming studies with temperate and boreal forest tree seedlings. Their general conclusions for heated soil results were that leaves emerged earlier and senesced later for a longer growing season. Incidence of and effects of herbaceous insects could occur. Litter decomposed more rapidly, resulting in increased nitrogen mineralization.

Butler *et al.* (2012) reported the results of 7 years of soil warming on growth responses of young forest trees at the Harvard Forest. Relative growth rate and leaf nitrogen increased considerably for red maple (*Acer rubrum*), and increased to a lesser extent for red oak (*Quercus rubra*) and white ash (*Fraxinus americana*). Differences in tree species responses were attributed to availability of increased soil nitrogen due to long-term warming.

Reich *et al.* (2015) designed a 3-year experiment to assess the influence of soil warming (approximately 3.4 °C) on the growth of 11 co-occurring boreal and temperate forest tree seedlings near their warm range limit. Net photosynthesis and growth were reduced for balsam fir (*Abies balsamea*) and white spruce (*Picea glauca*), intermediate for Scots pine (*Pinus sylvestris*), birch (*Betula papyrifera*), and poplar (*Populus tremuloides*), and enhanced for temperate species of maple (*Acer*) and oak (*Quercus*). In a similar soil warming experiment, Reich *et al.* (2016) determined rates of leaf respiration and acclimation in ten North American tree species to soil warming and local temperature variations. This suggests that soil warming will not increase leaf respiration at the expense of photosynthesis.

7.5 CONTROLLED EXPERIMENTS

7.5.1 *Interior Chamber and Greenhouse Experiments*

Early experiments with elevated carbon dioxide effects on trees were conducted in a variety of small interior growth chambers and

FIGURE 7.1 Greenhouse exposure chambers.
Controlled exposure.
(A black and white version of this figure will appear in some formats. For the color version, please refer to the plate section.)

greenhouse compartments (Overdieck, 2016). These chambers provided control over environmental factors that affect seedling growth and allowed detection of the effects of carbon dioxide with few confounding factors. Size limitations restricted the replication of treatments and the duration of experiments. An example of a small-chamber exposure system for exposing plants to ozone or carbon dioxide is shown in Figure 7.1. Predictive experiments compared tree growth and physiology at ambient carbon dioxide to the effects of doubled ambient carbon dioxide concentrations. Because of space constraints, seedlings or smaller trees grown in small chambers were often grown in small-volume pots. After initial growth stimulation due to higher carbon dioxide, growth and photosynthesis was often reduced. Arp (1991) attributed this to the restriction of volume for root growth.

Tjoelker *et al.* (1998) used growth chambers to investigate acclimation of net photosynthesis in boreal seedling tree species to elevated carbon dioxide (580 ppm) and temperature. Tree species, rather than temperature, appeared to be a better determinant of carbon dioxide effects on photosynthesis: increases in net photosynthesis were expressed more by the slower-growing conifers black spruce (*Picea mariana*), jackpine (*Pinus banksiana*), and larch (*Larix laricina*) than by the faster-growing deciduous aspen (*Populus tremuloides*) and birch (*Betula papyrifera*). Elevated carbon dioxide effects on net photosynthesis were better expressed on a leaf area basis rather than on a leaf mass basis. Because of the low number of growth chambers available, replication in time was necessary – that is, experiments had to be repeated to cover the number of different treatments required. Bazzaz *et al.* (1993) used greenhouse compartments to investigate simultaneously the effects of elevated carbon dioxide on six co-occurring temperate tree species: ash (*Fraxinus americana*), gray birch (*Betula populifolia*), red maple (*Acer rubrum*), yellow birch (*B. alleghaniensis*), striped maple (*A. pennsylvanica*), and red oak (*Quercus rubra*). Growth stimulation from elevated carbon dioxide for all species was greater in year one than in year three, but the growth stimulation declined at different rates for different species as affected by nutrient and light availability.

Similar small chambers were also used to investigate ozone effects on tree seedlings. Detailed chamber descriptions and evaluations are found in Manning (2005). Unlike carbon dioxide, ambient concentrations of ozone vary considerably in nature and are high enough to cause leaf injury and growth effects only on a periodic basis. Many of the early experiments involved steady-state (square wave) daily exposures of ozone concentrations for 8 hours a day. Reich and Lassoie (1985) used growth chambers to investigate the effects of 10-week exposure to a range of ozone concentrations (25, 50, 85, and 120 ppb) on growth and biomass of a hybrid poplar (*Populus deltoides* × *trichocarpa*). After 10 weeks, 85 and 120 ppb ozone reduced height, growth rates, and leaf senescence. Leaf, stem, root, and total dry weight per plant were reduced by 10–15% compared with plants exposed to 25 or 50 ppb ozone. Davis and Skelly

(1992) used chamber fumigations with ozone (75 or 150 ppb) to identify foliar ozone injury symptoms on eight deciduous tree species. Based on extent of symptom expression (stipple and defoliation), black cherry (*Prunus serotina*) was the most sensitive, followed by sweetgum (*Liquidambar styraciflua*), yellow poplar (*Liriodendron tulipifera*), white ash (*Fraxinus americana*), red maple (*Acer rubrum*), and yellow birch (*Betula alleghanensis*). Red oak (*Quercus rubra*) and white oak (*Q. alba*) did not have visible injury symptoms. Keane and Manning (1988) grew birch (*B. papyrifera*) seedlings in soil with or without added inoculum of the ectomycorrhizal fungus *Pisolithus tinctorius*. Seedlings were grown in greenhouse chambers for 12 weeks and exposed to either 60–80 ppb ozone or charcoal-filtered air. Ozone reduced birch seedling growth and the extent of mycorrhizal colonization. Mycorrhizal colonization did not reduce incidence of the effects of ozone on birch seedling growth. Pye (1988) has extensively reviewed early chamber experiments with ozone effects on young trees.

Much of the early experimental work with trees in interior chambers focused on single-factor (reductionist) predictive experiments comparing ambient carbon dioxide concentration with immediate 50–100% increases in carbon dioxide levels. Gradual adaptation to slower increases in carbon dioxide was not considered.

While advancing fundamental knowledge, results from small chambers are only relevant to the chamber conditions and exposure regimes for both carbon dioxide and ozone. From a toxicology perspective, however, small-chamber experiments, where treatments are replicated and where environmental conditions are controlled, are ideal for establishing cause/effect relationships. The short-term influence of carbon dioxide and ozone alone can be determined for tree growth, physiological functions such as photosynthesis, stomatal conductance, and respiration. Ozone injury can be documented and verified. Results from interior chambers provide short-term indications of what extreme future effects of carbon dioxide and ozone might be, from 2050 to 2100.

7.5.2 Field Chambers and Exposure Systems

Results from exposure experiments with small chambers encouraged researchers to develop techniques for use with larger trees in the field. Much interest in working with ozone, carbon dioxide, and temperature under more realistic ambient conditions prompted the development of a number of open and field chambers (Manning and Krupa, 1992; Manning, 2005; Overdieck, 2016). The size and long-term nature of these chambers made it possible to plant trees directly in the ground under more natural growing conditions. The movement to field chambers eliminated the completely controlled environmental conditions of the small interior chambers and introduced more variables in assessment of treatment effects on tree growth. Long-term, fully replicated, multi-year experiments under semi-controlled conditions were possible.

7.5.2.1 Open-top Chambers

Open-top chambers (OTCs) were developed for long-term experiments. Complete environmental control in the small interior chambers was lost and replaced by semi-controlled conditions and completely replicated treatments. Heagle *et al.* (1973) developed an OTC that remains widely used. Charcoal-filtered air, with or without addition of carbon dioxide or ozone, is introduced into a large, plastic-sided OTC (3.5 m diameter, 2.22 m high) by fan movement over trees with upward air flow out of the top of the chamber. An example of an OTC in the field is shown in Figure 7.2. OTCs reduce some available light and increase air temperature and relative humidity, while wind velocity is steady and reduced. Norby *et al.* (1997) modified the design and function of OTCs to include increased air temperatures. Despite concerns about environmental differences within OTCs, increases in chamber size and the ability to grow trees in the ground for long periods made OTCs very attractive for research.

Rey and Jarvis (1998) grew silver birch seedlings in OTCs, exposed to either 350 or 700 ppm carbon dioxide, for four growing

FIGURE 7.2 OTC in the field.
Semi-controlled exposure to ambient environment.
(A black and white version of this figure will appear in some formats. For the color version, please refer to the plate section.)

seasons. Elevated carbon dioxide increased photosynthesis by an average of 33% by the end of the four seasons. However, photosynthetic capacity – that is, the rate of photosynthesis per unit leaf area – was reduced by elevated carbon dioxide. Decreased carboxylation efficiency and regeneration of RuBP were concluded to be the basis for acclimation to elevated carbon dioxide. Hattenschwiler and Korner (2000) determined the influence of three different quantum flux densities (QFD) (ranging from 0.36 to 2.16 to 4.8% of full sun) on growth and biomass of six European forest tree species to 360, 500, and 660 ppm carbon dioxide, utilizing 12 OTCs at each QFD location. Tree species responded differently to carbon dioxide concentrations and site QFDs. Elevated carbon dioxide increased growth of shade-tolerant beech (*Fagus sylvatica*) and yew (*Taxus baccata*) at low-QFD locations, but not at high QFD. Sycamore maple (*Acer pseudoplatanus*), red oak (*Quercus rubra*), and white fir (*Abies alba*), which are less shade-tolerant, did not respond at low QFD, but did increase biomass at high QFD. Scots pine (*Pinus sylvestris*) is shade-intolerant and grew poorly. Greatest growth stimulation occurred at 500 ppm carbon dioxide. They concluded that elevated carbon dioxide may alter understory species performance and change the composition of future forests.

Bortier *et al.* (2000) compared the effects of ozone on poplar (*Populus nigra*) grown from cuttings and beech (*Fagus sylvatica*) grown from seed in OTCs. Ozone significantly reduced the growth and biomass of fast-growing poplar, but its effects on slow-growing beech seedlings were not significant. These results confirmed earlier observations that fast-growing tree species were more likely to be adversely affected by ozone. Calatayud *et al.* (2007) used OTCs in Spain to assess the effects of ozone on four species of maple (*Acer*). He exposed them to charcoal-filtered air (12-hr mean 11.6 ppb), ambient air (12-hr mean 46.3 ppb), and non-filtered air + 30 ppb (12-hr mean 65.1 ppb). Exposure to non-filtered air + 30 ppb caused some growth reduction for all four *Acer* species, with differing responses in foliar injury, gas exchange, and chlorophyll fluorescence. Norby *et al.* (1997) compared the response of yellow poplar (*Liriodendron tulipifera*) and white oak (*Quercus alba*) seedlings to elevated carbon dioxide in OTCs. There was no significant increase in dry mass at final harvest for yellow poplar, but a significant increase for white oak despite differences in photosynthesis and respiration. Results from differences in seedling biomass in response to elevated carbon dioxide might not be good predictors of long-term responses under forest conditions.

7.5.2.2 Whole-tree Chambers

OTCs are too small to accommodate large trees. Larger whole-tree chambers (WTCs) were developed to enclose single mature trees in situ. The same environmental modifications that affect results from OTCs also prevail with WTCs. Increased expense for construction, and the large amount of carbon dioxide required for daily release, have limited their use.

Hall *et al.* (2009) used WTCs to study elevated carbon dioxide and temperature effects on 45-year-old Norway spruce (*Picea abies*) in the boreal region of northern Sweden for two complete years. The focus was continuous assessment of net assimilation rate (NAR) in individual buds and shoots, beginning at early bud development and continuing until late August. Monthly temperature increases ranged from 2.8 °C in July and August to 5.6 °C in December. In response to temperature increase, shoot development began 1–3 weeks earlier and was completed earlier, with positive effects on NAR. Elevated carbon dioxide (700 ppm) increased NAR by 30% later in the season. Interaction did not occur between elevated temperature and carbon dioxide. Prediction for effects of future climate in 2100 are that current-year shoots will assimilate carbon 20–30 days earlier than now.

From similar experiments with Norway spruce, Sigurdsson *et al.* (2013) concluded that low nutrient availability, a key factor limiting tree growth in boreal forests, would limit spruce response to elevated carbon dioxide and temperature. Lamba *et al.* (2017) continued investigations on elevated temperature and carbon dioxide effects on mature boreal Norway spruce. They found that long-term physiological acclimation reduced the initial increased net carbon assimilation due to both carbon dioxide exposure and the effects of warming on water use. Current models may overestimate the effects of warming and elevated carbon dioxide on boreal Norway spruce.

7.5.2.3 Free-Air Carbon Dioxide Enrichment (FACE)

OTCs and WTCs do not provide enough open space or volume for long-term experiments with trees. They have innate effects on chamber environment that need to be considered. Free-air chamberless gas-dispensing exposure systems were developed to provide more space and to reduce experimental effects. Originally designed to dispense carbon dioxide (FACE stands for Free-Air Carbon dioxide Enrichment system), they can also be used to dispense ozone, or ozone and carbon dioxide together. Circular plots (25–30 m in diameter) were established. PVC pipe circles the plot or ring diameter. Upright PVC pipes, with inward facing holes, are placed at regular intervals in the ring. Blowers are used to dispense carbon dioxide through the holes and across the rings. A steady carbon dioxide concentration is maintained by monitoring carbon dioxide in the ring and adjusting it for wind speed and direction. The temperature in the rings is the same as ambient, and precipitation is included. The FACE system allows long-term, multiple-year experiments with fewer confounding effects. However, costs to establish and use with carbon dioxide can be very high.

The purpose of long-term experiments with elevated carbon dioxide and trees is to predict future rates of photosynthesis, carbon allocation, and carbon storage in wood in 2050 and 2100, and to determine what role this may play in partially mitigating global warming and climate change. FACE systems are suitable for this purpose. The carbon dioxide concentrations used range from immediate 50% to 100% increases from current ambient, with 400 ppm used as a control. Much has been learned about tree responses to long-term carbon dioxide exposure from 550 to 800 ppm. The results are used in predictive global carbon cycle models.

Drake *et al.* (2016) used their six-ring Eucalyptus Free-Air CO_2 Enrichment (EucFACE) site in Southeast Australia. The site contains mature native trees, primarily *Eucalyptus teretricornis*. Photosynthesis and soil carbon flux were determined at each step. Warren *et al.* (2014) summarized a small 12-year (1998–2009) FACE experiment on photosynthesis in sweetgum (*Liquidambar styraciflua*), using four FACE rings. Treatments consisted of two ambient and two 560 ppm carbon dioxide treatments, allowing for two replications. An additional adjacent non-FACE ring served as an ambient control. Elevated carbon dioxide initially increased photosynthesis, but it was not sustained when leaf concentrations of nitrogen decreased to sub-optimal. Their important conclusion was that elevated carbon dioxide may initially increase photosynthesis, but it may decline with time if nitrogen also declines. Additional treatment replications would have increased the strength of the conclusion.

FIGURE 7.3 AspenFACE experiment.
Exposure under ambient environmental conditions.
(A black and white version of this figure will appear in some formats. For the color version, please refer to the plate section.)
Photo courtesy of John Couture, UW-Madison

The largest and most productive FACE experiment, initially led by the late David Karnosky, was AspenFACE, established in Rhinelander, Wisconsin, and ran from 1997 to 2009. Twelve 30-m rings, in three replicates of four each, were established to include four treatments (elevated carbon dioxide 550 ppm, elevated ozone 60–80 ppb, elevated carbon dioxide + elevated ozone, and ambient control 350–380 ppm carbon dioxide and 30–50 ppb ozone). The field plot plan for this experiment is shown in Figure 7.3. Six aspen (*Populus tremuloides*) clones were planted in one half of each ring. The other half was divided into quarters. One quarter was planted with aspen/paper birch (*Betula papyrifera*) and the other with aspen/sugar maple (*Acer saccharum*). Elevated carbon dioxide increased photosynthesis and NPP for aspen and birch, but not for sugar maple (Karnosky *et al.*, 2007). Elevated carbon dioxide increased competitive space utilization in aspen/birch at the expense of aspen (Kubiske *et al.*, 2007). Elevated ozone reduced biomass for aspen and to a lesser degree for birch. Carbon dioxide did not provide complete protection from biomass reduction by ozone in the carbon dioxide plus ozone treatment (King *et al.*, 2005). By the end of the experiment, elevated carbon dioxide alone continued to stimulate photosynthesis and NPP, except for sugar maple. Negative effects of elevated ozone decreased by the end of the experiment (Burton, 2014; Talhelm *et al.*, 2014).

A complete summary of ecosystem carbon content, from mineral soil to tree foliage, after 11 years of treatment in AspenFACE with carbon dioxide, ozone, or carbon dioxide plus ozone, is illustrated in Figure 7.4. Overall, carbon dioxide had a 11% positive effect, while ozone had a 9% negative effect. Carbon dioxide stimulated tree growth and narrowly reduced the negative effects of ozone, with biomass close to ambient effects.

More than 120 researchers from nine countries collaborated in AspenFACE. These collaborations resulted in 207 publications, with 169 in scientific journals (Burton, 2014). Results and conclusions from AspenFACE provide much of what is known about the long-term effects of elevated carbon dioxide and ozone on growth and biomass production by seedlings and saplings of deciduous temperate-zone trees. Examples of recent elevated carbon dioxide FACE sites and trees include the Duke Forest site (North Carolina, USA), with *Pinus taeda* and *Liquidambar styraciflua*, and PopFACE international (originating in Italy), with *Populus* hybrids. Newer FACE sites have been developed in Australia, Switzerland, and Japan (Overdieck, 2016). FACE experiments with carbon dioxide are appropriate for temperate forest trees (Hickler *et al.*, 2008), but are not applicable to boreal or tropical forests.

Atmospheric carbon dioxide, however, increases slowly, and trees are also likely to respond and adapt slowly over time. This has been investigated, to some extent, with crop plants and grasses in growth chambers and outdoor dilution tunnels, using increasing concentrations of carbon dioxide. It would be prohibitively expensive to try to use the FACE method to determine the effects of realistic slow increases in

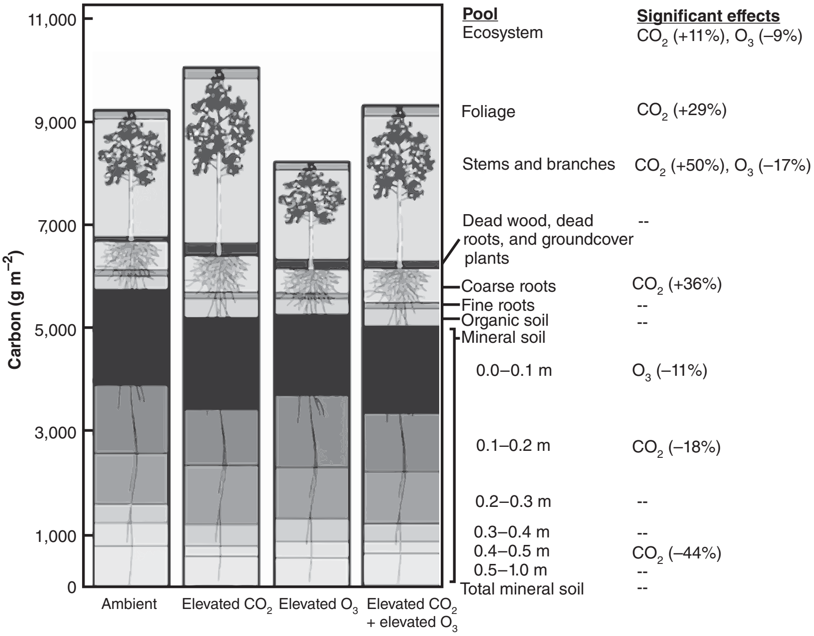

FIGURE 7.4 Ecosystem carbon content after 11 years of fumigation at the AspenFACE experiment.
Data are averaged across the three forest community types and include soil to 1 m in depth. The height of each bar segment represents the mean size of each pool, and the total bar height represents ecosystem C content for each treatment. For simplicity, soil C below 0.5 m in depth is grouped into a single pool because there were no significant treatment effects. Significant ($P \leq 0.05$) effects of the treatment gases and the size of these effects (%) are shown to the right of the figure. Pools without significant treatment effects are denoted with '–'. With the exception of two small pools (foliage, groundcover plants), there were no significant treatment × community interactions.
(A black and white version of this figure will appear in some formats. For the color version, please refer to the plate section.)
From A. F. Talhelm *et al. Global Change Biology*, Elevated carbon dioxide and ozone alter productivity and ecosystem carbon content in northern temperate forests © (2014). Adapted by permission of John Wiley & Sons, Inc.

carbon dioxide, ranging from pre-industrial levels to elevated carbon dioxide levels of more than 400 ppm (Gerhart and Ward, 2010).

Drake *et al.* (2016) developed an unique sequential step exposure system to gradually increase carbon dioxide at short defined

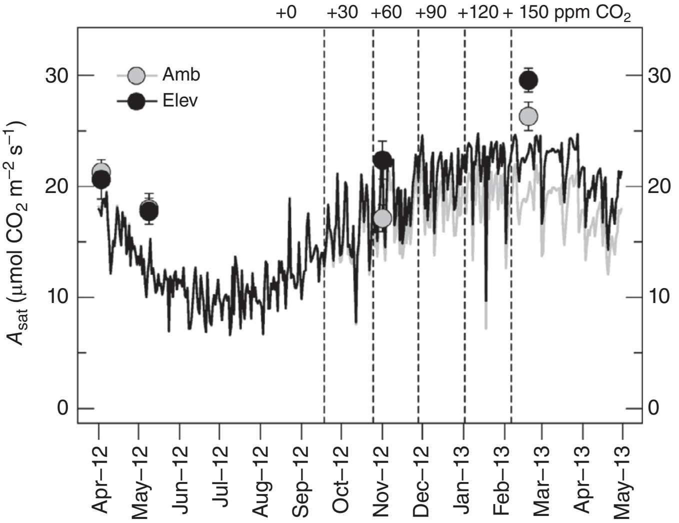

FIGURE 7.5 Measured and modeled rates of light-saturated photosynthesis (A_{sat}) in upper canopy leaves during the mid-morning during the stepwise increase in [CO_2] at EucFACE.

A_{sat} was measured on four campaigns (large circles) and modeled for each day (lines). Error bars reflect ±1 SE ($n = 3$).

From J. E. Drake *et al. Global Change Biology*, Short-term carbon cycling responses of a mature eucalypt woodland to gradual stepwise enrichment of atmospheric CO_2 concentration. Copyright © (2016) by John Wiley & Sons, Inc. Reprinted by permission of John Wiley & Sons, Inc.

intervals over time to allow study of short-term carbon cycling at each step, and overall at the conclusion of the experiment. Large eucalyptus trees, growing in nutrient-poor soil in Southeast Australia, were used in a FACE exposure experiment. Canopy leaf photosynthesis was the focus of the experiment. Treatments were 400 ppm control, with a menu of five step increases, beginning with step 1 at 30 ppm (total 430 ppm) and continuing with 60 ppm (460 ppm), 90 ppm (490 ppm), 120 ppm (520 ppm), and 150 ppm (550 ppm). Each step-addition exposure lasted 5 weeks. Photosynthesis in canopy leaves acclimated at step 2, 60 ppm (460 ppm), and remained the same through step 5, 150 ppm (550 ppm) (Figure 7.5). Soil carbon flux increased at both step 1 and step 2, but not at steps 3, 4, and 5. They interpreted the rapid increase in soil carbon flux to be due to rapid translocation of carbon from photosynthesis below-ground and release in respiration. They determined that soil carbon flux and photosynthesis interacted on a very short timescale, and that additional research is needed to investigate the significance of this in relation to effects of elevated carbon dioxide and the carbon cycle.

7.5.2.4 Branch-in-Bag Method

OTCs, WTCs, and FACE systems allow long-term research on growth and biomass of tree seedlings and saplings. The branch-in-bag (BiB) method was developed to ascertain how leaves and branches of older, more mature trees would respond, primarily to elevated carbon dioxide, under semi-field conditions. Ventilated transparent bags are placed over selected branches for either the short term or a whole growing season duration. Half are ventilated with ambient air carbon dioxide (control), and half are ventilated with ambient air plus carbon dioxide to desired concentration (treatment). Results from leaves are assumed to include the enclosed branch (Overdieck, 2016), but cannot be extrapolated to the whole tree.

The BiB method has been useful for investigations for detailed physiological responses of leaves to elevated carbon dioxide and the influence of other factors, such as soil nitrogen levels, over growing seasons. Roberntz and Stockfors (1998) used this method to investigate the effects for Norway spruce of ambient carbon dioxide (370 ppm), elevated carbon dioxide (ambient carbon dioxide plus 370 ppm), and soil nitrogen levels on photosynthesis, respiration, carbohydrate accumulation, and acclimation. Elevated carbon dioxide increased average light-saturated photosynthesis by 55%. Increases were higher in needles with higher nitrogen concentrations than lower ones. Elevated carbon dioxide decreased the photosynthetic capacity, reducing rates by 8–32%, reduced carboxylation efficiency, and increased respiration rates. Rates of carbohydrate accumulation were increased by elevated carbon dioxide, while levels of nitrogen, potassium, and magnesium were reduced. Acclimation to elevated carbon dioxide was larger in needles with lower nitrogen concentrations.

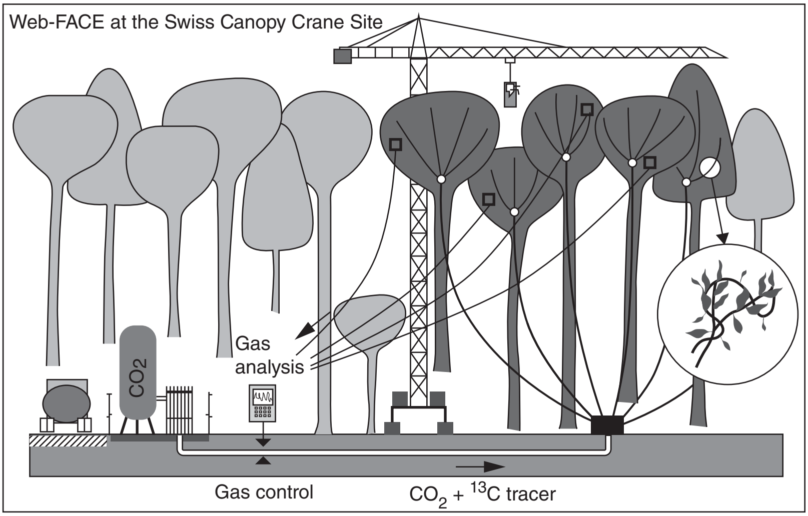

FIGURE 7.6 Web-FACE is a canopy free-air CO_2 enrichment system for tall trees in mature forests.

Adapted by permission from Springer Nature: Springer Nature Ltd, *Oecologia* **133**, 1–9, Web-FACE: a new canopy free-air CO_2 enrichment system for tall trees in mature forests, S. Pepin & C. Korner, © (2002)

7.5.2.5 Web-FACE

Branch bags (BiB) enable measurement of the response of leaves of trees to elevated carbon dioxide or ozone, but plastic bags alter the branch environment, and results cannot be extrapolated to whole trees. Recognizing this, Pepin and Korner (2002) developed a free-air method (Web-FACE) for applying carbon dioxide to the canopies of large mature trees in Switzerland. The site was called the Swiss Canopy Crane Site: a large crane was used to install a carbon dioxide release system within the crowns of large trees. Connected to it was a network of small tubes distributed uniformly in the tree canopies. Elevated carbon dioxide was released through small holes in the tubes throughout the growing season (Figure 7.6). To maintain 500 ppm carbon dioxide for 14 tall trees for one growing season required 2 tonnes of carbon dioxide per day.

Asshoff *et al.* (2006) used the Swiss Canopy Crane Site to assess the effects of 4 years of seasonal 540 ppm carbon dioxide exposure on stem growth of 11 tall trees: three sessile oak (*Quercus petrae*), three hornbeam (*Carpinus betulus*), four beech (*Fagus sylvatica*), and one big leaf linden (*Tilia platyphyllos*). They used δ^{13}C isotope data from tree rings before and after exposure to carbon dioxide to detect carbon dioxide uptake from exposure to elevated carbon dioxide (δ^{13} C = $[(^{13}C/^{12}C)_{sample}/(^{13}C/^{12}C)_{standard}] - 1$). The δ^{13}C signal varied, with linden the strongest and beech weaker (Figure 7.7). At the end of the 4-year experiment, there was no appreciable increase in stem growth. They concluded that future elevated levels of carbon dioxide are not likely to increase tree stem growth and stem wood.

Bader *et al.* (2013), also working at the Swiss Canopy Crane Site, exposed a natural forest site with mixed species of mature trees to 550 ppm carbon dioxide for eight growing seasons. The elevated carbon dioxide reduced tree water use and litter production, but radial growth for all hardwood species was unaffected. Using their results, they challenged the assumption that elevated carbon dioxide will provide a global fertilization effect that will increase forest tree growth. This was a concern for them, as this assumption is commonly used in predictive carbon cycle models.

Klein *et al.* (2016) exposed 110-year-old Norway spruce (*Picea abies*) to 550 ppm carbon dioxide for 5 years. The trees were not considered to be carbon-limited at the onset of exposure. Over time, the trees absorbed 37% more carbon dioxide than ambient control trees. There were no positive effects on stem diameters, apical growth, or needle litter. The authors proposed a missing sink for the increased uptake of carbon dioxide, one possibility being transfer to ectomycorrhizae associates with roots.

Leuzinger and Korner (2007) studied the oak, hornbeam, and beech at the Swiss Canopy Crane Site, exposing trees to 540 ppm carbon dioxide. Sap flow was reduced by 14% for all tree species, resulting in reduction of approximately 10% in evapotranspiration. Using stomatal response as a measure, the effects of elevated carbon dioxide were most pronounced in hornbeam and beech, but not evident in oak. During dry periods, soil moisture levels declined more slowly under trees treated with elevated carbon dioxide. Leuzinger

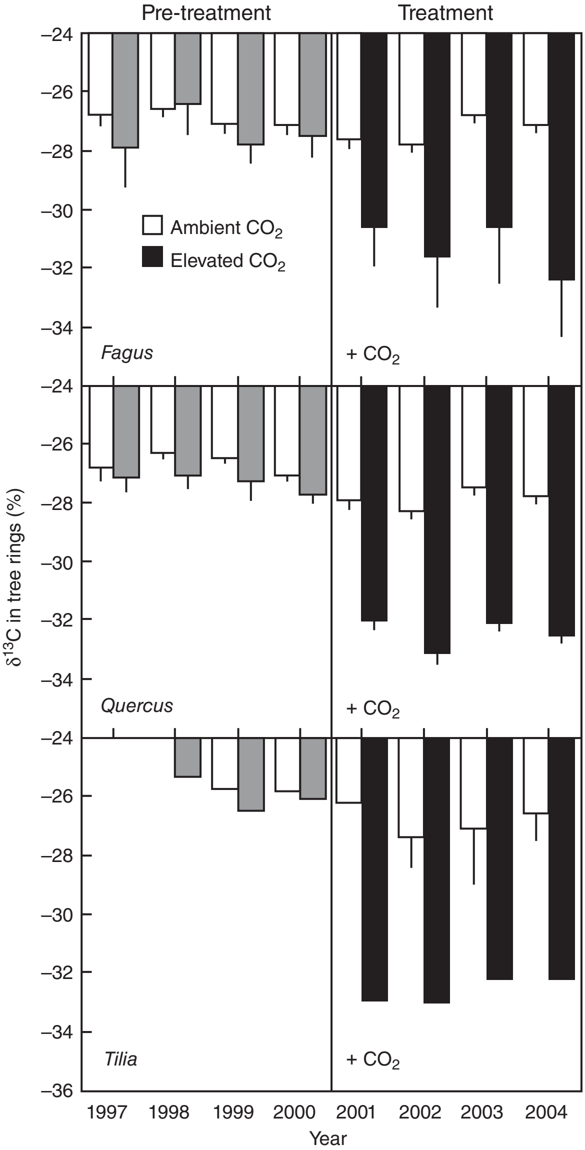

FIGURE 7.7 $\delta^{13}C$ of tree rings in the years before CO_2-enrichment (1997–2000) and during the experiment (2001–2004) for *Fagus*, *Quercus*, and *Tilia* (mean ± SE).

Treated trees and controls did not differ significantly in their $\delta^{13}C$ value before the onset of the experiment (2000, $P = 0.45$). Gray bars (1997–2000) indicate trees later exposed to CO_2.

From R. Asshoff *et al. Global Change Biology*, Growth and phenology of mature temperate forest trees in elevated CO_2. Copyright © 2006 by John Wiley & Sons, Inc. Adapted by permission of John Wiley & Sons, Inc.

and Korner suggested a 10% decrease in water use for these types of trees in response to future elevated carbon dioxide. Their documentation of an approximate 10% reduction in evapotranspiration by elevated carbon dioxide is important. Extending this to a large scale could mean a reduction in atmospheric cooling.

Matyssek *et al.* (2007), working in the Kranzberg Forest in Bavaria, reported the results of their crane Web-FACE experiment with whole-tree exposure to twice ambient ozone (maximum allowable concentration 150 ppb) for a 5-year period for 60-year-old 30-m beech trees (*Fagus sylvatica*). A non-significant decrease in average annual stem growth of 3% was found. Fine root and ectomycorrhizal development was stimulated.

7.6 CHEMICAL PROTECTANTS

Exposure chambers and FACE installations are designed primarily to determine the effects of projected future elevated steady-state concentrations of carbon dioxide and ozone on trees. Unlike carbon dioxide, levels of ambient ozone fluctuate widely. Periodic episodes of elevated ozone can cause foliar injury, which over time leads to growth reduction. Determining these effects under truly ambient conditions is difficult. However, a variety of chemicals have been recognized as having protective effects against ozone injury for plants growing in the field under ambient conditions, without chambers (Manning, 2000). Thus, by applying ozone-protective chemicals to some of the plants and not others, the effects of natural ozone exposure can be studied. This has allowed multi-year research on tree growth and biomass under natural ozone exposure and conditions. The most successful and widely used protectant chemical compound is ethylenediurea (abbreviated as EDU), N-[2-(2-oxo-1-imidazolidinyl)ethyl]-N′-phenylurea. The complete mode of action of EDU remains elusive, but it is known that it does not provide protection from ozone by acting as a nitrogen supplement (Manning *et al.*, 2011).

EDU was used to protect loblolly pine (*Pinus taeda*) seedlings from ambient ozone in a replicated treatment field plot upwind of

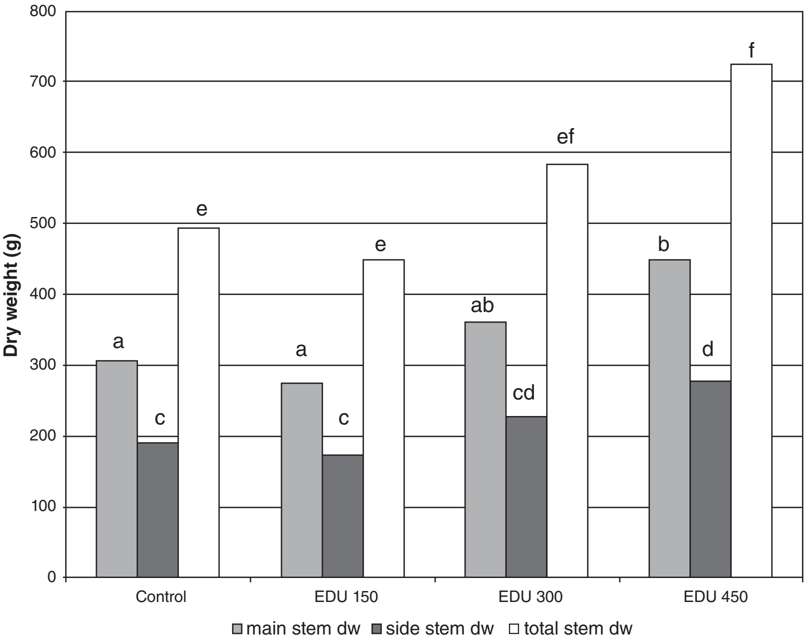

FIGURE 7.8 Dry weights for main stems, side stems, and total stem weight in relation to EDU treatments.
Values that have the same letter designations are not significantly different from each other ($P = 0.05$).
Adapted from *Environmental Pollution* **126**, 73–81, W. J. Manning *et al.*, Assessing plant response to ambient ozone: growth of ozone-sensitive loblolly pine seedlings treated with ethylenediurea or sodium erythorbate, Copyright (2003), with permission from Elsevier.

Houston, Texas, outside the town of Nacogydoches, Texas, for three growing seasons. EDU was applied as biweekly foliar sprays, at 150, 300, and 450 ppm, to ozone-sensitive half-sib loblolly pine seedlings during the growing season. Water sprays were used as the control treatment. Ambient ozone levels were often in the 50–60 ppb range, with periodic episodes as high as 118 ppb. At the conclusion of the third growing season, ambient ozone had significantly reduced the total biomass. EDU at 450 ppm prevented the effects of ozone; EDU at 150 and 300 ppm provided less protection (Figures 7.8 and 7.9). This provided verification of the effects of ambient ozone on

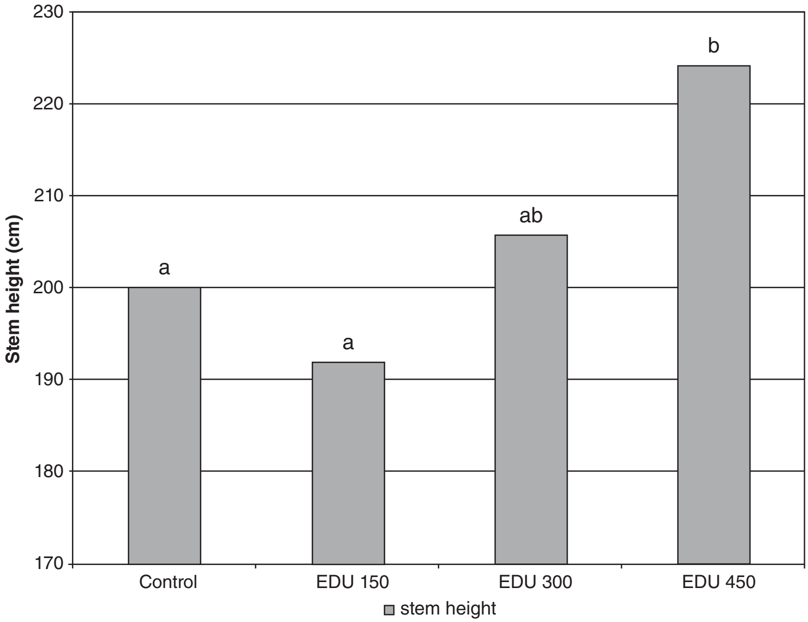

FIGURE 7.9 Stem height (in cm) in relation to EDU treatments. Values that have the same letter designation are not significantly different from each other ($P = 0.05$). Average of 30 seedlings per treatment.

Adapted from *Environmental Pollution* **126**, 73–81, W. J. Manning *et al.*, Assessing plant response to ambient ozone: growth of ozone-sensitive loblolly pine seedlings treated with ethylenediurea or sodium erythorbate, Copyright (2003), with permission from Elsevier.

loblolly pine under completely natural conditions (Manning *et al.*, 2003).

The influence of ambient ozone on growth and biomass of an ozone-sensitive clone of hybrid poplar (Oxford) was determined for three and six growing seasons in a field plot near Florence, Italy. Protection from ozone injury and growth reduction effects was found after 3 years (Hoshika *et al.*, 2013). By the end of the sixth growing season, the trees had been exposed to a total of 23 ppm ozone hours (AOT40 cumulative value). Ambient ozone reduced the biomass and root volume, and stem diameter decreased in the lower third of the stem. EDU treatments prevented the effects of ambient ozone (Carriero *et al.*, 2015).

7.7 META-ANALYSIS OF RESULTS FROM DIRECT METHODS

Results from FACE investigations and chamber experiments are available in hundreds of reports of numerical evidence for interactions between trees, carbon dioxide, ozone, and combinations of both gases. Meta-analysis is a statistical method that can be used to combine the findings of many experiments, find the average of the effects, make generalizations, and draw conclusions. The conclusions are often used in predictive models of the effects of elevated carbon dioxide and ozone on forests (Haworth *et al.*, 2016).

De Dios *et al.* (2016) used a meta-analysis to explore intraspecific variation in juvenile tree growth in response to elevated carbon dioxide and ozone, alone and in combination. Twenty-five reports from FACE, OTC, BiB, growth chambers, and greenhouses were used. Of the seven tree species used, Sitka spruce (*Picea sinensis*) and poplar (*Populus deltoides*) predominated. For elevated CO_2, tree growth and photosynthesis increased on average by 57.7%. Stem biomass increased by 36%, as did stem volume and stem biomass. Stem height increased only by 9.5%. Elevated ozone generally reduced height, stem volume, and photosynthesis. Trees that grew well with elevated carbon dioxide tended also to grow well with elevated carbon dioxide and ozone.

Wittig and Long (2004) published a very long and detailed meta-analytic review of the response of plants to elevated carbon dioxide in FACE exposure systems. Trees were more responsive than crop plants. Results from actively growing young tree species in Aspen-FACE, Duke Forest, Oak Ridge (USA), ETH-Z (Switzerland), and Pop-FACE (Italy) were the primary sources. In general, there was a 28% increase in above-ground dry matter due to exposure to elevated carbon dioxide. Stem diameter increased by 9%. Leaf number increased by 8%, but LAI did not change with tree growth. Stomatal conductance decreased, and photosynthetic acclimation increased.

Wittig *et al.* (2009) used meta-analysis to assess the impact of current levels of ozone (average 40 ppb) and estimated future levels of ozone (64 ppb and 97 ppb) on tree biomass, growth, physiology, and biochemistry in Northern Hemisphere forests. Current ozone levels reduced tree biomass by 7%, while 64 ppb reduced it by 11%, and 97 ppb reduced it by 17%. Elevated ozone reduced root/shoot ratios, leaf area, chlorophyll, and rubisco. Respiration rates were reduced, as were tree heights and stem diameters. The effects of elevated ozone were significantly less for gymnosperms than angiosperms. From this, Wittig *et al.* predicted that if ozone were to rise to the elevated levels used in their analysis, this would lead to a reduction in the future forest carbon sink.

Li *et al.* (2017) used meta-analysis to determine the future influence of elevated ozone (116 ppb) on growth and biomass, as affected by tree and leaf type. Chinese temperate deciduous species were more sensitive than deciduous species originally from Europe and North America in terms of effects on growth, photosynthesis, and respiration. Elevated ozone reduced tree biomass by 14%, also reducing tree height and stem diameter. Subtropical broad leaved evergreen and needle-leaf species were less sensitive than temperate deciduous trees. Given that subtropical broad leaved species are dominant in forests in China, future ozone effects may be less than predicted for increasing ozone levels.

Lyons *et al.* (2016) suggested that the generalizations derived from meta-analyses, because they are from average values, should be considered not whole truths, but half truths. Haworth *et al.* (2016) replicated some of the methods used in reported meta-analyses of tree and other plant responses to elevated carbon dioxide. They concluded that the meta-analyses exaggerated the magnitude of the effects by 20–40%. Their concern was that average values from meta-analyses are often used in models to predict the effects of future elevated carbon dioxide on trees and plants.

7.8 INDIRECT METHODS OF ASSESSMENT

Direct methods, such as experimental chambers and FACE, with limited numbers of trees, provide empirical evidence of biogeochemical and biogeophysical effects of elevated carbon dioxide and ozone. Much has been discovered about the influence of elevated carbon dioxide and increasing temperature on photosynthesis, transpiration, and water-use efficiency by leaves (Way *et al.*, 2015). Moving up to forest and ecosystem levels requires many different assumption-based methods or often combinations of these, resulting in less-specific generalizations, rather than empirical evidence. Indirect methods include use of flux tower data or satellite and remote sensing results, and many models that combine several methods and statistical analyses. The number of combinations is extremely large. Most of what we know about large-scale elevated carbon dioxide and ozone effects on forests was concluded from model results.

7.8.1 Flux Towers for Carbon Dioxide

Large towers, containing instrumentation to measure wind speed and direction, temperature, carbon dioxide, water vapor, and other gases, are placed above forest canopies. They continually and directly measure changes in covariance between the upward and downward movement of gases in turbulent air between the canopy and the atmosphere. A global network of more than 500 flux towers (FLUXNET) has been established (NCAR, 2017) and can measure how much carbon dioxide and water vapor flows in or out, in wind gusts or eddies (Baldocchi, 2003, 2014; Burba *et al.*, 2013). Carbon dioxide flux values are calculated on the half hour. Positive flux indicates net loss of carbon dioxide (from respiration), and negative flux indicates carbon dioxide uptake (photosynthesis). The flux data require additional processing to determine carbon dioxide uptake in photosynthesis and release in respiration (Campioli *et al.*, 2016).

Flux towers require turbulence to function well. They are also not effective for individual trees, small areas, and uneven topography (Baldocchi, 2003; Campioli *et al.*, 2016).

Ueyama *et al.* (2014) used 9 years of carbon dioxide flux data to investigate the role of summer warming, a longer growing season, and a warmer autumn on GPP and respiration in black spruce (*Picea* *mariana*). They concluded that black spruce shifted during the course of the experiment from a carbon sink to a carbon source, and that the effect was due to increased autumnal warming and respiration and not GPP. Hopkinson *et al.* (2016) compared repeat airborne laser scanning (ALS) of three-dimensional forest plot structure to data from flux towers for mixed-age jack pine (*Pinus banksiana*) in Saskatchewan. The flux data were used to estimate cumulative carbon dioxide fluxes and net ecosystem production (NEP). ALS was used to model variation and accumulation of total biomass. The authors concluded that ALS determination of accumulated biomass was greater than flux-measurement-based NEP.

7.8.2 Satellite Remote Sensing

The availability of high-resolution satellite remote sensing systems has increased accurate assessment of the condition of the Earth's forest areas. The satellites are moving sensors in orbit, and the number of observations of a given area or day are limited, as are observations on cloudy days. Some satellite assessments include all terrestrial vegetation. Zhang *et al.* (2018) have used long-term LAI records from satellite imagery, combined with global ecosystem models, to conclude that a widespread global increase in the growing season has resulted in a global 25–50% increase in LAI (greening), with less than 4% decrease in LAI browning. This is the global greening or carbon dioxide fertilization effect, and it is proposed that it reflects an increase in uptake and fixation of some of the anthropogenic carbon dioxide by global terrestrial vegetation (Smith *et al.*, 2015). It is also the basis for advocating very large-scale tree planting programs. Other satellite data confirm a significant increase in NPP from 1982 to 2011. Smith *et al.* (2015) proposed that their newer satellite data showed a smaller rate of growth increase over the period 1982–2011, compared with that estimated by the Earth System Model (ESM). They proposed a 2.8% ± 1.50% increase versus the ESM model's estimated increase of 7.6% ± 1.67% from 1982 to 2011. Accurate assessment of long-term trends in NPP is complicated, as

NPP is affected by changing balances between biogeochemical (carbon dioxide) and biogeophysical (temperature and water) factors, and by the availability of nitrogen, phosphorus, and other nutrients over long time periods (Smith *et al.*, 2015). Sun *et al.* (2017) used satellite remote sensing to detect and quantify total GPP. Images from the Orbiting Carbon Observatory-2 (OCO-2, NASA) were obtained for solar-induced chlorophyll fluorescence, a high-resolution signal which was used as global proxy for GPP. The use of an airborne chlorophyll fluorescence imaging spectrophotometer allowed determination of photosynthesis.

Satellite remote sensing has also been used to detect the condition of trees in forests. The Global Forest Watch (2015) program used satellite imagery (US Geological Survey Landsat and NASA) to detect global tree loss at a resolution of 30 m from 2000 to 2013. After analyzing 400,000 satellite images, they concluded that 18 million hectares (69,500 square miles) of tree cover was lost, either permanently or due to disturbances, insect infestations, or fires. Rogers *et al.* (2017) detected early incidence of decline in tree growth and mortality in boreal North American forests, using satellite-based indices, such as the Normalized Difference Vegetation Index (NDVI), and detection of time-series tree growth patterns. They concluded that tree mortality caused by drought and insect infestation is widespread in boreal forests. Bochenek *et al.* (2018) used satellite images (Landsat 5 TM and 8 OLI SPOT-5) to detect tree condition, diversity, and forest structure. They were able to detect and construct indices of water stress.

7.8.3 Modeling

How global warming is affecting the nature and function of forests, now and in the future, and what this means for forests and the Earth's atmosphere, are two questions that are difficult to answer using short-term traditional empirical evidence-based methods. Long-term experiments to answer the two questions are not possible. Therefore, models have been developed to try to understand the complexity of interacting environmental factors and future impacts on forests

(Medlyn *et al.*, 2011). They are often used to predict the future effects of carbon dioxide increase and atmospheric warming. While many models have been developed, the nature, use, and results of only a few types of models are presented here.

Models can be divided into groups depending on their intended use.

Process models simulate how environment affects trees and predict future climate effects (Peck, 2000). Ecological process models can predict how and when trees respond. Process models are often used to describe and predict forest response to environmental change (Ashraf *et al.*, 2015).

Statistical models are used to discover criteria that can be used to describe and predict the strength of relationships from available data. Significant differences and correlation are the desired outcome (Peck, 2000). Statistical species distribution models, niche, or bioclimatic envelope models can be used to establish relationships between species and their environment.

Simulation models are large computer programs that attempt to quantitate, integrate, and clarify interacting environmental processes (Peck, 2000; Medlyn *et al.*, 2011).

Kovenock and Swann (2018) investigated how a leaf trait acclimation of one-third increase in leaf mass per area in simulated climate warming affected climate and carbon cycling in ESM experiments. Global NPP decreases were related to current emission levels from fossil fuel combustion. Reduced evapotranspiration and increased absorption of sunlight increased warming. Leaf area growth is reduced as leaf mass increases, increasing carbon costs for leaf area construction. This results in decreased productivity and evapotranspiration, and thus results in warming.

As has been said, much of what we know about large-scale forest/environment interactions and predictions comes from the results and conclusions of many models. As they represent current perceptions of the reality of complex systems, the conclusions are usually accepted as the best information we have at present. The validity and utility of the results, however, depend on the model and how it was used, and most importantly, the number and nature of its assumptions. The number of assumptions that can be included in a model is limited – and missing out a factor may affect the application of the results. Environmental factors may be simplified or omitted (Peck, 2000). Medlyn *et al.* (2011) concluded that results from all types of models can be of value if the assumptions are clear, given, and understood.

Ashraf *et al.* (2015) used a new process model for growth and yield (JABOWA-3), and tree growth data from 3,000 permanent plots in Nova Scotia, Canada, to predict basal area and volume growth of individual trees in single or mixed forest stands. Model validation efficiency was 0.82–0.89 in predicting basal area and stem volume growth. Iverson *et al.* (2008) used three climate models to predict potential climate change impacts on future habitat areas for 134 tree species in the northeastern United States, using low and high carbon dioxide emission rates. Predicted opportunities for future habitat expansion generally were greater than constrictions. At the high emission rate, decreasing habitat area was predicted for the six key forest species balsam fir (*Abies balsamea*), paper birch (*Betula papyrifera*), red spruce (*Picea rubens*), black cherry (*Prunus serotina*), trembling aspen (*Populus tremuloides*), and bigtooth aspen (*Populus grandidentata*). A long-term prediction for the northeastern United States was for decrease in the spruce–fir zone and advancement of the oak (*Quercus*)–hickory (*Carya*) forest type.

7.8.3.1 The Temperature Gap

Climate simulation models predict trends in global air temperature. A number of investigators have concluded that observed temperature trends are significantly lower than the model-predicted trends. These observed trends have been slowly occurring for the last two decades. When the observed temperatures are subtracted from predicted temperatures, the result is a temperature gap. Temperature follows changes in carbon dioxide over time, so there may also be a carbon dioxide gap (Leggett and Ball, 2015, 2018). The significance of and rationale for this cooling and warming are given in later examples of cooling and warming.

7.9 ELEMENTS OF ATMOSPHERIC COOLING AND WARMING BY FORESTS

The roles of elevated carbon dioxide and ambient ozone in tree growth and function in photosynthesis, growth, and biomass accumulation, under varying experimental conditions, have been presented here. Knowledge about physiological responses, such as transpiration, gas exchange, photosynthesis, and respiration, for leaves and young trees in the initial rapid growth phase has been obtained from short-term experiments and is documented. Way *et al.* (2015) have illustrated confidence levels in tree responses to carbon dioxide and temperature in small-scale experiments (Figure 7.10). It is evident that confidence in results from these experiments only extends for a period of months. The exponential growth phase declines with time, as other factors such as water availability, nutrition, and adaptation occur (Kirschbaum and Lambie, 2015). Extrapolation of results from the exponential growth phase to larger, more mature trees is difficult, as the level of complexity and assumptions increases with tree size and numbers. This has complicated accurate wide-scale assessment of the response of older forest trees to elevated carbon dioxide. This level of assessment requires the use of indirect methods, such as tree ring analysis, flux towers, forest inventory data, models, satellite data, and remote sensing.

Increased global forest biomass, in response to elevated carbon dioxide, is considered an essential element of partial mitigation of anthropogenic carbon dioxide now and in the future. The IPCC's *Fifth Assessment Report: The Role of Forests* advocates for improved forest carbon sinks using "negative emission" techniques, such as reduction of deforestation and land-use change, improved forest management, and planting of new forests (afforestation) (Christ, 2014). Article 5 of the Paris Agreement promotes forest enhancement and conservation as part of a goal to keep long-term global average temperature less than 2 °C (and preferably 1.5 °C) above pre-industrial temperature

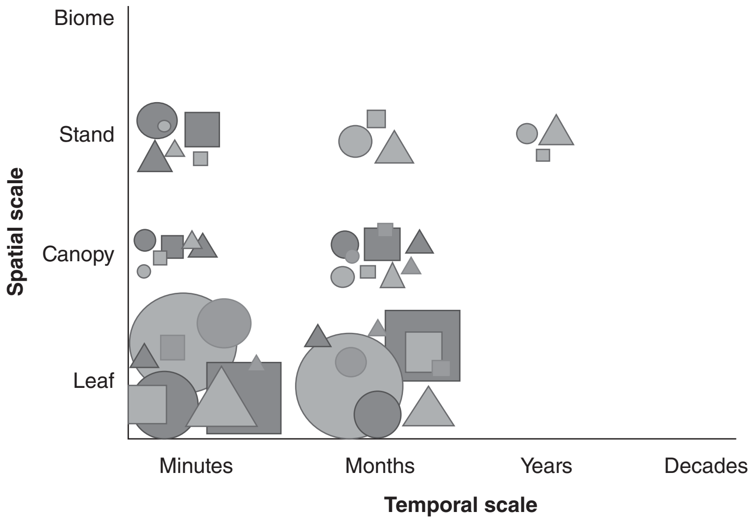

FIGURE 7.10 Conceptual diagram of our confidence in tree responses to elevated CO_2 (blue symbols), elevated growth temperatures (red symbols), or the combination of high CO_2 and temperature (purple symbols), with higher confidence shown by larger-sized symbols.
Circles represent photosynthetic responses, squares represent respiration responses, and triangles represent responses of stomatal conductance. While short-term, leaf-level responses to CO_2 (such as "A/Ci" curves, which depict net CO_2 assimilation rate versus calculated substomatal CO_2 concentration) are well understood, we have less data on longer-term CO_2 acclimation responses or responses at any time scale at larger spatial scales (such as stand level responses to CO_2 from FACE studies), and none that have run for decades or explored large-scale responses of forest stands to warming.
(A black and white version of this figure will appear in some formats. For the color version, please refer to the plate section.)

From D. Way *et al.*, *Plant, Cell and Environment*, The space-time continuum: the effects of elevated CO_2 and temperature on trees and the importance of scaling. Copyright © (2015) by John Wiley & Sons. Adapted by permission of John Wiley & Sons, Inc.

levels (Climate Focus, 2015). Minimizing deforestation in the tropics is proposed to be promoted by REDD+ and JMA (Joint Mitigation and Adaptation mechanism). Norway, Germany, and the United Kingdom will help to finance REDD+ projects. China, India, and other countries have begun massive afforestation projects (Walberg, 2018).

One of the anticipated climate benefits of large-scale afforestation is removal of anthropogenic carbon dioxide from air in photosynthesis and storage of carbon in wood. As discussed in previous chapters, other factors that affect the influence of forests on climate and temperature include respiration, transpiration and evaporation, vapor pressure deficit, BVOCs, aerosols, ozone, methane and nitrous oxide, water and soil nutrient availability, tree species, and albedo (Bonan, 2008; Lamba *et al.* 2017). Background information about some of these factors is given here and will be followed by examples of research results that support either atmospheric warming or cooling by forests.

7.9.1 *Photosynthesis and Respiration*

As described previously (see Section 4.3.1), photosynthesis is the primary process for carbon fixation and storage. It is expected to increase as carbon dioxide increases, unless limited by soil water availability and by levels of nitrogen and phosphorus in soils. Experimental evidence indicates that elevated carbon dioxide will decrease stomatal opening, and this will reduce transpiration and increase water-use efficiency (Long, 2012; Keenan *et al.*, 2013), although this is questioned by Frank *et al.* (2015). Rising temperature and ozone, together with drought, are predicted to reduce production of natural plant communities. Some of this may be reduced by increasing carbon dioxide (Long, 2012).

Terrestrial ecosystems (mainly forests) have been estimated to offset approximately 25% of anthropogenic carbon dioxide. This is attributed to a small imbalance between global photosynthesis and respiration, which is greater at night than during the day. Arneth *et al.* (2017) estimated that approximately 64 Gt of carbon dioxide per year are released to the atmosphere by respiration of terrestrial plants, offsetting approximately half of the total ecosystem GPP. They conclude that this level of emission is six times larger than all fossil fuel carbon dioxide emissions.

7.9.2 *Transpiration and Forest Water Cycle*

Transpiration is a key process in atmospheric cooling (see Section 4.6.2). Increased temperature and carbon dioxide have different effects on transpiration: temperature increases vapor pressure deficits, which can increase rates of transpiration, as warmer air can contain more water vapor; elevated carbon dioxide may partially close stomates, which will reduce rates of release of water vapor by transpiration and reduce surface cooling, which may increase atmospheric warming. Reduced transpiration rates may reduce soil water infiltration and recharge from rain, and reduce atmospheric water vapor, which may reduce precipitation, increase surface water runoff, and affect stream flow (Ellison *et al.*, 2017; Gimeno *et al.*, 2018; Kirschbaum and McMillan, 2018). Ellison *et al.* (2017) have summarized the effects of the forest water cycle on climate in Figure 7.11.

Evaporation is the process of transformation of liquid water to a vapor from any surface. The water does not move through or depend directly on plants. Evaporation rates are affected by sunlight and temperature. Evaporation from wet canopy leaves and moist soils affects long-term water balance and hydrology (Kirschbaum and McMillan, 2018).

Evapotranspiration is a collective term that includes transpiration and evaporation. Together with evaporation from oceans, lakes, and streams, evapotranspiration rates affect precipitation. Evapotranspiration and transpiration have sometimes been used interchangeably when only transpiration was intended, resulting in confusion.

Evapotranspiration includes physical evaporation of free water, and evaporation of water via stomatal conductance during transpiration from plant leaves. In many global-scale models, only transpiration is used to estimate global warming or cooling effects by trees and forests. While evapotranspiration may be the overall driver, it is not possible to accurately determine the magnitude and importance of the role of transpiration in warming or cooling. This is unfortunate and may be misleading. Lawrence *et al.* (2006) concluded that current

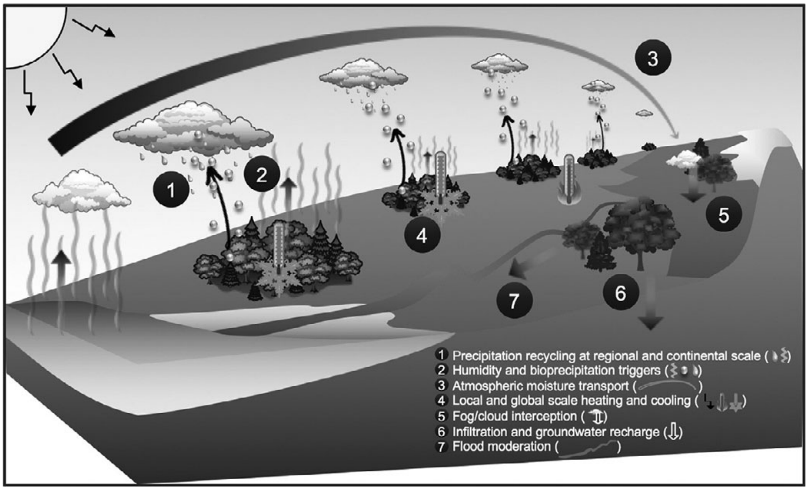

FIGURE 7.11 Effects of forests on water and climate at local, regional, and continental scales through change in water and energy cycles. (1) Precipitation is recycled by forests and other forms of vegetation and transported across terrestrial surfaces to the other end of continents. (2) Upward fluxes of moisture, volatile organic compounds, and microbes from plant surfaces create precipitation triggers. (3) Forest-driven air pressure patterns may transport atmospheric moisture toward continental interiors. (4) Water fluxes cool temperatures and produce clouds that deflect additional radiation from terrestrial surfaces. (5) Fog and cloud interception by trees draws additional moisture out of the atmosphere. (6) Infiltration and groundwater recharge can be facilitated by trees. (7) All of the above processes naturally disperse water, thereby moderating floods.
(A black and white version of this figure will appear in some formats. For the color version, please refer to the plate section.)
Adapted from *Environmental Change* **43**, D. Ellison *et al.* Trees, forests and water: cool insights for a hot world, 51–61, Copyright (2017), with permission from Elsevier.

knowledge at the time indicated that transpiration was the largest component of evapotranspiration, followed by soil and canopy evaporation. Frank *et al.* (2015) estimated that 60% of the water from land enters the atmosphere as transpiration. Jasechko *et al.* (2013) concluded that 80–90% of water flux from the Earth's surface enters the atmosphere from transpiration. They proposed that climate models should include greater simulations of transpiration, rather than evaporation or evapotranspiration. From this it could be assumed that effects ascribed to evapotranspiration are mostly caused by transpiration.

7.9.3 *Water-Use Efficiency*

One of the physiological benefits for plants from exposure to elevated carbon dioxide is partial stomatal closure, reducing the amount of water needed for plant growth and biomass. This results in increased water-use efficiency (WUE). WUE can be defined as a ratio between water used in metabolism and water lost via transpiration, or as the magnitude of dry biomass production per unit of evapotranspiration (Pallardy, 2008). Increased WUE, due to decreased transpiration, is a major contributor to increased growth in response to elevated carbon dioxide.

Keenan *et al.* (2013) found large increases in WUE and growth for trees in boreal and temporal regions of North America over the past two decades. They also detected increased photosynthesis, net carbon uptake, and decreasing evapotranspiration (principally transpiration). Together with increased WUE, they concluded that they had identified a "CO_2 fertilization effect," possibly due to partial stomata closure. This would allow maintenance of a steady concentration of carbon dioxide in a leaf, regardless of the external concentration of carbon dioxide, due to increased WUE. Holmes (2014) responded to Keenan *et al.* (2013) by proposing instead that declining levels of ozone, and of ozone precursors nitric oxide and nitrogen dioxide, in the northeast and Midwest United States might partially account for increases in WUE and decreased transpiration, and that carbon dioxide fertilization was not the complete cause. In reply, Keenan *et al.* (2014) allowed that ozone might play a role as ozone levels were increasing globally and in the western United States because of precursor transport from Asia, where ozone levels are high.

Frank *et al.* (2015) used a retrospective analysis of tree ring C^{13} isotope data for the twentieth century for *Quercus* and *Pinus* stands in European forests. Their results led them to oppose the proposal that partial closure of stomata caused by anthropogenic (elevated) carbon dioxide reduces transpiration. They proposed that a warming climate would increase LAI over an increasing growing season with resulting increased transpiration. Partial or complete stomatal closure might occur in controlled experiments, but ambient water vapor content has increased in Europe. They proposed two very interesting possible counteracting effects of elevated carbon dioxide on leaves in relation to transpiration:

1. Increased transpiration would increase latent heat loss and reduce surface temperature;
2. Increased transpiration could increase warming through feedbacks from water vapor and soil hydrology changes.

7.9.4 *Albedo*

Earth surfaces absorb and reflect incoming radiation during the day and reradiate some back to space at night. Albedo (see Section 4.6.1) is a measure of the degree of reflection, which determines the extent of surface absorption and heat retention. Clean white new snow has an albedo close to 1 and may reflect nearly all incoming light. Albedo values change with the seasons and for types of vegetation. Conifers have continuous dark color, and deciduous trees have somewhat less dark color when in leaf. Betts and Ball (1997) measured albedo in a boreal forest in Canada. Average albedo in summer for in-leaf aspen (*Populus tremuloides*) was 0.15, while spruce (*Picea mariana*) and pine (*Pinus banksiana*) sites averaged 0.083. Winter average albedo values with snow under canopies were 0.21 for leafless aspen, 0.15 for pine, and 0.11 for predominate spruce, with an average for conifers of 0.11. Albedo for forests increases in winter when snow under canopies is present. It was concluded that the albedo of conifer sites in winter would rarely reach 0.30. By contrast, average albedo values for grasslands in the area were 0.20 in summer and 0.75 when covered with snow in winter.

7.9.5 *Biogenic Volatile Organic Compounds and Clouds*

BVOCs, such as isoprene and monoterpenes (see Section 4.5), are emitted naturally by tree leaves, especially conifers, often in response to increasing air temperatures to prevent internal leaf damage. They affect several important aspects of the atmosphere. BVOCs rapidly oxidize in the atmosphere to form suspended sulfur and nitrogen aerosol particles, which reflect incoming light and may provide some atmospheric cooling (Spracklen *et al.*, 2008; Penuelas *et al.*, 2009). Oxidation of BVOCs may result in cloud condensation nuclei and formation of high clouds that may cool the Earth's atmosphere. BVOCs may also participate in the photochemical oxidant cycle (see Section 3.7) in warm months to enhance ozone production, which can have negative effects on tree growth and biomass. Ozone is the third most important reradiative greenhouse gas, and it slows the breakdown of methane, also an important greenhouse gas (Penuelas *et al.*, 2009; Unger, 2014).

7.9.6 Forest Carbon Sinks

In many global simulations and satellite assessments of global greening, increased responses are concluded to arise from all vegetation: that is, all plant forms and communities, from grasslands to shrubs to trees, and from tropical forests to boreal forests (Lapola *et al.*, 2008). Interpreting what the collective term "vegetation" means in terms of trees and forests can be difficult. There are currently 3.04 trillion trees on the planet, covering 30% of the terrestrial land surface (Crowther *et al.*, 2015). Forests provide approximately 50% of GPP and approximately 45% of stored carbon on and in land (Bonan, 2008). It would appear from this that, in terms of the global carbon cycle, trees play the major role in cooling and warming the planet (Schimel *et al.*, 2015). This is encouraging, as photosynthesis is the major mechanism for removal of carbon dioxide. Trees account for most of the carbon capture and long-term storage in terrestrial ecosystem. The expected outcome is that they represent a substantial negative feedback to atmospheric carbon dioxide concentrations, offering carbon sequestration and some potential mitigation of global temperature increase. Whether this is occurring, and to what extent, remains a large uncertainty for predicting future temperatures and climate change (Schimel *et al.*, 2015).

Tropical forests of the world, especially the Amazon rainforest, are assumed to be the largest terrestrial sinks for carbon from carbon dioxide. From experimental evidence, Schimel *et al.* (2015) expected that rising current carbon dioxide levels would increase global carbon dioxide uptake, primarily by trees, and storage in long-term sinks, especially in the tropics. Using simulation and other models and atmospheric estimates, they reported significant carbon dioxide uptake by tropical forests. By combining results from tropical forests and extratropical areas, they suggested that increasing carbon dioxide caused as much as 60% of the current terrestrial carbon sink.

Baccini *et al.* (2017) used 12 years of satellite data to measure live woody vegetation in tropical areas of America, Asia, and Africa. Gains from growth were compared with losses from deforestation and disturbances. They concluded that the forests they had evaluated went from being carbon sinks to carbon sources. Brienen *et al.* (2015) used historical evaluation of long-term plots to conclude that the Amazon carbon sink was in decline. The rate of biomass increase declined by a third since the 1990s, and mortality was increasing.

Elevated carbon dioxide is well known to stimulate growth and carbon sequestration of young trees in experiments (Korner, 2017). How long this continues in older trees under forest conditions, especially in the tropics, is less well known (Bugmann and Bigler, 2011). Brienen *et al.* (2015) concluded that tree longevity in the Amazon was shortened, especially for fast-growing trees, resulting in "shorter residence time" for carbon in trees. Bugmann and Bigler (2011) modeled growth responses to elevated carbon dioxide and changes in tree longevity for 141 temperate tree species. Their conclusion was that any growth stimulation mediated by elevated carbon dioxide would be offset by factors that reduced tree longevity, reducing forest mitigation. Korner (2017) views tree longevity as essential to increase stored carbon. Faster tree growth will not result in greater carbon sequestration.

7.10 ROLE OF FORESTS IN WARMING AND COOLING THE ATMOSPHERE

There is considerable interest at local, national, and global levels in the possible role of forests in cooling or warming the atmosphere, and what effects this would have on climate change. Given the size and complexity of forests, indirect assessment methods, such as the models, flux towers, satellite imaging, and remote sensing described in this chapter are necessary. Empirical data from large, long-term measurement studies in field plots are also available. Researchers have used combinations of methods to pursue aspects of the role of forests in cooling and warming the atmosphere, often in relation to forest types and latitudinal locations, and to draw conclusions or make predictions. Afforestation, deforestation, forest disturbance, tree physiology, tree nutrition, tree species and longevity, and albedo are all factors.

7.10.1 Influence of Forest Characteristics

Bonan (2008) published an extensive, well-illustrated review of the benefits of climate forcing and feedbacks by tropical, temperate, and boreal forests, with emphasis on albedo and evapotranspiration, the carbon cycle, and changes in forest cover and forest–atmosphere interactions. Using results from atmospheric and climate simulation models, he examined the role of forests in cooling and warming the atmosphere. This review is widely cited in other papers.

7.10.1.1 Tropical Forests

Tropical forests were estimated to contain approximately 25% of terrestrial carbon and account for approximately 33% of total NPP. Tropical forests are considered to be somewhere between carbon-neutral, owing to carbon release from deforestation, and carbon sinks, owing to extensive carbon uptake by intact undisturbed forests. Low albedo of trees causes moderate warming, offset by high rates of evapotranspiration, which cools air and affects precipitation rates.

A combination of carbon dioxide removal and evapotranspiration provides negative climate forcing. Deforestation, carbon sink reduction, fires, and drought will reduce negative climate forcing.

7.10.1.2 Boreal Forests

Many trees in boreal forests are dark-colored conifers that experience short growing seasons, resulting in only moderate gain and storage. Albedo numbers for conifers are low, resulting in positive forcing and warming. Evaporative cooling is low, also increasing warming. Considerable carbon is stored in soil and wetland. Boreal forests are at risk from fires and insect infestations.

7.10.1.3 Temperate Forests

Temperate forests contain approximately 20% of plant biomass and approximately 10% of stored carbon. Forests may be mostly deciduous, mostly coniferous, or mixtures. In general, forests have lower albedo than croplands. They may warm air in summer, which may be offset by moderate evaporative cooling and strong carbon sequestration. The effects of low albedo in winter interact with evapotranspiration in summer to determine mean annual temperature. Uncertainty prevails in predicting the extent of net climate forcing by temperate forests. Land-use change may reduce the extent of these forests.

7.11 EVIDENCE FOR THE ROLE OF FORESTS IN COOLING AND WARMING THE ATMOSPHERE

Gibbard *et al.* (2005) modeled the potential effects of replacement of forests with grassland or crops, and the reverse. They concluded that replacing grassland and crops with trees would reduce albedo and result in a global mean warming of 1.3 °C, similar to the effect caused by elevated carbon dioxide. Replacing trees with grassland and crops would increase albedo and would cool temperatures by 0.4 °C.

Bala *et al.* (2007) modeled the effects of global deforestation on air temperature. Deforestation results in release of carbon stored in trees and soils, causing a warming effect. They proposed that increased albedo and changes in evapotranspiration would offset the warming, resulting in cooling. Their results questioned the climate benefits of afforestation and tree planting programs. Together with conclusions by Gibbard *et al.* (2005), their results led to many articles in popular media saying that climate is cooler without trees.

Canopy transpiration plays a major role in determining the air cooling and warming effects of forests (Cao *et al.*, 2010). Increasing carbon dioxide has been shown experimentally to increase photosynthesis, plant growth, and biomass by partially closing stomata, reducing transpiration and increasing water-use efficiency. This has stimulated research on the effects that reduction of transpiration might have on forest cooling or warming, and soil water runoff. Methods used include models, observations and empirical data, satellite imagery, and combinations of these.

Cao *et al.* (2010) used simulation models to assess the future effects of elevated carbon dioxide (800 ppm): it reduced stomatal aperture, which affected canopy transpiration and soil evaporation, reducing the evaporative cooling effect of the forest. Water vapor in air was lower, which affected low cloud levels and in turn affected net surface radiative fluxes, resulting in air temperature increase. They termed this result, from partial stomatal closure by elevated carbon dioxide, "CO_2 physiological forcing". Increased surface water runoff removed water that might have been used in transpiration for air cooling. In 2010, they estimated that elevated carbon dioxide caused a global reduction in canopy transpiration of 8% (revised from 16% in 2009).

China has been converting cropland and marginal land to massive tree plantations since the 1980s. Peng *et al.* (2014) considered how increased land surface temperature from decreased albedo from the trees was countered by cooling effects of the trees, due to increased evapotranspiration (mainly transpiration). Satellite measurements of forest areas and adjacent grassland or non-forested areas were used to measure land surface temperatures. Afforestation reduced average daytime temperature by approximately 1.1 °C; nighttime temperature was increased by approximately 0.2 °C. Increased evapotranspiration was concluded to have caused the cooling. In dry regions, nighttime warming increased and offset daytime cooling for net warming of land surface temperature.

Ban-Weiss *et al.* (2011) examined the changes in surface latent heat and sensible heat by evapotranspiration from trees and forests. Evapotranspiration changes sensible heat to latent heat during evaporation of water. Latent heat flux to the atmosphere results in the cooling termed evaporative cooling. Water vapor eventually condenses, linking it with the hydrological cycle. They concluded that evaporative cooling was global, rather than local.

As mentioned above, partial stomatal closure in response to elevated carbon dioxide reduces transpiration of water vapor to the air. This can cause reduction in low cloud cover and a decrease in latent heat flux transfer to the atmosphere, resulting in warming (Cao *et al.*, 2010). Doutriaux-Boucher *et al.* (2009) used a climate–carbon-cycle model, with twelve 5-year experiments with doubled or quadrupled carbon doxide at the start of the experiments, to determine climate feedback. In less than a year, the influence of elevated carbon dioxide on stomatal conductance and transpiration resulted in a reduction in low cloud cover, increasing the incidence of incoming shortwave solar radiation. They estimated that this was equivalent to a 10% increase in radiative forcing, which resulted in warming.

Lee *et al.* (2011) used 33 FLUXNET towers close to forest sites to compare nighttime and daytime temperatures in cleared land near the towers with adjacent forests at higher altitudes in the United States and Canada. They found that open-air areas cooled the air at night more than forests in both northern and southern latitudes. Forests were warmer at night. They attributed this to air turbulence from trees drawing down warm air from above.

Shen *et al.* (2015) modeled the effects of increased vegetation growth on air cooling on the Tibetan Plateau. Compared to native grasslands, albedo for vegetation was reduced, and warming may have increased. Negative feedback from evapotranspiration resulted in cooling from vegetation, reducing atmospheric warming. Removal of vegetation and restoration of natural grasslands would increase cooling with higher albedo.

Using satellite data, Alkama and Cescatti (2016) investigated how changes in forest cover affect air temperature. Forest losses increase diurnal temperature variations and increase mean and maximum air temperatures. Tropical deforestation increases surface albedo, but also reduces evapotranspiration, and this may offset the air cooling due to increased albedo. High winter snow in deforested boreal areas could lead to climate cooling due to the high snow albedo. They compared the effects of variations of forest cover, from 2003 to 2012, on biophysical warming to the biogeochemical emissions of carbon dioxide from land-use change. They found that the changes in forest cover produced a mean warming corresponding to 18% of the carbon dioxide emissions. Changes in forest cover affect local climate.

Global satellite data were used by Schultz *et al.* (2017) who investigated the biophysical effects of deforestation on diurnal asymmetry of surface temperature response. Daytime warming after deforestation was due primarily to differences in absorbed solar radiation and latent heat flux, and was strongest in deforested tropical areas. Nighttime cooling was due to turbulence in forests and release of forest-stored heat; it was strongest in deforested boreal areas where open land is cooler than forests.

Li *et al.* (2015) felt that repeated satellite observations were preferable to global climate models to determine local cooling and warming effects on a global scale. They used extensive MODIS satellite data to investigate biophysical effects of forests on local land surface temperature, evapotranspiration, and albedo, comparing forests with grasslands. Latitudinal and diurnal features were determined. In general, daytime cooling was evident in most forests, when compared to open land, and was stronger in the tropics than boreal regions. Their results are summarized below:

Tropics 20° S to 20° N	Largest year-long cooling Little night warming
Mid-latitudes 20° N to 50° N	Annual net cooling Cooling in summer, moderate warming in winter Greatest night warming region
Boreal 50° N to 90° N	Strong warming in winter, moderate summer cooling Net annual warming

Forests in general have lower albedo and absorb more daytime shortwave radiation, which can result in warming. Depending on latitudinal location, evapotranspiration may increase latent heat loss and offset warming. This effect is strongest in tropical forests. Albedo effects increase with latitude, while the effects of evapotranspiration decrease (Li *et al.*, 2015). Betts (2000) identified two opposing forces that determine the effects of boreal forests on climate change: albedo and carbon sequestration. Low albedo would cause positive radiative forcing and warming, which could offset the negative radiative forcing expected from increased carbon sequestration. Some boreal forests might contribute to an increase in global warming, rather than decreasing it. Swann *et al.* (2010) used a global climate model to estimate the effects of north-expanding ranges of deciduous trees at high altitudes. They modeled the effects of addition of deciduous trees to bare ground at northern latitudes, and found that increased transpiration from the increased forest areas exerted a negative forcing effect that was 1.5 times that of the positive forcing effect of albedo. They also concluded that warming from additional water vapor in air would melt sea ice, resulting in positive forcing by changes in ocean albedo and surface evaporation.

Spracklen *et al.* (2008) used a global atmospheric model to considered the role of BVOCs in cooling and warming in boreal forests. BVOCs (see Section 4.5) are short-lived and become high cloud condensation nuclei. High clouds reflect incoming shortwave solar radiation. This results in "dimming" (see Section 1.3) that increases photosynthesis and carbon fixation, and creates a cooling effect. They referred to this as a homeostatic cooling effect for cold climates. Unger (2014) proposed that continuing large-scale deforestation for cropland expansion would reduce BVOCs from trees, and that this would result in global climate cooling. Deforestation releases stored carbon to the atmosphere, which causes warming. It also greatly increases surface albedo, which results in cooling. BVOC emissions, mainly isoprene, also promote the formation of ozone and prolong atmospheric residence time for methane. Both ozone and methane are strong greenhouse gases. Deforestation reduces BVOCs, increases release of stored carbon, increases the strength of surface albedo, and reduces ozone formation and methane residence time. Unger concludes that this results in a net global cooling effect.

Tang *et al.* (2018) conducted a detailed analysis of the effects of forests on temperature in relation to seasons and background climate in Europe. They compared land surface temperatures between forest and adjacent open areas for 48 sites near flux towers and examined the influence of local background temperatures on forest responses. Their general conclusions were that forests in northeast Europe increased air temperature and decreased temperature in other areas. In warm seasons, forest cooling occurred during daytime. In cold seasons, warming occurred at night. The cooling effect of forests was strongest for high background temperatures and lowest at cool temperatures. Background temperatures affected the spatiotemporal distribution of differences in albedo and evapotranspiration. During daytime, forests are likely to cool local temperature through elevated latent heat flux. At night, forests may store heat, resulting in local increased temperature. Over time, differences in soil moisture may affect evapotranspiration. Changes in soil color and wetness may affect albedo. Differences between open land and forest may decrease.

Kirschbaum and McMillan (2018) considered that transpiration rates were affected by biogeophysical factors such as air temperature and water pressure deficits, and by plant factors that included canopy leaf area and stomatal conductance (see Sections 4.6 and 7.9) . They proposed that two opposing forces would affect transpiration rates in future climate: increasing air temperatures will enhance transpiration rates due to increasing vapor pressure deficits; or partial stomatal closure by elevated carbon dioxide will reduce water vapor from leaves, decreasing rates of transpiration and increasing water-use efficiency. Using summary empirical evidence from numerous experiments, they developed simulations for case studies for the twenty-first century for six locations, from tropical to boreal forests, to estimate the effects of increasing air temperature and elevated carbon dioxide on transpiration rates. For most locations, reduction in stomatal conductance caused by carbon dioxide reduced transpiration rates more than future air warming increased it. Temperature increased the length of the growing season and increased transpiration for boreal and temperate forests.

For the past two decades, it has been noticed that there are trends in differences between observed and predicted air temperatures. This has been termed the global atmospheric temperature slowdown. When observed temperatures are subtracted from modeled expected temperatures, a temperature gap is revealed. Temperature does not reflect current carbon dioxide, but follows the change in carbon dioxide over time. Lower than predicted temperatures also indicate lower carbon dioxide than predicted, suggesting a carbon dioxide gap as well. The rationale for the temperature and carbon gaps is that enhanced "global greening" has significantly increased global uptake of carbon dioxide beyond what was predicted, accompanied by evapotranspiration (mostly transpiration) (Leggett and Ball, 2015, 2018).

There is evidence from satellite observations and models for global greening, a slow long-term increase in terrestrial vegetation. On the assumption that it is caused by steadily increasing concentrations of carbon dioxide, it is also sometimes known as the carbon dioxide fertilization effect. Among many papers describing global greening is one by Zhang *et al.* (2018). Using satellite imaging and models, they proposed that since 1982, global greening has slowed the increase in average global air temperature by approximately 0.09 °C. LAI increase, resulting in a 70% increase in evapotranspiration that offset the warming effects of increased albedo, was determined to be the cause. LAI and evapotranspiration increased in boreal areas, Europe, India, Eurasia, Northern Amazonia, and the Sahel, but not in eastern North America and East Asia. Their major conclusion was that global greening had reduced global land surface warming by 12% during the past 30 years.

Leggett and Ball (2015, 2018) approached an understanding in a similar yet different way. Rather than use LAI as a response surface, they used satellite measurements of global vegetative reflectance, using NDVI (Normalized Difference Vegetation Index), to measure global terrestrial photosynthesis. Close correlation was found between increasing NDVI and the trends of lower-than-modeled temperature (the temperature gap) and carbon dioxide (the carbon dioxide gap). They attributed this to increased evapotranspiration by vegetation. They also included data on ocean heat in their models and concluded that the ocean heat sink was a significant factor.

7.12 SUMMARY

This chapter has focused on the methods used to provide the knowledge base for determining the extent of the role of forests in cooling or warming the atmosphere. Seedlings and small trees are useful in controlled experiments with elevated carbon dioxide in various types of chambers, but extrapolation or scaling up of results is not possible. Results from longer-term field chamber and FACE experiments have more relevance, but also lack relation to mature trees in forests. The effects of elevated carbon dioxide on stomatal conductance, transpiration, water-use efficiency, acclimation, and growth and biomass accumulation by young trees, as well as soil nutrient limitations and other factors, were determined in these experiments. Dendrochronology or tree ring analysis allows recreation of past events, using older, more mature trees.

Re-examination of historical forest tree inventory data has provided long-term trends for forests. Indirect methods, such as flux towers, satellite imagery, simulation models, and combinations of methods are required to predict large-scale forest responses to warming and elevated carbon dioxide. Physiological considerations include photosynthesis, evapotranspiration (mostly transpiration), tree longevity, and BVOCs. Physical factors include temperature, albedo, aerosols, and clouds. Results from flux towers, satellite imagery, and models indicate that forest tree type and latitudinal location, season, and time of day are factors that determine how effective forests are in cooling and warming the atmosphere.

Most of what we know about the role of forests in cooling and warming the atmosphere comes from the results of simulation modeling and satellite imagery. From these, it has been concluded that tropical forests are most likely the major source of carbon capture and atmospheric cooling. Boreal forests are more likely to warm the atmosphere. Temperate forests may cool in summer, but this is uncertain.

Cooling and warming are influenced by albedo and transpiration. Low albedo could cause warming; and partial stomatal closure, in response to elevated carbon dioxide, could decrease transpiration and cause warming. Increases in global vegetation (global greening) during the last 30 years has been estimated to have caused a reduction in global temperature and carbon dioxide levels below their model-estimated expected levels, resulting in cooling. Carbon dioxide removal by photosynthesis and resulting increased transpiration are alleged to be the causes.

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8 Role of Forests in Mitigating Global Warming

Plant a Tree and Save the Planet

www.aurlns.com

Stop talking and start planting!

Felix Finkbeiner, One Trillion Trees program

The capacity of terrestrial ecosystems to store carbon is finite and the current sequestration potential primarily reflects depletion due to past land use.

Mackey *et al.*, 2013

8.1 INTRODUCTION

Global deforestation is increasing rapidly from timber harvesting, charcoal burning, fires, beetle infestations, drought, disturbances, and conversion of forests to managed land for agriculture and pasture. This reduces the global carbon sink and may increase global temperature. It was noted in the previous chapter, however, that observed average global temperatures and carbon dioxide concentrations are lower than would be expected from model estimates. This was attributed to a long-term global vegetation growth and greening effect, caused by increased photosynthesis and increased transpiration. Forest trees probably constitute most of the vegetation responsible. The potential for global greening has greatly increased interest in global large-scale efforts to prevent deforestation, stop forest degradation, restore forests (reforestation), plant new forests (afforestation), and manage existing forests.

The 21st Conference of Parties (COP-21) of the United Nations Framework Convention on Climate Change (UNFCCC) met with delegates from 195 countries in Paris in December 2015. Delegates agreed to climate mitigation targets to keep average global temperature increase at no higher than 2.0 °C, preferably limited to 1.5 °C. Reducing deforestation and enhancing the forest carbon sink through tree planting was one of the climate mitigation targets. Countries established targets for establishing new forests. Each country decided how to address the climate mitigation targets. These Intended Nationally Determined Contributions (INDCs) constituted the Paris Climate Agreement. Because the agreement allows for each nation to determine designation and achievement of mitigation targets, inconsistency in reporting greenhouse gas emissions and forestry gains can lead to decreased credibility for overall results (Grassi *et al.*, 2017).

8.2 REDUCING DEFORESTATION AND DEGRADATION TO MITIGATE GLOBAL WARMING

Deforestation and forest degradation release carbon to the atmosphere and have been calculated to rank second in importance to emissions from energy generation (UN-REDD+). Realizing that there is value in carbon stored in forest trees, the UNFCCC established the program REDD+ to encourage nations to reduce deforestation and forest degradation. Countries that develop acceptable programs to reduce deforestation (results-based actions) would receive payments for achievements (results-based payments). REDD+ also includes forest management and increased new forests. Karsenty and Ongolo (2011) question whether politically and economically unstable countries ("fragile states") can effectively participate in REDD+. Houghton and Nassikas (2017) estimated how global recovery of secondary forest growth following tree harvests for wood, or developing forests on abandoned farm land, and stopping deforestation, would affect negative emissions. They estimated that between 2016 and 2100, this would result in cumulative global negative emissions of 120 PgC, with wood product storage increasing this to 130 PgC.

8.2.1 Forest Management to Mitigate Global Warming

Humans have been using forests as sources of wood, fuel, and food for centuries. With increased population and demand for such products, the concept of establishing and managing forests for maximum benefit developed. Much of the early development of forestry management began in Europe, when planting forests to replace extensive native forest loss became necessary. Most European forests are planted with a few tree species and managed for wood harvest. Management practices, such as tree planting, tree species selection or replacement, thinning, fire prevention, fertilizing, and removal of fallen branches for firewood and litter, result in forests that are considerably different than natural forests. Management also includes scheduled tree harvests for wood for building, fuel, and forest products. The nature and extent of these management practices affect the forests' structure and function, which affects mitigation of climate warming through carbon storage, heat flux exchange, and transpiration to the atmosphere (Naudts *et al.*, 2016).

Nabuurs *et al.* (2013) used forest inventory data to establish trends for stem volume increment increase in Europe, focusing on the period 1960–2005, as stem increment growth is an indicator of carbon sink strength. Improvements in forest management and practices were concluded to have been the possible cause of trends of growth in stem volume increment from 1960 to 2005. Between 2005 and 2010, stem volume increment growth trends began to decline. By 2010, stem volume growth increment declined by 13 million m^3 for an area of 78 million hectares, assessed over all of Europe. Slowing growth in maturing forests, and deforestation and decreases in planting forests, were considered to be possible causes for declining forest carbon sink.

Average yearly forest loss for European countries from 1990 to 2010 is shown in Figure 8.1. Further analysis of data since 1990 indicated regional differences in sink saturation. Sink saturation seemed complete for Alpine and west Atlantic areas, slightly increasing in the

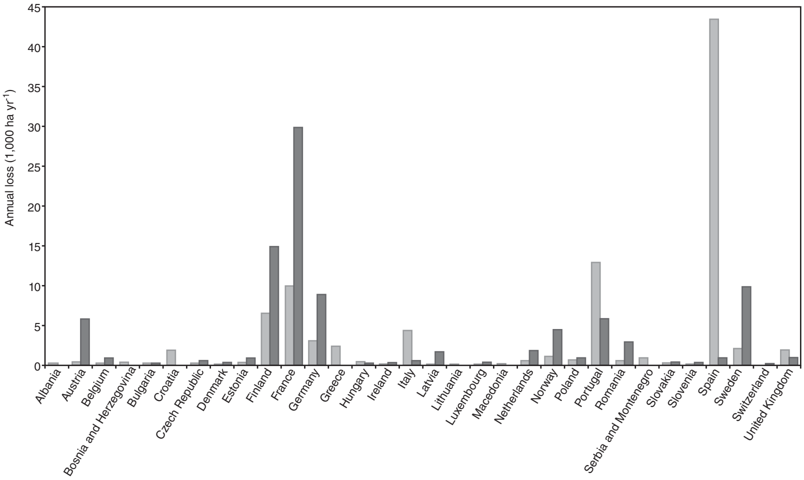

FIGURE 8.1 Average forest loss.
Light grey bars indicate the average forest loss based on remotely sensed CORINE Land Cover (CLC) data sets from 1990, 2000, and 2006. Dark grey bars reflect the reports to the Kyoto Protocol on deforestation between 1990 and 2010.
Adapted by permission from Springer Nature: Springer Nature Ltd, *Nature Climate Change*, First signs of carbon sink saturation in European forest biomass, G. J. Nabuurs *et al.* © (2013)

north and south of Europe, declining and then increasing again in eastern Europe. The first sign of carbon sink saturation in Europe is evident in the Alpine and west Atlantic areas.

Forests are generally considered to be negative climate forcing agents. Naudts *et al.* (2016) proposed that not all forestry contributes to climate mitigation. They reconstructed a history for land-use change and forest management practices for Europe from 1750 to the present, modeling factors such as tree species conversions, wood removal by thinning and tree harvesting, and removal of forest floor litter. During that time period, conifers began to replace deciduous trees in very large afforestation tree planting programs. Albedo values and transpiration decreased with conifers, and warming resulted. Human populations also increased during this time, resulting in greater demand for wood. Their results indicated that wood harvests exceeded the benefits of afforestation, resulting in accumulation of a debt of 3.1 Pg of carbon. They concluded that forest management from 1750 did not mitigate climate warming. Luyssaert *et al.* (2018) concluded that given current forests in Europe, forest management will not result in mitigation of climate change. Large-scale changes in silviculture and management might result in forests with neutral effects on climate change.

A warming climate will affect forest management, so reconsideration of current practices is needed, and proposals for alternative or active forest management practices are being considered. With warming, some forest tree species may become less productive. Schelhaas *et al.* (2015) propose replacing tree species with ones that will be more productive, either by removing ones that are there or using the new species in new forest plantings. Only 36% of the area in Europe where species change should occur will be accomplished by 2070. This might be increased to 40% if short rotations (harvests) are accompanied by planting new species. This strategy is likely to be more effective in northern Europe where faster adaptation of new species is anticipated. Progress is estimated to be less in southwest Europe. Bright *et al.* (2014) used models and meteorological data to investigate alternative management strategies for boreal forests in Norway. They determined daily, seasonal, and annual surface temperature differences for different trees. A 0.13 °C cooling was found at a deciduous tree site. Cooling at a clear-cut site was 0. 25 °C. Albedo was higher at the clear-cut site during the year. Alternative strategies that encouraged natural regeneration of the clear-cut areas by native deciduous tree species resulted in substantial climate cooling.

8.2.2 Afforestation and Reforestation to Mitigate Global Warming

Global planting of new forests (afforestation) and reforestation of harvested or former forest sites are widely advocated to partially mitigate global warming. As we have seen, removal of carbon dioxide from air via photosynthesis, at rates exceeding respiration, resulting in increased growth, biomass, and transpiration, means that trees can be effective carbon sinks. Reduction of carbon dioxide, and increased transpiration, result in negative climate forcing.

Achieving this goal of tree planting involves consideration of the long timeline of tree growth and changes that occur along the way. Some trees are propagated by cuttings, but the timeline for most trees begins when seeds germinate and small seedlings emerge. Direct in situ forest seeding can be used for native trees, but most seeds are planted in nursery seedbeds. Seedlings are grown in nurseries for several years before they are large enough to be planted out as saplings in reforestation projects. Mackey *et al.* (2013) have continued the timeline and have profiled tree age and development relative to carbon sink size. Young trees planted out will grow rapidly, and carbon fixed in photosynthesis exceeds that lost in respiration, leading to a net carbon sink. Carbon begins to be stored in trees and soil. As tree age continues over time, a change begins whereby growth rates decreases in relation to rates of respiration. The net carbon sink begins to decline. As they reach maturity, rates of photosynthesis and respiration begin to be more in balance. Slight differences between them determine the extent of carbon uptake and storage. The soil carbon deficit has been filled, and this sink is no longer functioning. Faster tree growth does not result in greater long-term carbon sequestration. The mitigation value of forest trees lies in their longevity: how long they live and retain their accumulated carbon (Mackey *et al.*, 2013; Korner, 2017).

8.2.3 Global Forest Establishment and Restoration Programs

Concern about deforestation, and its impact on climate, has resulted in numerous local, regional, and global tree planting programs. Several of the largest global programs are described here.

The Bonn Challenge was established at a conference in Bonn, Germany, in 2011. Governments pledged to restore 150 million hectares of deforested and degraded land by 2020 and 350 million hectares by 2030. By 2017, 160.2 million hectares had been pledged. To carry out its commitment, Pakistan launched a Billion Tree Tsunami and has reforested 350,000 hectares.

The Trillion Trees Program (2017) has been established as a partnership between the World Wildlife Fund, the Wildlife Conservation Society, and Birdlife International. It proposes a 25-year program of tree planting and forest restoration. A German University student, Felix Finkbeiner, developed a movement called Plant for the Planet, and expanded it to the Trillion Trees Program. Evaluating all the conferences and meetings being held about reforestation and afforestation, he reacted by developing the motto, "Stop Talking. Start Planting."

In collaboration with Conservation International, Brazil has launched the largest tropical reforestation project in history to establish 73 million trees in the Brazilian Amazon by 2023. The tree establishment practice is unique. Instead of obtaining and planting tree saplings, they will use a "muvuca" strategy. In Portugese, this means many people in a small place. Here, it means many tree seeds scattered inside every square meter of deforested land. Seed of more than 200 native forest tree species will be used. This practice has been used successfully elsewhere. The strongest seedlings survive and become trees.

In the United States, the National Forest Foundation, in collaboration with the USDA Forest Service, proposes to plant 50 million native tree species (Peter, 2018).

New York and Los Angeles successfully established million-tree planting programs. Planting schemes like this work well in cities that have grid layout and are not compact. In older American cities, and many European cities, there is not enough useful space for large-scale tree planting. Boston, for example, planned to plant 100,000 new trees. In addition to lack of space, many of the newly planted trees died after planting from lack of water and care, a common problem in large-scale urban tree planting programs. What is important is not the number of trees planted, but how many survive and flourish.

The value of urban trees is in air temperature reduction by shade and reduction of electricity use. This indirectly reduces carbon dioxide. McPherson *et al.* (2015) concluded that the carbon sink for trees in Los Angeles was offset by equipment use and by decomposition of wood and wood mulch.

8.2.3.1 Seed Availability

Ambitious tree planting programs involve transplanting millions of seedling trees or saplings on large scales over time. Some programs rely on using traditional forest trees. In Europe, this includes Norway spruce (*Picea abies*), Scots pine (*Pinus sylvestris*), and beech (*Fagus sylvatica*). At current planting levels, there should be adequate sources of appropriate seeds for these common forest trees. Jalonen *et al.* (2017) surveyed forest restoration programs and found problems with availability of very large quantities of high-quality tree seeds, especially for native or minor tree species. Using low-quality seed could lead to long-term problems, with influence on warming and climate change.

8.2.3.2 Tree Species Diversity

In planning large afforestation projects, monocultures of one species are easiest to establish, especially if harvests for wood are planned. These plantation-like forests lack the long-term benefits of species diversity. Pedro *et al.* (2015) found that increasing species diversity decreased the effects of forest disturbance on carbon storage. Diversity increased forest resilience and function. Thom *et al.* (2017) reported that mixed forests, appropriate for their climate and site, had increased climate forcing capacity. Care should be taken, however, when introducing non-native trees, such as black cherry (*Prunus serotina*) for forest diversity, as they may become invasive and have negative long-term impacts (Brundi and Richardson, 2016).

Liang *et al.* (2016) examined a huge forest/ecosystem productivity data set, finding a consistent relationship between biodiversity and productivity. They concluded that an average 10% reduction in tree biodiversity would result in a 3% loss in ecosystem productivity.

In tropical forests, Poorter *et al.* (2015) found that rare tree species incidence played an important role in promoting aboveground biomass, but rainfall was the major influence, followed by average tree stem diameter and then species richness.

Pataki *et al.* (2011) includes species composition in factors affecting water use and transpiration. Sap-flow sensors were used to determine different transpiration rates for a variety of coniferous trees in Los Angeles. This technique, together with results in the literature, could be used in selecting tree species for drought tolerance. Vitali *et al.* (2017) concluded that silver fir (*Abies alba*) and Douglas fir (*Pseudotsuga menziesii*) were more drought-tolerant than the widely planted Norway spruce (*Picea abies*), and planting of Norway spruce should be reduced.

Tree species selection for the carbon content of stem wood is a possible criterion. Lamlum and Savidge (2003) indicate that 50% carbon is often used as the standard for kiln-dried wood. They tested this by determining the carbon content in kiln-dried heartwood of 41 tree species. Hardwood species averaged 46–49.7% and conifer species 47.2–55.2% carbon. They concluded that carbon content in stem heartwood varies between species and even within species.

Changing the diversity of tree species in boreal forests could affect climate forcing. Astrup *et al.* (2018) proposed that increasing the content of broadleaved deciduous trees in conifer-dominated boreal forests could increase albedo, reduce fire incidence, and reduce positive climate forcing.

One tree selection criterion completely overlooked in planning huge tree planting programs is emissions of BVOCs from tree leaves. Tree species vary widely in emission rates. Broad leaved deciduous trees emit mainly isoprene, and conifers mainly monoterpenes. As considered in Chapter 4, BVOCs can participate in the photochemical oxidant cycle to form ozone, prolong methane in the atmosphere, and form aerosols that affect clouds and climate forcing (Unger, 2014).

Planting large numbers of high BVOC emittors would not be a good strategy for afforestation. Rankings of trees for BVOC emissions are available in the literature (Donovan *et al.*, 2005; Aydin *et al.*, 2014; Curtis *et al.*, 2014).

8.3 THE NATURE OF FORESTS

Forests are considered to play an essential role in partial mitigation of global warming. Large-scale tree afforestation (young trees planted in plantations in new areas), reforestation (young trees planted in former forested areas), and restoration (young trees planted in degraded existing forests) programs are intended to increase carbon sequestration and lower temperatures. The resulting forests will function differently. Natural regrowth of native tree species in harvested areas will result in the most effective forests for carbon sequestration.

Undisturbed forests are dominated by native tree species in various stages of development. These forests are naturally regenerated. Structure, composition, and function are determined by natural events, without human influence. Although trees dominate, it is only when they interact with other associated plants, animals, and microorganisms, functioning together, that a forest ecosystem occurs. Undisturbed forests and natural forest ecosystems are rapidly diminishing (Convention on Biological Diversity, 2006).

Climate change awareness has stimulated the development of criteria for assessment of global forest area. The United Nations Food and Agriculture Organization (FAO) considers that forests exist if trees are present and the land is not being used for anything else. More specifically, tree canopy cover must be more than 10% and the area larger than 0.5 ha. Young stands are included that are projected to develop a crown density of 10% and a height of 5 m. Forests include trees in many non-traditional locations, such as windbreaks and national parks. Natural forests and plantation forests are both considered to be forest, without distinction (Convention on Biological Diversity, 2006; Van Holtz and Putz, 2017). Sasaki and Putz (2009) examined a similar set of criteria developed by the UN Framework

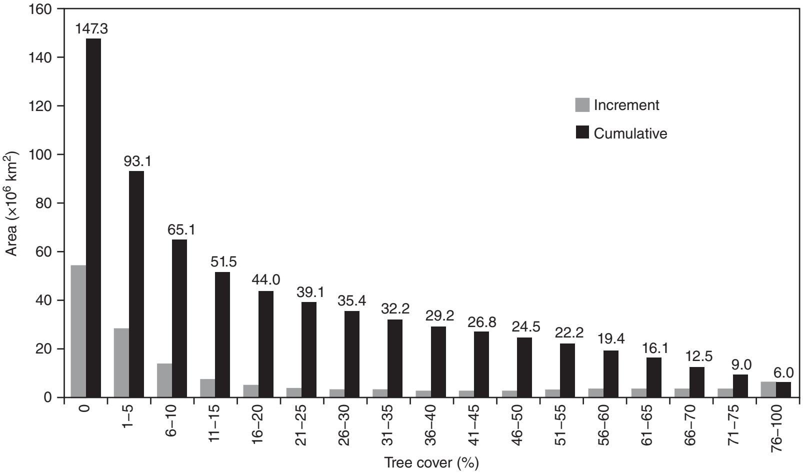

FIGURE 8.2 Global area of forest cover as a function of the tree-cover criterion.
Incremental values represent global area (in units of 10^6 km^2) × tree cover within each bin, and cumulative values refer to the global area with tree-cover values greater than or equal to that of the bin.
Adapted by permission from Springer Nature: Springer Nature, *Nature Climate Change*, Conservation policy and the measurement of forests, J. O. Sexton *et al.* © (2015)

Convention on Climate Change in 2001. A forest was defined as an area 0.5–1.0 ha with 10–30% cover of plants greater than 2–5 m tall at maturity. They recommended that the criteria be expanded to a height limit of greater than 5 m and tree cover at greater than 40%. Sexton *et al.* (2015) compared global forest cover in relation to the function of the tree cover criteria that were used to determine it. The criteria determine the outcome, and it matters which are used (Figure 8.2).

8.4 AFFORESTATION, REFORESTATION, AND RESTORATION

8.4.1 Native Forests

Native forests are self-generating and not managed. The extent of regenerating native forests, especially in degraded areas, is deemed insufficient if forests are expected to play a considerably expanded role in carbon capture and global temperature reduction. To this end, huge global areas of new and deforested and degraded land are being newly planted or re-planted, and new forest areas are being created. Native tree species are used in some instances. Many of the newly planted forests largely consist of closely planted monocultures of same-aged trees, often of one non-native tree species, managed for eventual harvest for wood and wood products. These are called plantation forests (Grotta, 2015). Plantations provide extensive tree cover, but the question is: are they really forests in terms of long-term forest ecosytems?

8.4.2 Afforestation in China: New Plantations

China has the world's largest continuing tree planting program. More than 100 billion dollars has been spent in the past decade to plant trees (Ahrendts *et al.*, 2016). Since the 1990s, new tree plantings have exceeded 4 million hectares per year, with more promised for the future (Xu, 2011). The 1999 Grain for Green Project was designed to reforest mostly sloping farm land to lessen soil erosion or encroachment of desertification. In 2013, satellite imagery indicated that China is going green (Macias-Fauria, 2018).

Forests in China include primary forests, regenerating forest, and plantations of mostly non-native, often single species, or at most two to five tree species, making up the afforestation effort (Xu, 2011; Hua *et al.*, 2016). Macias-Fauria (2018) indicated that forests in China can be classified as ecological (80%) or economical (20%). Ecological forests could be part of a timber quota and might eventually be logged. Economical forests include fruit orchards and trees for medicinal use. Hua *et al.* (2016) indicated that most of the trees planted in the Grain for Green forests are intended to be harvested for wood, fruit, and other wood-related products, with biodiversity secondary or incidental. The purpose of the plantation forests is to provide a sustainable source of wood on a scale not available from smaller natural or primary forest resources. This involves carbon capture and long-term storage in wood in trees and wood for construction.

China also established a national tree planting program, the China Fast-Growing and High-Yield Plantation Program, to develop and sustain wood supply (Jiang and Zhang, 2003). Given the size of China, and large variations in climate zones from north to south and east to west, different appropriate fast-growing tree species were chosen to establish plantations. Conifers for softwood production included Masson pine (*Pinus massoniana*), China fir (*Cunninghamia lanceolate*), slash pine (*Pinus elliotti*), Yunnan pine (*Pinus yunnanensis*), loblolly pine (*Pinus taeda*), spruce species (*Picea* spp.), Mongolian Scots pine (*Pinus sylvestris* var. Mongolica), larch species (*Larix* spp.), and Korean pine (*Pinus koraiensis*). Hardwood species included eucalyptus (*Eucalyptus* spp.), acacia (*Acacia* spp.), Paulownia (*Paulownia* spp.), locust (*Robinia pseudoacacia*), poplar (*Populus* spp.), and birch (*Betula* spp.). Slash pine and loblolly pine, and probably Korean pine, are not native to China, nor are eucalyptus and locust. Poplar species may be native, but their origin is not clear.

Hua *et al.* (2018) reviewed forest tree cover change in China between 2000 and 2015. A 32% increase in tree cover was attributed entirely to conversion of cropland to tree plantations, primarily monocultures. During that time, native forests experienced a net loss of 6.6%. They advocated protecting native forests and encouraging natural regeneration to restore native forests.

Tree plantations are long-term renewable tree plantings that function as agroecosystems, not traditional natural forest ecosystems. Examples of a new plantation in Brazil, an existing eucalyptus plantation in Brazil, and a palm oil plantation in Malaysia are shown in Figures 8.3, 8.4, and 8.5. They do store carbon in wood and soil, but wood is removed, which means tree replacement. Closely planted, they provide closed canopies and tree cover. As such, they do not function as forests (Van Holt and Putz, 2017). Leaf litter and soil nutrients are reduced. Albedo levels will decrease, depending on tree species, and transpiration and low cloud cover may be affected (Williamson, 2016).

FIGURE 8.3 Deforestation and new plantation in Brazil.
Replacement of original forest.
(A black and white version of this figure will appear in some formats. For the color version, please refer to the plate section.)
Credit: luoman / E+ / Getty Images

FIGURE 8.4 Eucalyptus plantation, Brazil.
(A black and white version of this figure will appear in some formats. For the color version, please refer to the plate section.)
Credit: FernandoPodolski / E+ / Getty Images

FIGURE 8.5 Oil palm plantations in Malaysia.
(A black and white version of this figure will appear in some formats. For the color version, please refer to the plate section.)
Credit: simonlong / Moment / Getty Images

Competition with agriculture and rapid urbanization may push plantations to unsuitable land areas (Ahrends *et al.*, 2016). Tree plantations are also being established where trees have never been grown before. Xu (2011) considered planting trees in Mongolian grasslands to be unwise. Satellite imagery has been used to demonstrate the success of plantations in China, but Macias-Fauria (2018) indicates that trends detected by satellite have not been validated by ground measurements. Huge numbers of trees have been planted, but how many survived and are functioning well is not evident.

Liao *et al.* (2010) used a meta-analysis of 86 synthesized experimental comparisons in paired-site design to look at differences between plantation forests and adjacent naturally regenerated primary and secondary forests. Plant and soil carbon (total ecosystem stock) was 284 Mg C ha^{-1} in natural forests. This was reduced by 28% in plantation forests. Compared with natural forests, there was a general pattern of reduction in plantation forests of NPP (11%), litter fall (34%), fine root biomass (66%), soil carbon (32%), microbial carbon (29%), and lower available nitrogen (22%), phosphorus (20%) and potassium (26%). These patterns were not affected by type of tree, tree age, tree species, or land-use history. Based on their analysis, Liao *et al.* concluded that they would not recommend replacement of natural forests by plantations to mitigate global warming.

Huang *et al.* (2018) investigated the role of tree species diversity in carbon accumulation in plantation forests in China. They planted 150,000 trees in 16 different plots, with species diversity ranging from 1 to 16 species. After 8 years of growth, trees in 16-species plots accumulated twice as much carbon as trees in single- or dual-species culture plots.

Peng *et al.* (2014) reported positive benefits for China from afforestation. They used satellite measurements to determine land surface temperatures (LSTs) for planted forests paired with nearby cropland or grasslands. Averaged out, they reported a decrease in land surface temperatures of approximately 1.1 °C for the forested areas, due to increased evapotranspiration (probably transpiration from increased or closed canopy cover) with a nighttime increase of 0.2 °C. Nighttime warming decreased with average rainfall and increased with latitude. Net daytime warming increased in dry areas owing to offset of daytime cooling by increased nighttime warming.

8.5 POPULATION GROWTH AND AFFORESTATION

Population growth is likely to continue in the future, and there will be continuous demand for living space. The great majority of people will live in megacities and associated periurban areas, where land use is intensely managed. Rising incomes and expectations, however, will greatly increase demand for more and better food, including more grain and meat. Global food demand is estimated to increase 59–99% from 2000 to 2050 (Jackson and Baker, 2010). A projected need for more space for agriculture could lead to deforestation to create new cropland and pasture, which would release carbon from soils, decrease forest carbon sinks, and reduce space for afforestation.

8.6 BENEFITS OF AFFORESTATION

Afforestation as a mitigation strategy for reducing atmospheric carbon is part of the Paris Agreement climate project to keep average global temperature increase to below 2 °C, preferably at 1.5 °C. How much afforestation would be required in order to contribute to global temperature reduction? Arora and Montenegro (2011) developed scenarios for how afforestation of the global area currently used for agriculture might reduce average global temperature. For a 50-year simulation run-time, they found that if 100% of the area was afforested, the temperature reduction would be 0.45 °C. If only 50% was afforested, the temperature reduction would be 0.25 °C. There would be little reduction produced by areas below 50%. Boysen *et al.* (2017) consider removal of carbon dioxide from air by fast-growing trees and grasses, and conversion to carbon storage, to be negative emission techniques to offset failure to reduce carbon dioxide emissions from combustion. To accumulate enough biomass carbon to keep the temperature increase no higher than 2 °C, afforestation and grass plantings would have to replace all global natural ecosystems and drastically reduce food production.

With the reductions in carbon dioxide emissions pledged at the Paris Agreement, afforestation and grass areas required would still be huge. One-third of natural ecosystems and one-quarter of current cropland would be converted to forest, reducing food production enormously. Afforestation alone cannot keep global air temperature at or below 2 °C. Partial mitigation increases with irrigation and fertilizer and reduction of emissions of carbon dioxide.

8.7 SUCCESSIONAL DEVELOPMENT: AN ALTERNATIVE TO AFFORESTATION

Restoration is an alternative approach to encourage natural regeneration of native trees, after harvesting or degradation, resulting in new-growth forests. Depending on scale and circumstances, natural regeneration can be passive (or unassisted) or assisted for acceleration. The result is forests that closely resemble the native ones that they are restoring (Chazdon and Uriarte, 2016). Lamb *et al.* (2005) recommend managing and protecting large areas of secondary or natural regrowth regenerated forest. They conclude that successional tree regeneration can be rapid, following deforestation, utilizing available residual tree seeds and any remaining trees, in what they refer to as successional development or self-repair. They report that large-scale natural forest regeneration has been demonstrated in Puerto Rico, Tanzania, Costa Rica, and Brazil.

8.8 SUMMARY

Deforestation and forest degradation are continuing at a record pace. This decreases the carbon sink in wood in tree stems and branches and in the soil, and reduces evapotranspiration. Deforestation can be considered as the world's second highest source of emissions of carbon dioxide and other greenhouse gases. The decreased forest carbon sink contributes to global warming.

The United Nations REDD+ program was established to encourage countries to decrease deforestation through direct payments for results achieved. The Paris Agreement on climate, and other international conferences, recognized that there is value and climate benefit in carbon stored both in trees and in the wood used for construction and other related wood products.

Countries and organizations have pledged to replant deforested land (reforestation) and to plant huge new areas with millions of new trees (afforestation) designated as forests. Afforestation and reforestation are expected to play key roles in partial mitigation of elevated or anthropogenic carbon dioxide to keep average global temperature increases at 1.5 °C and below 2.0 °C. Some of these programs are in progress, while others are in the planning or early activity stages.

This has raised the question: what is a forest? A natural forest contains long-term native tree species in varying stages of development and associated flora, fauna, and microorganisms, resulting in a forest ecosystem that regulates exchange of heat and water with the atmosphere. Many natural or native forests are managed for wood production, and this decreases their mitigation contribution. The response to the call for increased tree planting has been mostly answered by the establishment of huge new tree planting programs. In afforestation, marginal land, former cropland, and even former native forests may be replaced with closely planted fast-growing trees, often of one non-native species. These are called plantations or plantation forests. The purpose is to ensure a reliable source of wood from relatively short-term harvests. China's enormous new tree plantings result in plantations. The mitigation effects of plantation effects have not been extensively explored, but it is evident they do not function in the same way as native forests. Allowing or encouraging native forests to regenerate after harvest is an effective alternative to afforestation, but regrowth may be slower, and plantations are easier to establish.

It has been clearly established that there is not enough land area available for forests to completely mitigate or offset all anthropogenic carbon dioxide emissions. A combination of reduction of emissions and the mitigating influence of forests, working together, is the only effective strategy to prevent global warming increase above 2 °C.

In the next chapter, everything in the previous chapters will be brought together to determine the answer to the question: do forests warm or cool the atmosphere?

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9 Bringing It All Together

> Thus, unless the residence time of carbon (tree residence) is maintained or enlarged, faster growth does not mean there is more carbon sequestered.
>
> Korner, 2017

> Transpiration recharges atmospheric moisture, affecting rainfall and recharge of ground water for transpiration, affecting local and global temperatures, causing cooling.
>
> Ellison *et al.*, 2017

> In the near future, tropical forests are likely to become carbon sources, owing to continued forest loss and the effects of climate change on the ability of the remaining forests to capture excess carbon dioxide.
>
> Mitchard, 2018

9.1 INTRODUCTION

This chapter provides a review of interactive forest-related factors that influence the temperature of the atmosphere. Factors revisited and expanded from previous chapters include carbon dioxide, carbon accumulation, deforestation and afforestation, evaporation and transpiration, albedo, BVOCs, and ozone (Bonan, 2008; Mackey *et al.*, 2013; Unger, 2014; Ellison *et al.*, 2017). Occurring together, and influenced by many other factors, they constitute the system by which forests cool or warm the atmosphere.

9.2 FOREST-RELATED FACTORS THAT INFLUENCE ATMOSPHERIC TEMPERATURE

9.2.1 *Carbon Accumulation*

Tree leaves remove carbon dioxide from the air through photosynthesis. Carbon gain, or sequestration, depends on the rate of photosynthesis being greater than the rate of respiration. The difference between them may be small, and it is the fixed carbon that can accumulate and be stored in wood, biomass, and soil (Mackey *et al.*, 2013; Griffin and Prager, 2017). The accumulated or stored carbon is carbon that was previously in the atmosphere as carbon dioxide. It has been estimated that the terrestrial biosphere (primarily trees) currently removes approximately 20% of anthropogenic carbon dioxide from fossil fuel combustion (Arneth *et al.*, 2017).

Given the slowly continuing increases in carbon dioxide in the atmosphere, tree planting and forest cover increases would seem to be an effective strategy to fix even more atmospheric carbon dioxide and lower the air temperature. This strategy has been widely promoted and adopted, from the local to national and global levels. The Paris Agreement and the UN REDD+ program advocate protecting and restoring forests and planting new ones. The Bonn Challenge and the Trillion Trees Program are sponsoring international tree planting programs. These are all designed to try to keep average global temperature increase at 1.5 °C and below 2.0 °C. The strategy begins with planting small tree seedlings or saplings, or with direct seeding in the tropics. The number of trees that survive is more important than the number planted. Depending on species and conditions, these young trees will require many years to reach large canopy size. Growth rate and maturity will affect their function to remove carbon dioxide from the air and function as sinks for stored carbon. Given the considerable interest in tree planting in the hope of partially mitigating global warming, it is worthwhile to revisit the views and conclusions of Mackey *et al.* (2013) about tree growth rates and stages, and carbon accumulation and storage.

- Young trees are planted: net uptake of carbon dioxide (sink) exceeds respiration, rapid growth, carbon accumulates in woody biomass and soil.
- Progress toward maturity: net sink begins to decline, and growth rate decreases in relation to respiration rates.
- Maturity: photosynthesis and respiration approach balance; small differences could allow some sink activity.

Korner (2017) concludes that faster tree growth does not mean that more carbon will be sequestered. Fast-growing trees in the tropics have short life spans and low wood density. Once new forests reach maturity and full carbon storage capacity, additional carbon will not be sequestered. The carbon residence time in wood storage determines carbon sequestration. Centuries-old trees with stored carbon in wood should be protected. New tree plantings should consist of slow-growing tree species (Korner, 2017).

Carbon accumulation in forests is strongly dependent on nutrient availability. It has been noted that forests growing in high-nutrient soils have high GPP and NPP. Forests growing on nutrient-poor soils lose much of GPP to respiration (Fernandez-Martinez *et al.*, 2015). Evergreen eucalyptus trees did not grow well in phosphorus-deficient soils, but did when phosphorus was added (Ellsworth *et al.*, 2017). Craine *et al.* (2018) examined foliar nitrogen patterns from samples obtained from a 37-year time period. They concluded that foliar nitrogen had declined by 9%. Global warming promotes a longer growing season, particularly for trees, and greater demands for nitrogen may slow future growth and carbon sequestration. Wieder *et al.* (2015) modeled future nitrogen and phosphorus limitations to 2100. They projected a 19% reduction in NPP for nitrogen limitation alone, and 25% if both nitrogen and phosphorus were limited.

Canopy air temperature has recently been shown to influence GPP in a tropical forest (Pau *et al.*, 2018). They used near-continuous thermal imaging to monitor canopy temperatures in a well-documented tropical forest. Canopy temperatures were as high as 34 °C, and as much as 7 °C above air temperature, with evergreen canopies cooler than deciduous canopies. Results from eddy covariance towers indicated that estimated GPP canopy temperatures had more influence than air temperature or vapor pressure deficit. They noted that GPP began to slow at canopy temperatures above 28–29 °C, increasing to 31–32 °C. From their results, they concluded that in a warming climate, canopy temperatures might increase by as much as 40% over air temperatures, with possible adverse effects on GPP.

Tropical forests are expected to benefit from elevated carbon dioxide by increasing biomass, which should provide extensive negative climate forcing and atmosphere cooling through development of large carbon sinks. This has stimulated the use of models, satellite imagery, long-term plot observations, and tree ring growth analyses to determine whether this expectation is being realized. From their model and analysis, Schimel *et al.* (2015) conclude that there is significant uptake of carbon dioxide and growth in tropical forests. Others disagree with their conclusion. Long-term growth stimulation was not found (Groenendijk *et al.*, 2015; Baccini *et al.*, 2017). Brienen *et al.* (2015) found more faster-growing, shorter-lived trees and increased tree mortality. Using tree ring growth analysis, van der Sleen *et al.* (2014) found biomass increase but did not attribute the growth stimulation to carbon dioxide, ascribing it instead to increased efficiency of water-use.

Long-term carbon accumulation in temperate forests is also an area of interest. Most European forests are planted and managed for wood production. This changes the structure and function of the forests. Long-term forest records are available, and productivity trends can be established. Carbon sink saturation has been noted in European forests and is at least partially attributable to the effects of long-term forest management and replacement of deciduous trees with conifers (Nabuurs *et al.*, 2013; Naudts *et al.*, 2016). Using forest inventory data and modeling, Zhu *et al.* (2018) examined the possible future influence of climate change on the increasing North American forest carbon sink, developing as a result of recovery from deforestation. Overall growth is predicted to be limited, suggesting the beginning of carbon saturation. In the 2080s, forest carbon sequestration is predicted to be only 22% of current levels.

9.2.2 *Deforestation and Afforestation*

Deforestation – by tree harvests for wood and fuel, and conversion of forests to cropland, pastures, and industrial and urban areas – significantly reduces carbon accumulation and the forest sink for carbon from carbon dioxide. Crowther *et al.* (2015) estimate that there are 3.04 trillion trees in the world and that approximately 15 billion are removed by humans each year. They also estimate that the number of trees in the world has been reduced by 46% since civilization began. The Industrial Revolution also greatly increased deforestation and began the imbalance between the land and ocean sinks for carbon dioxide. Deforestation is considered to be the second largest source of anthropogenic carbon dioxide, after fossil fuel combustion. Combustion of forest biomass and microbial decomposition of tree debris left behind after tree harvest contribute approximately 20% of anthropogenic carbon dioxide (van der Werf *et al.*, 2009).

Afforestation to increase carbon accumulation in trees is the goal of numerous large global tree planting programs. Some are in response to deforestation and are meant to replace forests. The purpose of others is to plant uniform plantation forests to stabilize soil and provide scheduled wood harvests. Most of these are located in China and have been reviewed here and in Chapter 8. Compared with natural forests, plantation forests store 25% less carbon in tree biomass and soils (Mackey *et al.*, 2013). The effect of these tree planting programs on keeping average global temperature increase at 1.5 °C and below 2.0 °C is considered to be small. There is insufficient space available to plant enough trees to do this without drastic conversion of cropland and natural ecosystems (Arora and Montenegro, 2011; Boysen *et al.*, 2017). Even if there were large reductions of croplands and natural areas for tree planting, the capacity of land to store carbon is finite (Mackey *et al.*, 2013). Drake *et al.* (2016) drew a significant conclusion regarding carbon dioxide storage:

> It is possible for elevated carbon dioxide to cycle through an ecosystem without stimulating net carbon dioxide storage.
>
> Drake *et al.*, 2016

9.2.3 Evaporation and Transpiration

Considered collectively as evapotranspiration, evaporation from surfaces and via leaf stomata contributes water vapor to the atmosphere. This influences rainfall, which may then be evaporated from leaves or soil, soak into the ground, or be taken up by plants and transpired, to complete the terrestrial water cycle (Ellison *et al.*, 2017). Evaporative cooling occurs when liquid water changes state and in the process changes sensible heat to latent heat. Latent heat flux results in a local cooling effect (Ban-Weiss *et al.*, 2011). More than 80% of evapotranspiration is transpiration, and it is the major source of water vapor for local air cooling (Jasechko *et al.*, 2013). Transpiration is the most important evaporative part of the water cycle (Kirschbaum and McMillan, 2018). Transpiration generally decreases with increasing latitude (Li *et al.*, 2015).

Transpiration depends on available soil water and soil water recharge. With drought increasing worldwide, transpiration rates may decrease. Transpiration is also affected by many factors, including carbon dioxide, air temperature, sunlight, shading, canopy structure, vapor pressure deficit, wind speed and boundary layer resistance, stomatal conductance, leaf and canopy area, available water and soil nutrients, and foliar pathogens and insects (Kirschbaum and McMillan, 2018).

Forest fires are increasing globally, especially in boreal areas. Large forest fires destroy trees and eliminate transpiration, resulting in land surface temperature increase (Liu *et al.*, 2018). Burned areas require many years for planted or natural forests to return to previous transpiration levels.

In experiments with tree responses to elevated carbon dioxide exposures, it was noted that partial to near-complete stomatal closure occurred quickly (Long, 2012). This would decrease transpiration and increase water-use efficiency, while maintaining a steady state level of carbon dioxide for photosynthesis, resulting in increased growth and biomass. Farrior *et al.* (2015) examined results from experiments and models, and constructed a possible mechanism by which increased water-use efficiency, due to partial stomatal closure in response to elevated carbon dioxide, could result in increased carbon accumulation in forest trees. They proposed that, with increased water-use efficiency, trees in soil-water-limited forests were able to decrease the extent and amount of fine roots needed to search for and transport limited soil water, resulting in greater investment in carbon storage in woody biomass.

Kirschbaum and McMillan (2018) investigated how two opposing biophysical factors in the future might affect transpiration. Increased temperature might increase the vapor pressure deficit and increase transpiration. Increased water-use efficiency from increased carbon dioxide exposure would cause partial stomatal closure, reducing transpiration. They concluded that stomatal opening reduction caused by carbon dioxide would produce a stronger reduction in transpiration than the stimulatory effect of increased temperature on increased transpiration.

Leggett and Ball (2018) have proposed that a global atmospheric temperature slowdown is in progress, with observed average air temperatures not always consistent with those resulting from most climate simulation models. When actual temperatures are subtracted from the predicted model temperatures, they perceived a "temperature gap." From their analysis, they concluded that the ocean heat sink and evapotranspiration were the cause of the differences between modeled air temperature and recorded temperatures. Most of the evaporative effect was due to transpiration. Zeng *et al.* (2017) attributed global greening to a 12% reduction in surface warming during the past 30 years. Increased evapotranspiration was considered to be responsible for 70% of the effect.

Water vapor from transpiration also influences low cloud cover, increasing albedo and cooling (Ellison *et al.*, 2017). Doutriaux-Boucher (2009) used a coupled climate carbon cycle model for a 5-year period to look at how carbon-dioxide-caused stomatal closure would affect low cloud cover. Reduction in the low cloud cover over land would result in additional incursion of incoming shortwave radiation, causing a 10% increase in carbon-dioxide radiative forcing.

9.2.4 Albedo

Light reflection by land, trees, and low clouds affects the incidence of incoming solar radiation and affects air and land surface temperatures. Albedo values from 0 to 1.00 indicate the intensity of light reflectance. Clean new snow has values approaching 1.0, followed by open grassland at 0.25, deciduous trees at 0.15–0.18, and conifers at 0.08–0.15. Low albedo values – that is, less light reflection by forests – result in positive radiative forcing and warming, especially in boreal regions (Betts, 2000; Bonan, 2008; Mykleby *et al.*, 2017). This may override any negative radiative forcing from carbon sequestration (Betts, 2000).

Tree species differ in their albedo effect. Deciduous trees with high albedo include birch, aspen, and poplar. Norway spruce has very low albedo, with Scots pine at intermediate level (Mykleby *et al.*, 2017). Afforestation of open areas with deciduous trees would result in less decrease in albedo than conifers. Deforestation would increase albedo and might lead to cooling (Gibbard *et al.*, 2005). The influence of albedo on warming increases with latitude, especially in and approaching boreal forest areas (Li *et al.*, 2015).

9.2.5 Biogenic Volatile Organic Compounds and Ozone

BVOCs are naturally released by tree leaves. Isoprene is released from deciduous tree leaves. Its formation is dependent on temperature and light, and its rates of emission vary with tree species. Monoterpenes are associated with conifers. Monoterpenes are constitutive, meaning that release from leaves is associated with temperature.

Release of BVOCs increases with increasing atmospheric temperature. They are indirectly involved in atmospheric cooling through their role in low cloud formation and resulting negative feedback. Paasonen *et al.* (2013) have provided a pathway for low cloud formation. Chemically active BVOCs are oxidized on release by ozone or the hydroxyl ion (OH). The products condense on existing aerosol particles, which act as cloud condensation nuclei, leading to droplets which form clouds. Albedo of clouds reflects incoming solar radiation, resulting in cooling. Using a global atmospheric model, Spracklen *et al.* (2008) calculated that boreal forests double the regional cloud condensation nuclei and increase cloud cover, resulting in cooling. However, from historical records, Unger (2014) concluded that reduction of BVOCs through conversion of forests to agricultural land increased surface albedo and resulted in cooling. The involvement of BVOCs in ozone formation, ozone's prolongation of methane in the atmosphere, and aerosol formation are considered to be negatives for BVOCs (Unger, 2014). In addition to reflecting incoming shortwave radiation during daylight hours, low clouds can also retain some of the infrared radiation returning to space, enhancing the greenhouse effect.

BVOCs from trees, mainly isoprene, also participate in the photochemical oxidant cycle, at above-background levels that damage leaves and reduce photosynthesis and thus biomass and carbon accumulation. Ozone and ozone injury in forests are declining in northern Europe and the eastern United States, but increasing in the western and Pacific northwest United States, influenced by long-range transport of ozone and precursors from Asia. Ozone and ozone injury continue to increase in Asia.

9.3 DETERMINATION OF ATMOSPHERIC COOLING AND WARMING BY FORESTS

Determining how forests affect local and global temperatures goes well beyond results from experiments with trees. Models and satellite imagery, sometimes including results from experiments, and eddy covariance towers are examples of methods and technology used to analyze complex systems. The focus of many investigations has been on predicting future global temperature. There are a few examples of results that indicate what is occurring now. How forests relate to atmospheric cooling and warming has been considered in Chapters 1 and 6. Further consideration is given here of some examples that relate methods to conclusions.

9.3.1 Examples from Models and Satellite Imagery

9.3.1.1 Cooling

Models can be used to predict future cooling and warming. Bala *et al.* (2007) modeled the influence of drastic deforestation on temperature.

Evapotranspiration and cloud cover decreased, causing warming, but albedo increased, to result in net cooling. Models have also been used to predict the influence of afforestation on temperature. Shen *et al.* (2015) used simulation modeling of increasing vegetative growth in Tibetan Plateau grasslands. Conversion to trees would result in lower albedo and warming, partially offset by increased evapotranspiration. Swann *et al.* (2010) modeled afforestation of bare ground in the high-altitude Arctic with deciduous trees. Tree canopy decreased surface albedo and increased warming, but the effect of increased transpiration was stronger than that of albedo change, resulting in negative forcing and cooling.

9.3.1.2 Warming and Cooling

Models can also be used to assess the current status of forests and cooling and warming. Zeng *et al.* (2017) used modeling to assess the influence of increased global greening on warming during the past 30 years. They related areas of LAI increase to a decrease in average global temperature by 0.09 °C since 1982 and proposed a total 12% decrease in land surface warming. The degree to which Chinese plantation forests cool the atmosphere is controversial. Very large, mostly deciduous forests with lower albedo could cause warming. Peng *et al.* (2014) used satellite imagery measurements of forests and adjacent non-forest land areas to compare temperatures. They concluded that increased evapotranspiration resulted in daytime cooling, offsetting albedo effects, with only a slight increase in nighttime temperature.

Gibbard *et al.* (2005) simulated land cover changes that would result in either cooling or warming. Global tree removal would lead to a global average temperature increase of 1.3 °C. If the trees were replaced with grasslands, an average cooling effect of 0.4 °C would occur. Schultz *et al.* (2017) used modeling to explore the effects of deforestation on the diurnal asymmetry of temperature in relation to forest types. Deforestation increases warming during the day, with cooling at night. Daytime warming is due to increased solar radiation and decreased evapotranspiration and latent heat flux. Nighttime cooling results from release of heat stored during the daytime by turbulence. Reduction of evapotranspiration from deforestation in the tropics results in localized warming. Deforestation in boreal areas results in nighttime cooling, as deforested areas have higher albedo and cool faster.

9.3.1.3 Warming

Cao *et al.* (2010) modeled how increasing carbon dioxide to 800 ppm would increase atmospheric warming. Elevated carbon dioxide would decrease stomatal opening and reduce canopy transpiration, reducing latent heat flux to the atmosphere. This would affect atmospheric water vapor and clouds. An 8% decrease in transpiration would lead to a mean atmospheric warming of 0.1 °C.

9.3.2 Examples of Cooling and Warming from Other Methods

9.3.2.1 FLUXNET USA and Canada

Lee *et al.* (2011) used FLUXNET (forest eddy covariance towers) and adjacent weather stations in the United States and Canada to record surface air temperatures in open land and adjacent forested areas. Forest air temperatures were higher than in adjacent open land. The effect was strongest north of 45° N. Nighttime temperatures were not related to albedo change. Open land cools more than forested land. They hypothesized that at nighttime, tree-caused turbulence drew atmospheric heat to the forest surface.

9.3.2.2 FLUXNET Europe

Tang *et al.* (2018) developed an extensive European network of 48 sites to carry out an empirical analysis of how forests influence on local temperatures is affected by season and ambient background temperature. Each forest site was paired with an adjacent forest area and a weather station and flux tower. MODIS spectoradiometry was used for land surface and air temperatures. In general forests in Northeast Europe generally increased land surface and air temperatures, while decreasing them in other areas. Daytime cooling prevailed in summer, with night warming in cold seasons. Effects of forests on local temperature were negatively correlated with ambient background temperatures. The cooling influence of forests was strongest during heat waves.

9.3.2.3 Cooling by Urban Trees

Cooling from shade from urban trees is most effective when air temperatures are very high. In a recent investigation, Rahman *et al.* (2018) followed air temperature reductions by two common street trees, European linden (*Tilia cordata*) and black locust (*Robinia pseudoacacia*), for a growing season. Linden has larger leaves and greater sapwood area, resulting in a transpiration rate 3 times that of locust. As the season progressed and became warmer, temperature reductions for locust canopies progressed from 1.5 °C to 0.5 °C, and for linden from 1.8 °C to 1.3 °C.

9.3.2.4 Warming from Forest Management

European forests have been planted and managed for several centuries. Abundant records of planting, management, inventory, and productivity are available. Naudts *et al.* (2016) reviewed historical records for forest inventory and productivity and related this to a current warming atmosphere. They found that the long-term trend in replacing slower-growing deciduous forest trees with darker, faster-growing conifers has changed the albedo of the forests. Managed conifer forests absorb more incoming solar radiation, which might increase atmospheric temperature by 0.12 °C. They concluded that less carbon is stored in today's well-managed forests than in the past.

9.4 FOREST COOLING AND WARMING BY LATITUDE AND FOREST TYPES

Tropical, temporal, and boreal are the major forest types of the world. Using results from simulation and carbon cycle models (Bonan, 2008) and satellite observations (Li *et al.*, 2015), these forest types have been characterized in relation to their characteristics, effectiveness in carbon storage, and atmospheric cooling and warming. Interactions between albedo and evapotranspiration, influenced by rain and snowfall, determine the immediate cooling or warming (Li *et al.*, 2015). Anderson *et al.* (2011) summarized the characteristics of major forest types and non-forested areas in summer and winter, including their effects on reflection of solar radiation and latent and sensible heat flux, and how this would likely affect atmospheric cooling (Figure 9.1). A summary of all of these assessments is presented here.

9.4.1 Tropical Forests

Tropical forests have the strongest air-cooling effect that continues throughout the year, as many trees are evergreen and continue growing. Evapotranspiration rate is very high, resulting in cooling and increased rain. The albedo of the trees causes air warming. The rate of evapotranspiration offsets warming caused by low albedo. Carbon storage is high, but is affected by drought, deforestation, and fires.

9.4.2 Temperate Forests

Temperate forests contain both deciduous trees and conifers. As a result, albedo is higher than tropical forests, and evapotranspirational cooling is lower. Moderate cooling in summer and moderate warming in winter results in net cooling. Again, carbon storage is high, but affected by deforestation, drought, fires, and insects.

9.4.3 Boreal Forests

Conifers in boreal areas have low albedo and low rates of evapotranspiration, resulting in low latent heat flux. Deciduous trees have higher albedo and higher latent heat flux. Overall, boreal forests warm somewhat with snow in winter and have moderate to weak cooling in summer. Carbon storage is low in trees, but high in soils and permafrost. Carbon storage is affected by frequent fires and logging.

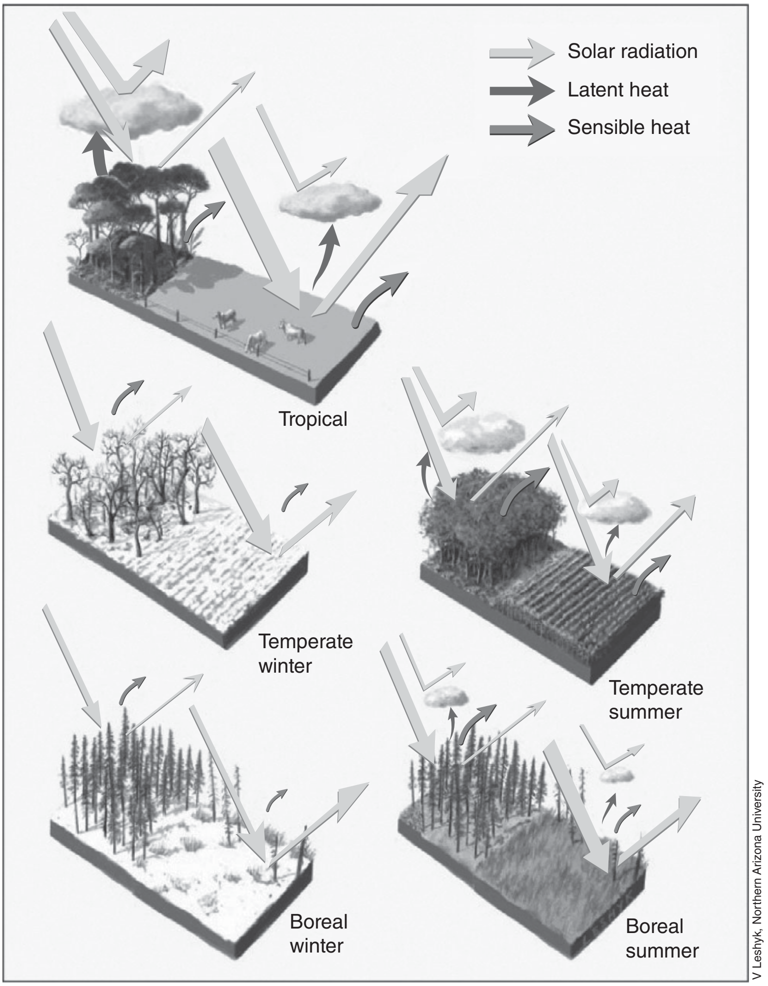

FIGURE 9.1 Effects of forest and non-forest ecosystems on surface energy fluxes in tropical, temperate winter, temperate summer, boreal winter, and boreal summer scenarios.
Forests have greater heat fluxes than non-forest ecosystems, resulting from their greater surface roughness. Tropical rainforests have large latent heat fluxes that result in the development of clouds, which reflect solar radiation back to space. Temperate and boreal forests have major seasonal variations in energy fluxes and can reduce seasonal cooling by masking snow.
(A black and white version of this figure will appear in some formats. For the color version, please refer to the plate section.)
From R. G. Anderson *et al. Frontiers in Ecology and Environment*, Biophysical considerations in forestry for climate protection. Copyright © (2011) by John Wiley & Sons, Inc. Adapted by permission of John Wiley & Sons, Inc.

9.5 CONCLUSIONS

A large, wide-ranging body of literature was reviewed for assembly of the chapters that make up this book. A series of conclusions from the chapters that relate to background and research is presented in relation to the greenhouse effect, global warming, and the role of trees and forests in cooling or warming the atmosphere. These are followed by an answer to the question "Do forests cool or warm the atmosphere?" and a discussion of how this answer might change in the future.

9.5.1 The Anthropocene: A New Epoch

Humans are significantly and directly influencing the physical and biological factors that regulate the functions of the Earth. This has resulted in continuing global warming. A new epoch, the Anthropocene, has been proposed to replace the Holocene. Global warming will continue as population growth and human needs and desires continue to grow.

9.5.2 Carbon Dioxide

Carbon dioxide levels have risen from approximately 278 ppm, before the Industrial Revolution, to elevated levels at more than 400 ppm now. This is due to emissions from fossil fuel combustion, cement production, and deforestation. Forests and the oceans absorb much of the elevated carbon dioxide. What remains in the atmosphere, around 40%, is persistent anthropogenic carbon dioxide. This is the most prevalent non-condensable gas that regulates the greenhouse effect and global warming. Carbon dioxide thus controls the temperature of the Earth, and its reduction is essential to reduce temperature and global warming.

9.5.3 Forests and Anthropogenic Carbon Dioxide

Models estimate that 20–30% of anthropogenic carbon dioxide is removed from the atmosphere by forests, through increased photosynthesis and transpiration and some carbon sequestration, resulting in some atmospheric cooling. This negative forcing by forests is considered a partial mitigation of present global warming.

Forests are not able to remove all the remaining anthropogenic carbon dioxide from the atmosphere. To do that, most cropland and natural ecosystems would have to be converted to forests. This would require 60% or more of US cropland.

9.5.4 *Trees and Future Elevated Carbon Dioxide*

Many have proposed that trees might be able to continue to slow or even eliminate future global warming by using present and future increasing carbon dioxide for photosynthesis, transpiration, and carbon sequestration. A very large number of experiments have been conducted during the past 30-plus years, using predicted future levels of carbon dioxide exposures, ranging from 500 to 800 ppm. Experimental design and duration, exposure regimes, and the young age of the trees typically used prevent extrapolation of the results to large trees or to the forest. Initial growth stimulation from elevated carbon dioxide exposure either did not occur or was not sustained in the absence of sufficient soil nutrients, mainly nitrogen and phosphorus, and growth could also be limited by acclimation. These limits on growth could also limit possible increases in the partial mitigation of future global warming by forests.

Results from multi-year Web-FACE experiments with mature trees in Switzerland showed that elevated carbon dioxide did not increase tree growth. Similar results were found from several FACE experiments. There is also evidence that combined ozone plus carbon dioxide exposures could reduce or eliminate biomass gain caused by elevated carbon dioxide. It seems unlikely that increased growth and carbon sequestration by future forests will significantly increase the partial mitigation of global warming in the future by reducing carbon dioxide.

9.5.5 *Deforestation*

Deforestation is the second largest source of carbon dioxide. Deforestation, particularly in tropical forests, continues as harvesting, land-use change, drought, bark beetle infestations, and fires increase. This reduces forest biomass for photosynthesis, transpiration, and carbon sequestration. Albedo increases in cleared areas result in cooler air temperatures. That increasing albedo, from very numerous, very large-scale afforestation and reforestation programs, especially with conifers, could increase air temperature would seem to be worth investigating.

9.5.6 Tree Planting: Reforestation

In response to widespread deforestation, large-scale tree planting programs for reforestation have been proposed by the Paris Agreement conference, and others are in various states of implementation, sponsored by the United Nations, several international conservation groups, and national governments. The goal of long-term reforestation is to re-establish forests to increase forest biomass and carbon sequestration, and reduce or maintain global temperature. In some early tree planting programs, inappropriate tree species were used, and many new trees died. Credibility in reporting the extent and results of tree planting programs can be a problem.

9.5.7 Tree Planting: Afforestation and Plantations

New areas are being used for tree planting to establish huge plantations of mostly single-species, fast-growing trees, especially in China. It has been estimated that these sequester 25% less carbon in trees and soils than native forests. Balancing transpirational cooling against warming from canopy albedo may be a problem. Many seem to be intended for scheduled harvests for wood. Encouraging natural reforestation by seeding or encouraging native tree species to regrow seems less expensive and labor-intensive, and a better long-term ecological strategy.

9.5.8 Tree Planting: Long Life Matters

Tree species, growth rate, and wood storage capacity determine long-term carbon sequestration. Fast-growing, short-lived trees produce biomass quickly and sequester some carbon, but it mostly goes back into the atmosphere when they die. Slow-growing, long-lived trees sequester more carbon and retain it in wood. Carbon sequestration by trees is largely determined by how long carbon remains stored in living trees. Old-growth mature forests are living carbon reservoirs.

9.5.9 Atmospheric Cooling and Warming

9.5.9.1 Photosynthesis, Transpiration, and Albedo

Carbon dioxide, transpiration, and albedo determine atmospheric cooling or warming by forests. The physiological role of trees in forests in cooling or warming the atmosphere is determined by stomatal conductance and gas exchange. Carbon dioxide diffuses inward and is used in photosynthesis, with some carbon sequestered in wood. Photosynthesis thus promotes cooling by increasing the terrestrial carbon land sink. Water vapor diffuses outward in transpiration which results in evaporative cooling. Transpiration cools the air, promotes low cloud, and regulates the terrestrial hydrological cycle. The physical role of trees and forests in cooling or warming the atmosphere is determined by albedo. Low tree albedo levels, especially in dark conifer forests, result in low reflection of incoming solar radiation, and this can warm the atmosphere. The balance between transpiration and albedo directly determines cooling or warming of the atmosphere by forests.

9.5.9.2 BVOCs and Ozone: Roles in Cooling and Warming

BVOCs from trees can increase atmospheric cooling by forming cloud condensation nuclei that lead to formation of low clouds. BVOCs from trees, mostly isoprene, are also part of the photochemical oxidant cycle that results in ozone formation above normal background levels. The raised ozone levels can injure leaves, reducing photosynthesis and biomass and carbon accumulation. BVOCs here may indirectly contribute to warming. Elevated ozone may reduce growth stimulation in response to elevated carbon dioxide. Ozone and ozone injury are declining in northern Europe and the eastern United States, but increasing in the Pacific Northwest, aided by long-range transport of ozone and precursors from Asia. Ozone and ozone injury continue to increase in Asia. Ozone remains a problem in forest health.

9.5.9.3 Factors That Affect Cooling and Warming

Geographical, biological, environmental, and cultural factors affect the extent of atmospheric cooling and warming by forests. Latitude, growing season, forest species and species composition, available soil water and nutrients (especially nitrogen), BVOCs, ozone, fires, bark beetles, and drought affect growth and biomass production.

9.5.9.4 Latitude and Forest Types

Results from models and satellite imagery have led to conclusions that latitude, tree species, and types of forest strongly affect cooling or warming of the atmosphere by forests. Boreal forests are largely coniferous, have low to moderate carbon storage, low transpiration and low albedo, and seasonal warming effects. Temperate forests have more carbon storage and transpiration, higher albedo, and moderate summer cooling and some winter warming. Tropical forests have the greatest cooling effects from year-round growth and photosynthesis and transpiration. Transpirational cooling is greater than the warming effects of the lower albedo of tree canopies. Carbon storage is usually assumed to be high, but this is currently questioned, and some people now consider that different tropical forests can be carbon sinks, carbon-neutral, or carbon sources (or are predicted soon to become carbon sources). These conflicting conclusions are of grave concern, as tropical forests are considered to be major sources of atmospheric cooling and carbon storage.

9.5.10 Evidence of Cooling and Warming

Most of what is known or concluded about the role of forests in cooling and warming the atmosphere results from indirect evidence from models, satellite imagery, and spectral radiometry and lasers in various combinations.

9.5.10.1 Shade

The air in the interior of many forests is cooler because of the shade. People instinctively seek shade in forests and parks, even under single trees, as refuge from high temperatures. There is evidence that the extent of tree plantings, canopy size, nature, and tree species determines atmospheric cooling in cities. The benefits of tree canopy temperature reduction are most effective when ambient air temperatures are high. Urban trees that shade buildings reduce energy use for cooling and thus carbon dioxide emissions from power plants.

9.5.10.2 Forest Inventories and Forest Management

The nature of tree species influences atmospheric warming and cooling. Forest inventory data have been used to determine long-term trends in the effects of forest management and forest tree composition in Europe. Long-term replacement of deciduous trees over time with faster-growing dark conifers, mostly spruce, increased forest albedo and resulted in a small calculated increase in air temperature. Reduced growth and early carbon sink saturation has also been noted. Forest management is good for scheduled wood production, but the tree species used can have a definite effect on warming the atmosphere.

9.5.10.3 FLUXNET Tower Forest Open Space Comparisons

Direct evidence has been obtained from extensive studies comparing surface temperatures and carbon dioxide concentrations between open land and lower-albedo adjacent forests, using eddy covariance FLUXNET tower systems. In general, forests have higher air temperatures, especially at night, than adjacent open areas.

9.6 DO FORESTS COOL OR WARM THE ATMOSPHERE?

The current answer to this question depends on the kinds of trees and forests and where they are. The latitude determines the length of the growing season, and the kind and color of the trees. This affects photosynthesis and the balance between transpiration and albedo that determines atmospheric cooling or warming by forests. Atmospheric cooling by forests decreases with distance from the equator, with the greatest cooling from tropical forests.

An answer about the future role of forests in partial mitigation of global warming by atmospheric cooling is less certain. The forests that provide partial mitigation of global warming now are under great pressure from deforestation, fires, drought, ozone, and insects. New evidence indicates that foliar nitrogen levels are decreasing as a result of extended growing seasons and increased photosynthesis. The role of tropical forests is controversial as to whether they are carbon-neutral, carbon sinks, or carbon sources. How this will affect forests in maintaining their current partial mitigation of global warming is not clear. It seems unlikely that forests will provide additional mitigation of global warming in the future.

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