Plant Science

Growth, Development, *and* Utilization of Cultivated Plants

Margaret J. McMahon

Sixth Edition

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GROWTH, DEVELOPMENT, AND UTILIZATION OF CULTIVATED PLANTS

SIXTH EDITION

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Department of Horticulture and Crop Science
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The sixth edition of *Plant Science* is dedicated to my grandfather, Harold Deeks, and my parents, Bob and Marty McMahon, who taught me to love growing plants and appreciate science. It is also dedicated to my son, Rhys, who to my delight has become a very knowledgeable horticulturist.

brief contents

contents

Preface

Enter the fascinating and colorful world of plant science through the sixth edition of *Plant Science*. Discover why we depend on plants and the people who know how to grow them for our survival. Find out how plants provide sustenance for our bodies and add enjoyment to our lives (food for body and soul). Learn how to grow, maintain, and utilize plants to make a living and benefit people and the environment. Whether your interests range from running the family farm to managing a tournament golf course, or directing an international business, rewarding, challenging, and fulfilling careers are open to anyone skilled in plant science.

Human survival absolutely depends on the ability of plants to capture solar energy and convert that energy to a form that can be used as food. The captured energy stored in plant tissues also provides fiber and oil for fuel, clothing, and shelter. The production of plants that meet our needs for survival is an important application of the knowledge of plant science; however, the essentials for human nutrition and shelter can be provided by relatively few plant species. Life would be boring, though, if those few were the only species produced for our needs. Fortunately for those who dislike boredom, thousands of plant species can add enjoyment to life by providing a variety of flavors, colors, and textures in food and fiber. Other plants brighten our lives when used in landscaping and interior decoration, while others provide the basis for many pharmaceuticals. The importance of turfgrass in athletic and outdoor recreation sites is evident around the world. Animal feeds are another critical use of plants. Animals provide nutrition and variation in our diets, along with materials for clothing and shelter. They also reduce labor in many parts of the world and add pleasure to our lives through recreation or as pets.

Plants have tremendous economic impact in developed and developing nations. The career opportunities created by the need for people with an understanding of plant growth are unlimited. *Plant Science* is written for anyone with an interest in how plants are grown and utilized for maintaining and adding enjoyment to human life as well as improving and protecting the environment. The beginning chapters of the text provide the fundamentals of environmental factors, botany, and plant physiology that affect plant growth. There is also a brief discussion of the methods of scientific investigation and how anyone growing plants can use those to make good professional decisions. The later chapters integrate the aforementioned topics into strategies for producing plants for food, fiber, recreation, and environmental stewardship.

New to This Edition

The sixth edition of *Plant Science* has been updated to include the most recent statistics, production methods, and issues concerning the production and utilization of plants. New information has been added, and outdated information has been deleted. The discussion of photosynthesis has been expanded to provide more detail on the process. What was the Floriculture chapter has been expanded and is now Controlled Environment Agriculture to reflect the tremendous increase in food production in greenhouses and other indoor facilities.

Unit I focuses on the human and environmental factors and issues that influence how, why, and where plants are grown. The unit includes how natural ecosystems influence plant cultivation and how the scientific method and research is applied to growing plants.

Unit II addresses the biological basis of plant science. Plant physiology and biochemistry, genetics, an expanded section on genetic engineering, propagation, biodiversity and germplasm preservation, water relations (among soil, plant, and air), as well as mineral nutrition are the topics.

Unit III integrates the information from the previous units to provide guidance for the production and/or use of major plant commodity groups.

Acknowledgments

The author and editors would like to thank the reviewers of the sixth edition for their thoughtful comments and ideas. They are: David Berle, University of Georgia; Jack R. Fenwick, Colorado State University; Sharon Frey, Sam Houston State University; Mary Ann Gowdy, University of Missouri; Steve Hallett, Purdue University; Malcolm Manners, Florida Southern College; Don Mersinger,Wabash Valley College; Ellen T. Papparozzi, University of Nebraska - Lincoln.

The editors also thank all those who contributed to earlier editions of this book. Those contributors are Curtis Alley, A. H. Allison, Victor Ball, Robert F. Becker, Brian L. Benson, Alison Berry, Itzhak Biran, Arnold J. Bloom, James W. Boodley, Robert A. Brendler, Royce Bringhurst, Thomas G. Byrne, Jack Canny, Will Carlson, Kenneth Cockshull, Charles A. Conover, Beecher Crampton, Began Degan, Frank Dennis, Francis DeVos, Dominick Durkin, Roy Ellerbrock, James E. Ellis, Clyde Elmore, Thomas W. Embledon, Harley English, Elmer E. Ewing, Michael Farhoomand, Gene Galleta, Melvin R. George, Marvin Gerdts, Ernest M. Gifford, Victor L. Guzman, L. L. Haardman, Abraham H. Halevy, Richard W. Harris, R. J. Henning, Charles Heuser, James E. Hill, Jackson F. Hills, Karl H. Ingebretsen, Lee F. Jackson, Subodh Jain, Merle H. Jensen, Robert F. Kasmire, Thomas A. Kerby, Dale Kester, Paul F. Knowles, C. Koehler, Harry C. Kohl, Dale W. Kretchman, Harry Lagerstedt, Pierre Lamattre, Robert W. Langhans, Roy A. Larson, Robert A. H. Legro, Andrew T. Leiser, Gil Linson, Warner L. Lipton, Oscar A. Lorenz, James Lyons, Harry J. Mack, John H. Madison, Vern L. Marble, George Martin, Shimon Mayak, Keith S. Mayberry, Richard Mayer, Donald N. Maynard, Arthur McCain, Charles A. McClurg, Harry A. Mills, Franklin D. Moore III, Yoram Mor, Julia Morton, James L. Ozbun, Jack L. Paul, William S. Peavy, Nathan H. Peck, Jack Rabin, Allan R. Rees, Michael S. Reid, Charles Rick, Frank E. Robinson, J. Michael Robinson, Norman Ross, Edward J. Ryder, Kay Ryugo, Roy M. Sachs, Robert W. Scheuerman, Art Schroeder, John G. Seeley, William Sims, Donald Smith, L. Arthur Spomer, George L. Staby, W. B. Storey, Vernon T. Stoutemyer, Walter Stracke, Mervin L. Swearingin, Herman Tiessen, Edward C. Tigchelaar, Ronald Tukey, Benigno Villalon, Stephen Weinbaum, Ortho S. Wells, Bernard H. Zandstra, Naftaly Zieslin, and Frank W. Zink. The authors who wrote or revised chapters in the current edition are listed on the opening page of his or her respective chapter.

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About the Author

Margaret (Peg) J. McMahon Associate Professor, Emeritus, of Horticulture and Crop Science The Ohio State University

Margaret J. McMahon is a fourth generation horticulturist who grew up working on the family farm and in the ornamental and vegetable greenhouses owned by her family. She earned a B.S. in Agriculture with a major in Horticulture from The Ohio State University in 1970. After graduation she worked for fifteen years as a grower and propagator for Yoder Bros., Inc. (now Aris Horticulture, Inc.), a multinational greenhouse company. She started at their Barberton, Ohio facility, transferring to operations in Salinas, California then Pendleton, South Carolina.

While in South Carolina, Dr. McMahon earned her M.S. in Horticulture and Ph.D. in Plant Physiology from Clemson University in 1988 and 1992, respectively. Her masters project focused on the early detection of chilling injury in tropical and subtropical foliage plants. Her Ph.D. research was in photomorphogenesis, specifically, the use of far-red absorbing greenhouse glazing materials as a potential technology to reduce unwanted stem elongation in greenhouse crop production.

In 1994, Dr. McMahon started a faculty position in the Department of Horticulture and Crop Science (HCS) at The Ohio State University, retiring in 2017. Her research continued in the area of photomorphogenesis. She taught several classes each year including both the introductory and senior capstone courses in horticulture and crop science, as well as classes in indoor gardening (interiorscapes), basic irrigation principles and practices, plant propagation, and greenhouse crop production. She also taught a graduate level class to help prepare the graduate teaching assistants in HCS to be effective teachers.

Dr. McMahon has published many peer-reviewed as well as trade journal articles on photomorphogenesis, teaching methods, and other subjects. She was part of two teams that were awarded several hundred thousand dollars from the USDA/NIFA Higher Education Challenge Grant program.

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unit one

Environmental, Cultural, and Social Factors That Influence the Cultivation and Utilization of Plants

1

History, Trends, Issues, and Challenges in Plant Science

Michael Knee and Margaret McMahon

Learning Outcomes

After reading this chapter, you should be able to:

1. Discuss the role that plant science has played in history and continues to play in the world.
2. Discuss the trends and issues impacting plants and the methods used to grow them, including economic, social, and environmental considerations.
3. Understand how plant scientists take trends and issues into consideration when researching the solution to a problem.
4. Describe the fundamental principles of scientific inquiry used by plant scientists when addressing the challenges that come with growing plants.

INTRODUCTION

Domesticating and growing plants to feed, decorate, and entertain the human race has been a noble human endeavor for thousands of years. From nearly the beginning and perhaps unwittingly at first, plant science has been a part of that effort. Plant science can be described as the combination of the study of plant biology (**botany**) and the production and use of plants for food, fiber, decoration, and recreation. Anyone who makes a living growing plants or grows them as a hobby is a plant scientist. As you will learn throughout this text, there are many aspects of growing plants as well as many challenges. Meeting these challenges makes it an exciting time to be a plant scientist.

HISTORY

As citizens of the twenty-first century, we tend to pride ourselves on how we have used agriculture to shape the modern world to serve and please us. We have reason to feel that way—our agricultural practices have changed the world. But if we were to use H. G. Wells' time machine to transport us back 150 million years, we would see many plants very similar to those common in our century. We would see some of the same trees that grow in our world, along with other members of the **angiosperms**, the group of plants to which grasses, flowers, vegetables, fruits, trees, and shrubs belong. We would also see many plants that no longer exist. Some dinosaurs would be feeding on these plants. As time progresses, the dinosaurs would disappear and other animals would appear and evolve, and some would die out. Plant life would change, some as a result of changes in climate, and become most of the plants we know today. During this time, humans had no influence on changes in life forms that occurred or disappeared.

Humans as a race appeared around 3 million years ago and modern man, *Homo sapiens,* appeared about 28,000 years ago. For thousands of years, *H. sapiens* existed without doing much to change how plants grew. As hunters and gatherers, the nomadic tribes followed herds of animals and gathered plant materials along the way. The plants they probably gathered would have been some of the same nuts, grains, and fruits we eat today. Other plants known today would have also provided shelter.

Then something happened around 12,000 to 10,000 years ago (perhaps earlier, according to recent archaeological finds) that had a dramatic impact not only on human lifestyle, but the entire global **ecosystem**. Humans began the purposeful growing or **cultivation** of plants to improve the supply of materials obtained from these plants. The science of understanding the cultivation of plants, plant science, was born. Plant cultivation is believed to have started in tropical and subtropical regions in the Middle East and Africa. Today there is an incredible array of plants cultivated for not only food and utilitarian uses (e.g., clothing fiber, medicinal, forest materials) but ornamental and recreational purposes (**Fig. 1–1**). All of these plants were selected from the wild and, through the use of methods to be presented in this book, were domesticated and cultivated to become the plants we know and use today.

By cultivating plants, humans reduced the need to travel to follow the food supply. Those who did the traveling became traders more than gatherers. Commerce began when goods from distant places were transported and sold or traded to a local population. Many of these products were plants or plant products. Along with trading the goods, ideas about cultivating plants also spread. By 6,000 to 5,000 years ago, crops were being grown in Europe and Mexico. However, the types of crops grown in the various areas differed for reasons that will be explained in later chapters.

At first, the developing lifestyle had little effect on global ecosystems; as trading increased, however, commercial or urban centers developed. The population of the urban centers increased along with the need to bring in more food and other plant products from rural areas to support that population. However, the citizens of these urban areas became less and less aware of how the plants they used were produced. The **rural/urban interface** developed. In many areas, this interface was a very distinct line of demarcation with a defense wall separating urban from rural areas. As populations grew, the urban areas spread out away from the central urban area. The rural areas were forced to move outward too, quite often into areas less favorable for growing plants.

As demand for plant products increased, cultivation methods were developed to help produc-

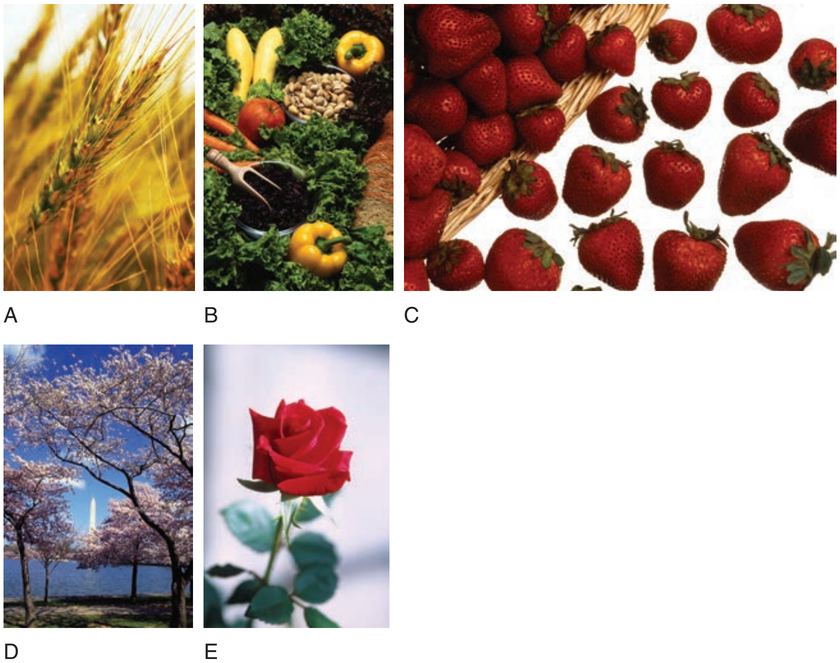

Figure 1–1

Examples of the many types of crops grown using the techniques developed through plant science: (A) Wheat. (B) Vegetables, fruits such as strawberries. (C) Landscape plants. (D) Florist plants. Source: USDA, https://www.ars.usda.gov/oc/images/image-gallery/

tion keep up with the demand. Some of the earliest products of the industrial revolution were farm implements for crop cultivation, such as plows, and planting and harvesting equipment. The closely related disciplines of agronomy and horticulture were born and developed. **Agronomy** is the study of field-grown crops such as wheat, soybeans, corn, forages, and those used for industrial purposes. These crops require relatively low input during the growing part of their life cycle but usually require significant processing to be used for purposes other than animal feed. **Horticulture** is the study of crops that require more intense and constant care, from planting through delivery to the consumer. Examples of horticulture crops include fruits and vegetables and ornamentals. Most edible horticulture crops can be eaten with little or no processing. There are gray areas where the disciplines overlap. Tomatoes grown for processing and **turfgrass** are examples of crops that can be designated agronomic or horticultural.

TRENDS AND ISSUES AFFECTING PLANT SCIENCE

Background

Traditionally crops are commodities that are exchanged for money in the marketplace. In the case of recreation areas such as golf courses, the use of that field is exchanged for money. According to classical economics, the price of commodities (or user fees) results from the balance between the supply of commodities (recreational areas) and the demand for them. The supply should be influenced by the availability of the resources and raw materials required for production, and the demand should be influenced by the value that consumers perceive in the commodity.

Many people have drawn attention to the mismatch between ecological and money values. If excess **fertilizer** from a crop pollutes a river, the cost of cleaning up the pollution will not be reflected in the price of the commodity. On the other hand, many people may enjoy seeing an ornamental tree planted by someone else, and it can also help to absorb the carbon dioxide (CO_2) produced by cars, but those benefits seem "free." Economists call costs and benefits that are not included in the price **externalities**. Some argue that environmental degradation occurs when no one owns a resource. If land is under common ownership, it will be overcropped or overgrazed because it is in no one's interest to conserve the resource. Thus, they refer to the general problem of the tragedy of the commons. According to this view, if everything is privately owned, individuals have an interest in its preservation, those who use resources have to pay the owners, and the value of the resources is reflected in the price of the commodity.

Classical economics assumes that buyers and sellers are fully informed of the value of commodities in the market and make wise decisions that maximize their welfare. However, many people make unwise choices on both sides of the market relationship. In the 1930s, farmers in the American Southwest contributed to **soil erosion** on their own farms through their crop management practices. The market for tobacco products remains strong after fifty years of health warnings. Individuals may not know all of the consequences of their decisions, and it may take the input from many people to arrive at a full accounting. However, people are capable of making decisions to conserve resources. The soil conservation service was born out of the dust bowl experience. Plant science research and education grew out of a perception that wider public good would be obtained by applying scientific principles to food production. Now, as you will learn in this book, we need to go beyond production to look at ecological consequences and the consequences for the individuals who consume the produce.

Using market value alone to regulate crop production practices does not consider costs to the environment. For example, low yields in future years because of soil degradation due to poor but less expensive **soil management** currently may appear to be less important than high profit margins this year. The idea of **sustainability** as a guiding principle in crop production has been established to address the issue of current versus future conditions. Sustainable practices consider not only what is good today, but what will allow future generations to thrive, too. You will learn more about sustainability later.

Maintaining a viable balance among components of an ecosystem are central to stable, sustainable ecological relationships. In stable ecosystems, most of the energy and resources (nutrients, **organic** and inorganic material, etc.) used in the system are eventually recycled back into the system. Like natural ecosystems, crop production requires energy

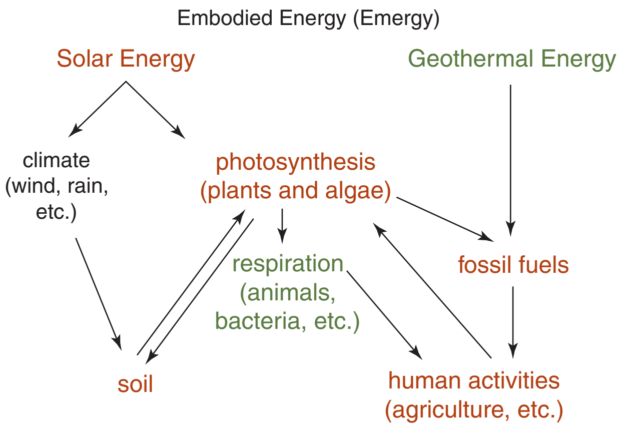

Figure 1–2

Derivation of embodied energy, or emergy, from primary energy sources. Source: Michael Knee.

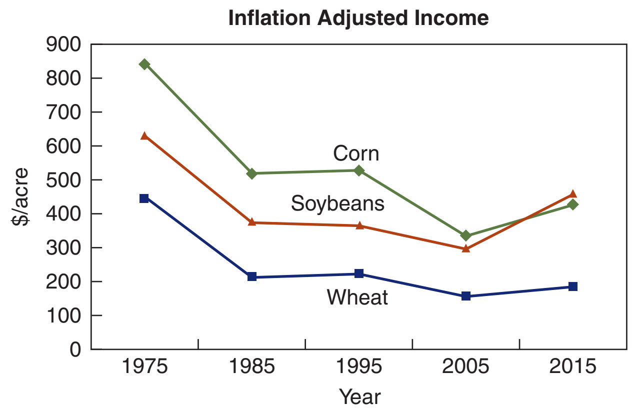

Figure 1–3

Income per acre from selected crops from 1975 to 2015, corrected for inflation by estimating on the basis of 2015 dollar value. Source: USDA National Agricultural Statistics Service.

and resource inputs at several points. However these inputs create energy and resource imbalances in the crop ecosystems because they are not recycled back into the system, but leave with the harvest. Many plant scientists study natural and crop ecosystems to understand how to create stable crop systems. **Agroecology** is the term used to describe the study of environment and crop production interactions.

Ecologist Howard Odum has suggested that we use energy accounting to try to correct some of the distortions introduced by using market value to determine pricing. Ecosystems depend mostly on solar energy and existing resources, but crop production systems require the input of energy from several sources including fuel, the energy to produce fertilizer and chemicals, etc. To arrive at a common basis for accounting, Odum proposed that all forms of energy used in a system should be related back to the primary source, which is usually the sun. Odum's concept of **emergy** is the amount of equivalent solar energy represented in the resource or commodity (**Fig. 1–2**). When the amount of emergy in a product is used to calculate its market value, the cost of most products would likely increase.

Domestic Trends and Issues

In the United States, the prices of many agricultural commodities continued to fall in real terms in the last quarter of the twentieth century. Even though yields continued to increase, income per acre declined (**Fig. 1–3**). This is one reason that it has been impossible to break away from the system of price support for selected commodities. In 2000, the subsidies amounted to half of farm income. The payments are supposed to help farms stay in business but end up as one more factor encouraging consolidation in the industry: large farms get more government assistance than small farms do. The number of farms decreased as individual holdings got larger in the second half of the century.

The number of farm workers also continued its long-term decline so that there is now a little more than one full-time worker for each farm. The numbers of farms and farm workers seem to have stabilized as the number of farms in 2012 was 2.1 million and workers was 2.7 million, and these numbers may be minimum sustainable values (**Fig. 1–4**). Most farms are run as part-time businesses, and about 10 percent of the farms

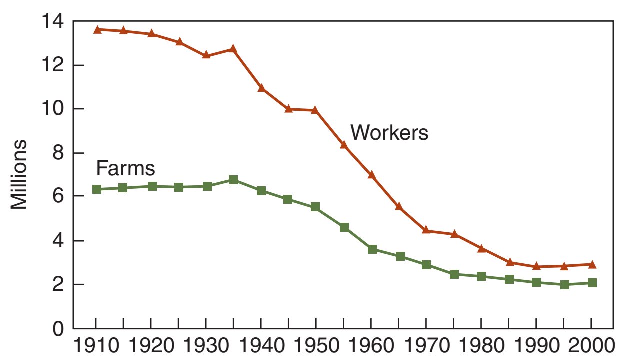

Figure 1–4

Number of farms and farm workers during the last century (1910–2000). Source: USDA National Agricultural Statistics Service Information (NASS).

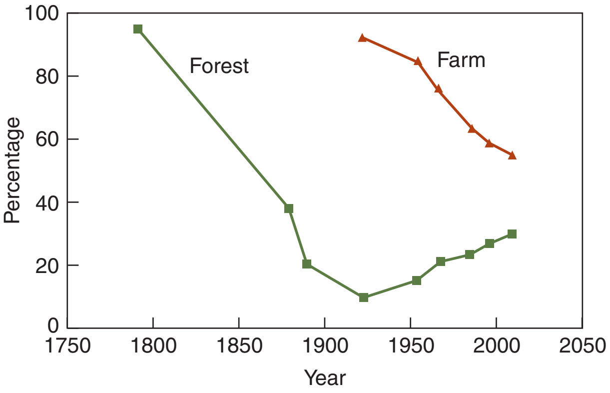

Figure 1–5

Percentage of forested land and farm area in Ohio since European settlement. Source: Michael Knee.

remaining in the United States account for 70 percent of production. The profitability of farming has been helped to some extent by diversifying the uses of staple crops (e.g., ethanol and syrup from corn and tofu from soybeans) and by adopting alternative crops. The area of farmland has also declined from its high point at the beginning of the twentieth century. In contrast to many other countries, the United States has seen an overall increase in the area of woodland (**Fig. 1–5**). Some of the increase comes from the conversion and/or reversion of farmland to woodland (**Fig. 1–6**).

The increase in US population during the last century was mainly in urban areas so that rural population decreased in relative terms from 60 percent in 1900 to 25 percent in 2000. This decline was associated with a loss of economic and cultural vitality in rural communities. Such communities were more likely to survive if there were large towns that provided an economic stimulus to the surrounding areas. This may be the reason why rural populations persist in such heavily populated states such as California, Florida, New York, New Jersey, and Ohio, which have several large towns and cities.

Figure 1–6

Woodland developing on land in Ohio that has not been farmed for thirty years. Source: Margaret McMahon, The Ohio State University.

Urban populations have increased in every US state. The increases were most marked in the coastal states, the East and West, and along the shores of the Great Lakes. Although this is classed as urban development, it is more accurate to call it suburban. Average lot sizes for new homes are about 0.15 hectare, or 0.4 acre. The spacious lifestyle of the suburbs depends on personal transportation for access to work, shops, and leisure, which accounts for much of our energy demand. Many people have criticized this and other aspects of suburban sprawl, but it leads to new opportunities. The new homes are an expanding market for landscape supplies and services. Surviving farms can market directly to the surrounding population. Families can enjoy a visit to the local farm to buy or pick their own produce. This interaction may help maintain contact and understanding between the mass of the population and the few remaining farmers.

The aesthetic and recreational use of plants is important in urban and suburban areas. The appearance and playability of fields are vitally important to many sports. Golf alone is now equivalent to about two-thirds of major crop sales and involves 12 percent of the US population. The number of golf courses has increased over threefold in the past several decades. Residential and commercial landscaping is a business that generates billions of dollars annually in the United States alone. Producing and maintaining a vast array of ornamental and recreational plants in ecologically sound ways is particularly challenging because they often require large inputs of energy to grow and maintain them.

The rising cost of fuel to grow, maintain, harvest, and distribute plants and plant products has greatly increased costs to both the producer and consumer. Even though energy use may not have increased markedly, the increased cost has created a fundamental need for greater fuel-efficient production and delivery methods.

Global Trends and Issues

Two major trends that will affect crop production and the global environment are the increases in human population and energy use. After two centuries of exponential growth, world population shows signs of stabilizing at about 9 billion in 2050 (**Fig. 1–7**). Energy use, however, is projected to rise about twice as fast as population because of economic development (**Fig. 1–8**). People have long argued about the potential for the future growth of population in relation to energy and other resource use and about the related question of the earth's carrying capacity. Estimates of carrying capacity have varied from the low billions to the trillions.

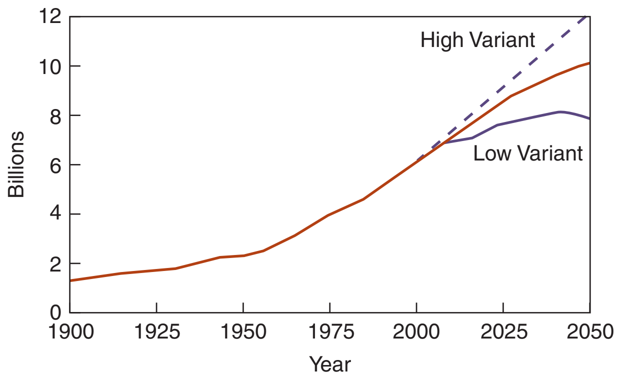

Figure 1–7

Projections of world population growth. Source: US Global Change Research Program, USGRCP Seminars, *http://www.usgcrp.gov/usgcrp/seminars/*

Assessing the world's food situation involves other factors besides the utilitarian one of meeting minimal food needs. When the people of a country become more affluent, they want and can afford to purchase a greater proportion of their **protein** requirements in the form of the more palatable animal products—steaks, chops, eggs, processed meats, and dairy products. This shift in food consumption patterns coupled with the tremendous increase in world population, especially in developing regions (**Fig. 1–9**), requires continuing increases in the world's food-producing capability. Much of the world's best agricultural land is already under cultivation, although there is still unused productive land awaiting development in Argentina, Brazil, Canada, Sudan, and Australia. However, in most if not all developed countries such as the United States (see Fig. 1–4), Japan, and those in Europe, farmland is being lost forever to industrial, residential, or recreational development. In addition, in the United States, even though the number of farms is decreasing, the size of farms is increasing. The loss of the small family farm and the increase in corporate megafarms has become a serious social and political issue. In the mid-1970s various projections implied that the world was on the brink of famine or ecological disasters due to desperate food needs. But this assessment changed in the 1980s, especially in the less-developed countries, by improved production technology and greater incentives to use it. Agricultural research made

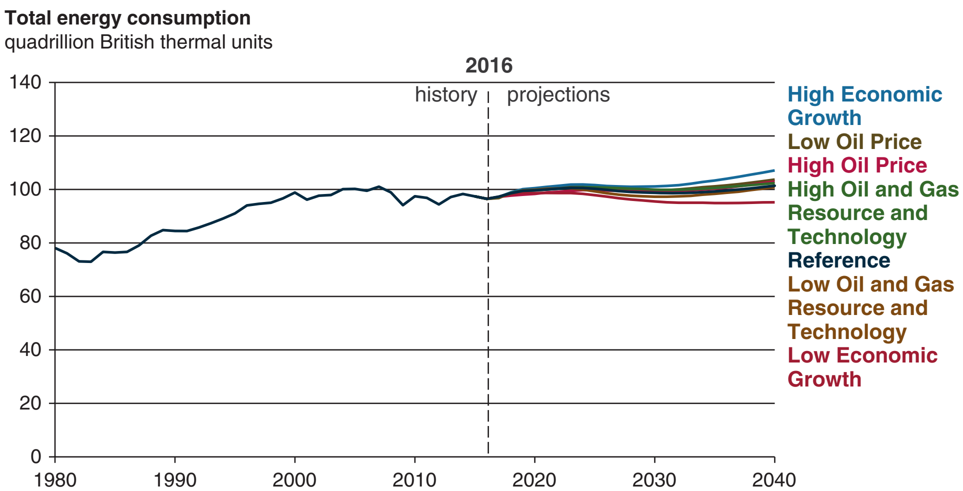

Figure 1–8

History and projection of world energy consumption (1970–2025). Sources: *History:* Energy Information Administration (EIA), International Energy Annual 2001 DOE/EIA-0219 (2001) (Washington, DC: February 2003), www.eia.doe.gov/iea/. *Projections:* EIA, System for the Analysis of Global Energy Markets (2003).

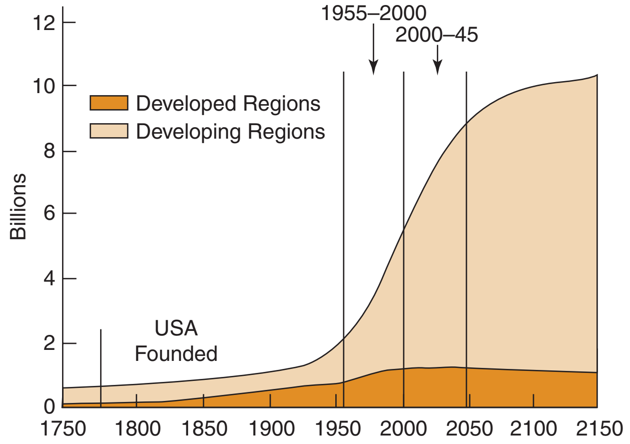

Figure 1–9

Trends and Projections (UN Medium Variant) in World Population Growth (1750–2150). Source: World Resources Institute (WRI) in collaboration with United Nations Environment Programme (UNEP), United Nations Development Programme (UNDP), and World Bank, *World Resources 1996–1997: The Urban Environment* (Washington, DC: WRI, 1996).

new **cultivars** (cultivar = *culti*vated *var*iety) of high-yielding wheat, rice, corn, and other crops available to highly populated developing countries. Much of this improved technology can be attributed to assistance from agricultural researchers in the United States and other developed countries working with less-developed countries.

However, there are still areas where people experience food insecurity. **Food security** as described by the 1996 World Food Summit "exists when all people, at all times, have physical and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life." Where food insecurity exists, people experience malnutrition and starvation.

A high proportion of these underfed populations are in the sub-Saharan regions of Africa, where drought, wars, and political instability are major problems, along with high human fertility rates, low per capita income, and insufficient monetary investment in agricultural production. In addition to the above-mentioned factors, poor distribution of available food contributes to starvation in many areas, including areas of developed countries. However, for much of the world, the situation is projected to improve. The USDA-ERS International Food Security Assessment for 2018–2028 suggests that the share of the population that is food insecure will fall from 21.1 percent in 2018 to 10.4 percent, the number of food-insecure people will fall from 782 million to 446 million, and the intensity of food insecurity will decline by 34 percent. Sub-Saharan Africa will continue to be the area where most food insecurity exists.

As you will learn in Chapter 3, it is possible to feed an adult on a plant diet from about 0.2 hectares of land. This would feed about 8 billion people, the current approximate population. However, the yields we achieve in industrial countries need to be achieved worldwide. These yields in turn require that inputs, at least of fuel, fertilizer, and probably pesticides, have to rise in other countries to match those in North America and Europe. While agriculture accounts for only about 2 percent of energy consumption in North America and Europe, it would amount to about 10 percent of energy demand in the rest of the world.

China alone represents a major challenge to the world's food supply. It has about 20 percent of the world's population but less than 7 percent of the world's cropland. It had about 0.2 hectares per person in 1950 and now has about 0.08. It has managed to feed itself and actually improve people's diet over the past decade. However, with its population set to increase by an additional 25 percent before stabilizing at 1.6 billion, it is doubtful that this trend can continue. Fertilizer use is high and further increases will not bring much additional yield. There are already problems of **nutrient** pollution and soil degradation, and the area of agricultural land is shrinking because of urban development.

The United States has about twice as much cropland as China but one-fifth of its population. It is one of a handful of countries with a relative excess of cropland in relation to population. Others include Canada, Australia, and the Russian Federation. China is undergoing rapid industrial development and now supplies other industrial nations with a wide range of the manufactured articles that they used to make. But in the future it is likely to be a major customer for US agricultural products. Other countries may try to follow China's road to economic development. Even if they do not, it is likely that China's demand for food will raise prices of agricultural commodities, which could be good news for US producers. Of course, US consumers are likely to be unhappy as food becomes more expensive after many years of falling prices.

Grain-fed meat production is increasing in China, which increases the land required to meet its dietary needs and cannot be sustained on a global scale. To provide an adequate diet for everyone, good cropland needs to be devoted to feeding people. Animal production needs to be based on more marginal land that will support grazing but not crops. But overgrazing and desertification are a constant threat in arid lands.

A 50 percent increase in global energy use is expected over the next fifty years, and it seems likely that most of this energy will come, as it does now, from combustion of CO_2-generating fossil fuels. Although the oil industry is confident that supplies will extend beyond the forty years of known reserves at current rates of consumption, concern for negative effects on the environment from exploration for and extraction of oil has limited the exploitation of potential new sources. Natural gas reserves are a little higher: at about sixty years (but little of this is in the United States). Coal reserves are considerably higher: at over 200 years. Coal is more evenly distributed, and its consumption is rising faster than consumption for gas and oil outside the United States and Europe. However, in some areas the coal is of low grade (high polluting) or in environmentally protected areas. As we continue to increase the use of fossil fuels atmospheric CO_2 will continue increasing for the next fifty years. Other gaseous pollutants will also increase as coal consumption rises. The threat to the environment from the increased production of fossil fuels will also increase during that time.

Although some individuals continue the argument against the connections between rising atmospheric CO_2, rising temperatures and other weather changes, evidence overwhelmingly supports the connections. Productivity of some crops could increase with rising CO_2, as long as rainfall patterns are not disrupted, but disruption is likely to occur. High temperatures could lead to decreases in yields of many crops, even if precipitation patterns do not change. A likely scenario is that favorable rainfall and temperatures will shift to higher latitudes where soils are less fertile. Climatic changes impose additional stress on natural plant communities, and many doubt whether forest ecosystems can adapt fast enough to survive the changes. For example, American beech and sugar maples may become extinct over a large part of their present range, and they may not be able to spread north fast enough to take advantage of new habitat. There is also the risk that other atmospheric pollutants that accompany CO_2 from fossil fuels will cause more damage to crops and wild plants.

Global energy demand is only a fraction of the energy captured in photosynthesis and stored in plants. Increasing the use and efficiency of plant biomass and bio-based fuel would be a way to utilize photosynthetically captured energy. About 40 percent of the world's population relies on biomass as its primary energy source, but these same people are mostly in undeveloped countries and consume very little energy by US standards. Even in areas where biomass is the primary energy source, gathering firewood for energy consumes more and more of these people's time as the supply progressively dwindles. Developing methods of sustainable production of biofuels seems like the answer to many of the problems of energy supply. However, this approach requires massive changes in land use and a large investment in equipment for conversion of biomass to usable fuels. The major growth in fuel requirements is predicted for use in transportation, but biomass-to-fuel conversion processes (such as corn to ethanol) may not ultimately generate enough of an energy profit to support this growth. One solution now under investigation is the use of algae as a source for biofuel.

The demand for food and fuel is leading to deforestation in many tropical countries. The loss of biodiversity and environmental quality is unfortunate for the resident population, but it also has implications for us. The tropical forests are a major **sink**, or depository, for the CO_2 that we generate through our fossil fuel consumption. Losing that depository contributes to increasing atmospheric CO_2 and global warming.

International trade is being progressively expanded, removing tariffs and duties that restricted imports of food and other commodities. Industrial nations are also under pressure to eliminate the subsidies that favor their own producers. This change will allow poor countries to export commodities such as sugar and grains to the rich countries. Classical economics predicts that production will become more efficient and profitable in the long run when the market is no longer distorted by the subsidies. This prediction does not seem to account for the fact that poor countries often cannot get good prices even for commodities such as bananas or coffee that are not produced by the United States and Europe. A side effect of the globalization of trade is that pests and diseases are spread around the world more easily. An example is the introduction of the emerald ash borer (*Agrilus planipennis*) into the Great Lakes region from wooden pallets carrying goods from China to the Port of Detroit. The borer is threatening the survival of all North American ash species, much as Dutch elm disease decimated the elm population in the United States a century ago.

Bioterrorism is a recent, but major threat to agriculture. Terrorists may be able to introduce pests or chemicals that will destroy a good portion of crop production in certain areas. Because of this fear, quarantines and restrictions to free trade may increase. In 2003 and again in 2004, some geranium growers in the United States were ordered by the USDA to destroy much of their geranium crop because it came in from abroad infested with *Ralstonia solanacearum* race 3 biovar 2, which is listed in the Agriculture Bioterrorism Act of 2002. *Ralstonia* is a bacterium that is **endemic** in some parts of the world but is not found in the United States. However, it was not fear of what *Ralstoni*a would do to geraniums that prompted the USDA's action. *Ralstonia* is a serious pathogen of several of our food crops. The potential of the **fungus** to devastate those crops is the reason it has been listed as a bioterror organism. Although the disease was imported unintentionally, its designation as a bioterror organism prompted the need to destroy the geranium crops. The negative financial impact on foreign and domestic geranium growers was devastating.

MEETING THE CHALLENGES IN PLANT SCIENCE

Many of the changes in the issues of crops and their role in the world have prompted plant scientists to change the focus of their research. For several centuries, plant scientists studied ways to improve crop productivity in a cost-effective way. They studied light, soil, water, and temperature and developed ways of managing or monitoring those factors to influence or predict plant growth. Improved understanding of plant genetics lead to breeders developing plants that would produce more reliably. A scientific approach to pests and their management reduced losses to those factors. Traditional economic analysis was used to see if the new production methods were cost-effective. Great gains were made, but as you have read, increasing evidence showed that some agricultural practices were having negative effects on the environment. Agriculture became the focus of public scrutiny, and a negative public opinion of agriculture developed. This opinion was exacerbated by the fact that most urban dwellers today have very little understanding of their dependence on agriculture. Plant scientists have to find ways to meet our need for food, fuel, and other products and services from plants without negatively affecting the environment. When calculating the cost-effectiveness of a production procedure, costs can no longer include just material and labor costs. The cost to repair any resulting environmental damage must also be factored into cost analysis.

Although it may seem like a relatively simple calculation to factor in environmental costs, it is not. Assessing environmental impact and the cost to repair negative impact can be a challenge. It can be difficult to predict what will happen when a new production practice moves from the lab or experimental field to the real world. For example, genetically engineered plants, sometimes called **genetically modified organisms (GMOs)**, have been created that dramatically reduce the need for pesticides and field tillage. Pesticide runoff and erosion are reduced, which is beneficial for the environment. But there is concern that heritable traits from the GMOs will "escape" and become part of the wild or native plant populations if engineered plants can breed with native plants. The fear is that wild plants with these traits may have serious negative impacts on the ecosystem in which they grow. Determining the likelihood of a gene escaping requires many long-term studies both in the lab and in the field.

Organic farming has been proposed as a solution to many problems related to crop production and environmental impact. Organic farming does not allow the use of GMOs and certain types of chemicals for pest control and fertilization. Many organic farms are successful, thus demonstrating that the process works. However, it is not known if organic farming has the capability to produce the quantities of crop products needed in today's world. Also there is great debate regarding what constitutes organic farming. In addition, some organic farming practices, such as soil cultivation leading to erosion, may have negative environmental impact.

The public often wants to see plants growing "perfectly"—a very unnatural state for plants. Generally this occurs when plants are used in leisure and recreational settings. Immaculately groomed and weed-free landscapes, flawless floral arrangements, and impeccable golf courses and athletic fields are sources of pride to those who own or use them. Ask any golf course superintendent what his greens committee would say if the fairways and greens had even a few weeds or insect and/or disease problems in them. Who would buy a bouquet if some petals were chewed? Maintaining perfect plants almost certainly has some degree of negative environmental impact.

Plant scientists and growers can find all the current uncertainty and controversy about their fields discouraging and wonder why we should even bother to try to solve seemingly insurmountable problems. We must remember that, although most plants grow very well without human intervention, the cultivated grains and grasses, fruits, vegetables, and ornamentals have become dependent on human intervention to survive. Without cultivation, these plants would likely die out after several generations and be replaced by hardier species such as wild grasses and thistles. But the dependence is mutual—we need these plants to survive and that is why we have to solve the problems.

The nearly 8 billion people now living in the world (compared to the estimate 1.2 billion 100 years ago) depend on cultivated plants for nourishment and to provide quality to their lives. The global population cannot survive as hunters and gatherers. The need for plant scientists to increase knowledge about crop plants and their place in the ecosystem and the need for professionals who know how to use that knowledge to grow plants in environmentally sound ways will not disappear. In fact, it should increase, perhaps dramatically, if the world population increases as predicted (11 billion by 2100).

Currently, enough food is produced to feed the world's population. However, malnutrition and starvation exist in both developed and undeveloped countries mostly because social and political issues prevent the distribution of food to those who need it. If the social issues cannot be resolved, it will likely become the responsibility of plant scientists and growers to find creative ways to produce food crops locally in starvation-prone areas.

The solution to the loss of small family farms will no longer lie primarily in increasing productivity of traditional crops. New uses for old crops and production strategies for new crops will have to be developed to allow the family farm to remain viable.

Many of the improvements in production were developed not only to reduce labor and increase productivity and profit, but also to allow farmers to be better stewards of the environment. But these improvements come with their own issues. High-oil corn has been bred to yield a product that can be used to replace petrochemicals in some industrial uses but may replace some food crops. No- or low-till farming reduces labor costs and is less detrimental to the soil than traditional cultivation practices are. However, no- or low-till farming requires the use of herbicides to control weeds. To make **herbicide** use more effective and to reduce the amount of herbicide used, GMOs were developed that are resistant to a very effective herbicide, Roundup®. Weeds are susceptible to the chemical, but Roundup Ready® crops are resistant. As a result, only one or two applications of a single herbicide is required in a season to get the same or better weed control compared to multiple applications of several herbicides in nonresistant fields.

A genetically modified corn (Bt®) synthesizes a naturally occurring protein that is lethal to the larva of many species of *Lepidoptera*, such as corn borer. The production of a natural larval toxin in corn has reduced the need to spray insecticides for control of a very destructive pest. Rice has been genetically modified to produce beta-carotene in the grain (golden rice). Beta-carotene (vitamin A) provides a critical nutritional element that is predicted to save the eyesight of millions of children in areas where vitamin A deficiency causes blindness.

But the public has demonstrated a negative response to each of the aforementioned uses of GMOs. There is fear that the Roundup Ready® gene will escape into the native weeds adjacent to the fields where Roundup Ready® crops are being grown, thus creating weeds that are resistant to

Roundup® though they would not be resistant to other types of herbicides. A more likely scenario is that the weeds themselves will evolve to be resistant. This has proven true with the appearance of Roundup® resistant giant ragweed, palmer amaranth, and other weeds. The monarch butterfly (a member of the *Lepidoptera* species) was at one time thought to be threatened by Bt® corn, though this has been shown to not be the case. Golden rice cannot be grown in many of the areas where vitamin A is needed, mostly because of concern about the beta-carotene gene escaping into the traditional rice crop. Flavr Savr® tomatoes have disappeared from the market because chefs and diners refused to buy or eat them out of fear of what the altered gene would do to human health if consumed. It will be up to those who study and work with crops to determine if there are undue risks with the new plants.

However, one approach could work. Perhaps the best way for plant scientists to meet today's challenges is to include the concepts of production efficiency, environmental compatibility, social responsibility, and economic viability in all aspects of plant science.

This approach is being used at many institutions where plant science is studied. This approach is also called sustainable agriculture, which is discussed in detail in Chapter 16.

SOLUTIONS THROUGH SCIENTIFIC INQUIRY

Scientific inquiry, or the **scientific method**, is the systematic approach to understanding and solving a problem. The steps to scientific inquiry are: identify the problem or question and make a hypothesis (educated guess) of the cause of the problem/question; test the hypothesis by doing experiments or a study; check and interpret the results; and report the results.

Hypothesis

Scientific inquiry or research begins with an objective and some idea of how the objective can be met. The objective might be to solve a problem or improve a procedure. The idea can be stated as a **hypothesis**, such as "This is the source of the problem" or "This is how the process can be improved." A simple problem might be determining if a common landscape species will grow well in compacted soil. You may have observed what appears to be suitable growth in compacted soils, but maybe you would like more scientific evidence before you start using that species in compacted landscape soil.

From your observations or other information (such as claims from seed companies), you can create the hypothesis that the species will have the ability to grow acceptably well in compacted soils. From this hypothesis, a simple experiment can be developed to test the validity of the hypothesis. The two species can be grown in compacted and porous soil, and the differences in plant growth between the two soils (treatments) can be measured. From our hypothesis, we predict that **compaction** would not affect growth when compared to the plants growing in porous soil. If this prediction turns out to be validated, then we have confirmed our hypothesis.

If our supposed compact-tolerant species did not grow as well in compacted soil as in porous soil, perhaps our hypothesis was false or perhaps we might have achieved better results if the experiment had been designed differently. By doing more experiments, we can gain confidence that our hypothesis is correct or incorrect. Our confidence can be increased if we can explain why the growth was no different in porous soil. We can set up more experiments that look at subhypotheses; for example, maybe the root system's growth was not affected by compaction.

The example above is a relatively simple problem. At the other end of the scale are complex ecosystem problems such as determining if agricultural practices have a role in creating the dead zone of the Gulf of Mexico. The dead zone is an area off the coast of Louisiana where an unusually large number of marine life dies each summer. It is generally not wise to focus on a single hypothesis to solve a complex problem such as an ecosystem problem. It is quite likely that there is no single cause of the problem. For example, the dead zone may also be caused by industrial activity, natural causes, and/or something else. It is best to develop several hypotheses that represent as many explanations as we can imagine. We can then look for experimental evidence that will support or refute the different hypotheses. After extensive research, we can build a plausible description that is consistent with the data our experiments have generated. From this research, we may be able to suggest ways to correct the problem.

Experiments

Controlled experiments are the most certain way of obtaining reliable information on which to base decisions. Experiments are artificial situations where we try to exclude everything except our immediate area of interest, such as plant response to compacted soil or the effect of erosion sediment on marine life. In large and complex problems, a full-scale experiment is most likely impossible for testing our hypotheses. However, we can isolate parts of the problem and study those parts, eventually putting it all together to address the complex situation.

The key to a meaningful controlled experiment is to be sure that the only factor affecting the outcome is the factor that we set out to study. If we are testing whether the growth of a plant is affected by soil compaction or not, we need to be sure it is only compaction that is affecting the plant. For example, we would select plants of the same age to evaluate for response to compaction. If we had plants of different ages, we cannot be sure that age was not a factor in response to soil compaction.

In a typical experiment, plants of uniform characteristics are planted in compacted soil and others with the same characteristics are grown in non-compacted soil. The type of soil is called the **independent variable**. Plant growth is the **dependent variable** because its value depends on changes in the soil. Compacted soil is called the treatment. Non-compacted soil is called the control, or check. Controls allow for the comparison needed to draw conclusions about treatment effects. In practice, it is difficult or even impossible to make everything completely uniform. Replication and randomization are used to avoid unintentional bias resulting from lack of uniformity. Replication means that we base our conclusions on more than one observation on a single experimental unit (**Fig. 1–10**).

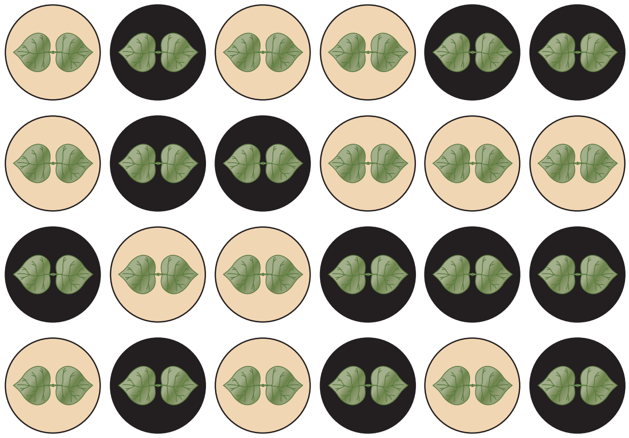

Figure 1–10

Randomized arrangement of pots containing compacted (dark-colored) and non-compacted (control) soil (light-colored). Source: Michael Knee.

UNITS OF MEASURE FOR VARIOUS SYSTEMS

All scientific studies present data in scientific units. Although they may be less familiar than US units, they are often much easier to work with and they are used in scientific literature (including agronomy and horticulture). There are two versions of the metric system. The old system is being replaced by Système Internationale (SI). This table lists some corresponding units and common conversions that might help as you move through the book.

Quantity	Old Metric	SI	US	Conversion
Length	Centimeter (cm)	meter (m)	foot (ft)	1 m = 3' 3''
Area	cm^2 hectare (ha)	m^2 km^2	ft^2 acre	1 ha = 2.47 acre
Volume	cm^3 liter (L)	m^3	gallon	1 L = 0.265 gal
Mass	g, ton (1,000 kg)	kg	pound (lb)	1 kg = 2.2 lb
Force	kg	Newton (N)	pound	1 kg = 9.81 N
Pressure	kg cm^2	Pascal (Pa)	psi	1 kPa = 0.15 psi
Energy	calorie (cal)	Joule (J)	btu	1 kJ = 0.95 btu
Power	dyne	Watt (W)	hp	1 kW = 1.34 hp
Temperature	°C	K	°F	°C = (F − 32)*5/9
Light	lux	mol $m^{-2}s^{-1}$	foot candle	

Note: Common prefixes: micro (μ)(÷1,000,000), milli (m)(÷1,000), kilo (k)(×1,000), mega (M)(×1,000,000)

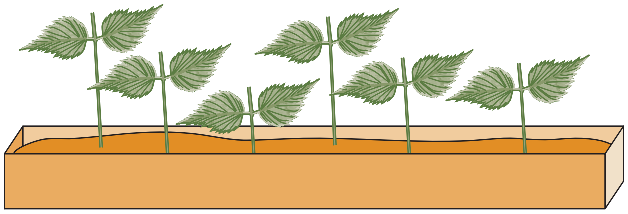

Figure 1–11

Plants showing natural variation in height from genetic and/or environmental conditions. Source: Michael Knee.

The average of the response of experimental units to a treatment is what we base our conclusions on so there is less chance that an aberrant individual is the basis for a conclusion. Working with more than one individual is the first step to ruling out chance variation (**Fig. 1–11**) as a factor that can affect our conclusions.

Randomization takes into account that no two plants are exactly alike. Even **cuttings** from the same plant may have come from different size branches or have other differences, such as mutations (Fig. 1–10). Randomly selecting the plants to be treated helps to reduce the chance that all the plants for one treatment are inherently different from those for another treatment. For example, if, from a group of plants chosen for an experiment, only the short ones were used for the compact soil treatment while the tall plants grew in non-compact soil, then the difference in height might carry all the way through the experiment and the conclusion that the plants grew best in non-compact soil would not be accurate. By mixing up the size of the plants within the treatments, changes in plant growth would more likely be the result of the treatment (**Fig. 1–12**).

Blocking is another way to reduce the effect of variation. An example of blocking is to arrange plants in groups by height, then subdividing those groups so that each height group receives all the treatments, not just one. Similarly, in a field trial, an experimental field can be divided into treatment plots or blocks where the treatments are replicated. Each plot has all treatments randomly assigned within it (**Figs. 1–13** and **1–14**). With this method, you reduce the chance that another factor, such as a wet area of the field, influences only one treatment. The more you know about the area you are using for an experiment, the more effective the blocking design can be. In greenhouse experiments, pots with compacted and non-compacted soil can be arranged randomly on a bench to eliminate the effect of drafts and drying out on those pots on the perimeter of the bench. Controlled experiments are ideal for studying one or a few variables; however, one of their disadvantages is that treatment effects on factors other than the defined dependent variable are often not considered. Other factors may be detrimentally affected.

Although current scientific inquiry into agricultural and horticultural problems sometimes involves simple situations, such as determining how insect-resistant one new cultivar is compared to another, or what fertilizer rate is the best

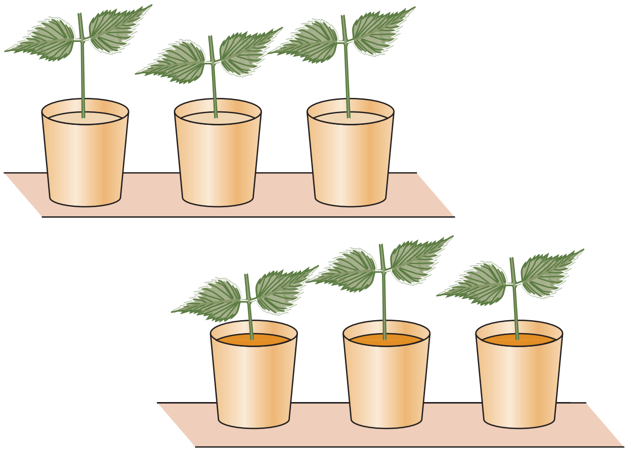

Figure 1–12

Randomized placement of plants with different heights at time of planting into pots with compacted (dark-colored) and non-compacted (light-colored) soil. Source: Michael Knee.

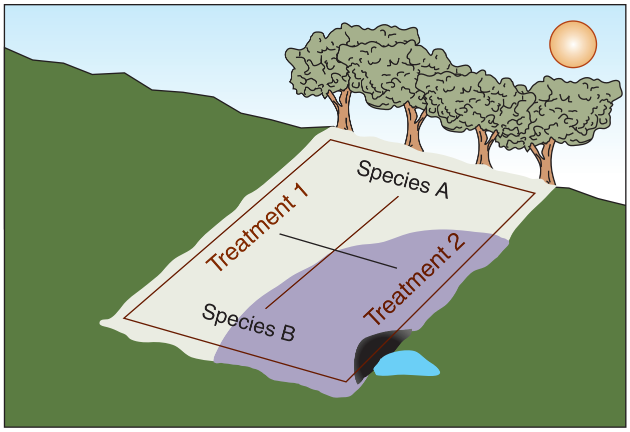

Figure 1–13

Example of a field experiment where the treatments (1 and 2) are represented only in the experiment. The darker portions of the field are wet areas that could distort or confound the data and increase the chance of making an incorrect conclusion. Source: Michael Knee.

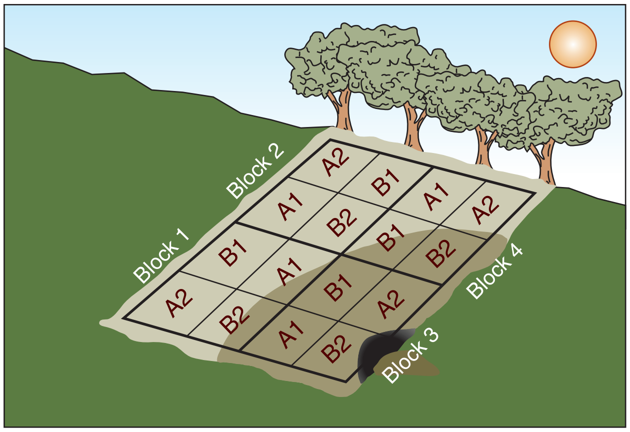

Figure 1–14
Example of a field experiment with multiple plots or blocks in which species A & B are receiving the two treatments (1 and 2) are randomly placed. Blocking helps to separate the effects of the wet areas from the effects of the treatment, reducing the chance of making an incorrect conclusion. Source: Michael Knee.

for **flower** development of a newly introduced ornamental, most research now involves some aspect of ecosystem study. We have learned the hard way that plants do not grow in isolation and what we do to help in one aspect of plant growth may have detrimental consequences elsewhere. These oversights created the suspicion that the public attaches to scientific study and the reassurances from the scientific community that a procedure is safe. For example, organochlorine insecticides were widely adopted after they were shown to be effective against a wide range of agricultural pests. After many years, however, the chemicals accumulated in animals at the end of the food chain. They were particularly harmful to birds of prey because they caused the birds' eggshells to be thin and brittle. Failure to hatch young led to a collapse in the populations of many birds of prey. Pesticides are now tested for effects on nontarget organisms, but no amount of research can ever prove that any chemical will be safe under all conditions of use and for all time.

The complexity of ecological research requires the use of different methods than experimental research that has one or only a few variables. Ecological research is often descriptive of a situation within an area that represents the larger ecosystem. Here, correlation analysis generates a descriptive model of the relationship between or among variables. Determining the scale of the area to be described is analogous to deciding what factor is to be the subject of an experiment. The scale has to be sufficiently large to represent the ecosystem but small enough to be effectively described. Many more variables are often recorded than in an experiment in a laboratory or greenhouse. In an experiment, variables that we do not want to influence the treatment must be controlled or held constant. In the real world, this condition is usually not possible, so the extra variables are recorded in case they are found to have an influence in the system. Dependent and independent variables are less clearly defined in descriptive research than in experimental research. The research method chosen depends on the factor or factors to be studied.

Examples of ecological research may be the study of the effects of farm runoff on the aquatic life in a single creek that feeds a larger river (**Fig. 1–15**). By studying the creek, inferences about the larger river's watershed can be made. Likewise, it might take fifty years to see the consequences of clear-cutting a rainforest to create farmland. However, by studying other rainforests that have been cut at different times during the past, we can look for patterns in the data that might show what happens to deforested land over time. In the case of Bt® corn, a more comprehensive study of the ecosystem of the monarch butterfly, not just of how the butterfly larva was affected when fed only Bt® corn pollen,

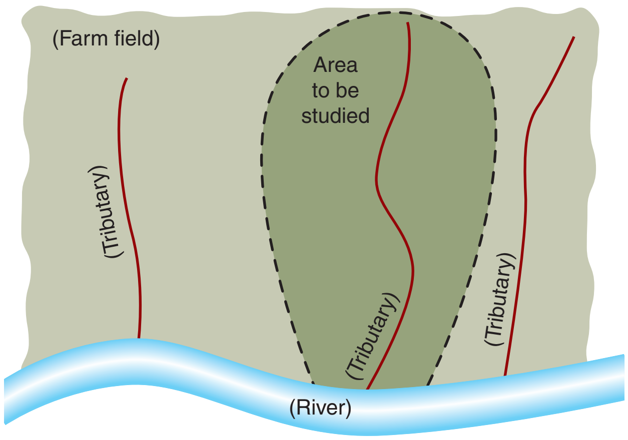

Figure 1–15
Correlative studies are conducted on a small area and make correlations to a larger area. For example, a section of a field that has a small tributary stream running through it can be examined closely for effects from a farming practice. Inferences can be made regarding how other tributaries in other parts of the field are also affected by that practice. Source: Margaret McMahon, The Ohio State University.

revealed that Bt® corn pollen was one of the least of the butterfly's threats. The conclusions from that study showed that the original public outcry stating that Bt® corn threatened the monarch population was unfounded. However, in other cases it might be shown that a genetically engineered plant was detrimental to an ecosystem.

Data Interpretation

So how does a scientist arrive at conclusions from a set of experimental data? The data must be analyzed statistically to see if the original hypothesis is supported or not. But we can never be sure that it was our treatment and only our treatment that caused a difference in the dependent variable. We usually assign a **percentage probability** that something else was the cause. In most cases, if we can say that there was a 95 percent or greater chance that the treatment caused the effect, then we can claim our treatment had an effect. If the probability is less than 95 percent, we say that our results were nonsignificant.

To determine the probability, the natural variability in the population being tested has to be compared to the variation caused by the experimental treatments. In our compacted soil experiment, suppose we look at the number of roots of the intolerant plant in the pots of compacted soil and the number of roots in the pots of loose soil. We may see a wide range of numbers in both situations. If the variation in the pots is great enough, then the compacted pots may be no different from the control, even though the two treatments may have different average root sizes. We would have to say that our treatment had no effect. For example, suppose we had four pots of porous soil and four pots of compacted soil. The average number of roots in the loose soil was fifteen, and the average number of roots in the compacted soil was ten. We would be tempted to say that the plant roots grew better in the porous soil. However, suppose we looked at the individual numbers and saw that the porous pots had twenty-two, eight, twenty-one, and nine roots and the compacted pots had fourteen, twelve, eight, and six. There may be so much variation that the differences in the two averages could have occurred without any treatment. One reason for having as much replication of experimental units as possible is to get a better estimation of natural variation.

In complex systems, correlation analysis is used to generate a relationship model. We can use the relationship model to determine whether it would be worthwhile to change a variable under our control, such as fertilizer use in a watershed, or whether changing the variable would be unlikely to have any effect.

No statistical method is completely reliable. There is always a risk of saying that there was an effect when there really was not. Conversely, we can say that results were nonsignificant when they were. That is why it is important when reporting experiments to describe in detail how they were done. Thus, future researchers can compare their results and methods to yours. It is not failure to have the results of a well-conducted experiment later contradicted by other researchers. The difference in results from different experimental situations quite often leads to a better understanding of a problem.

Reporting Findings

Once results are obtained and interpreted, the study is reported in a manuscript. First it goes for review to the scientific community. The reviewers examine the methods used and conclusions drawn and accept or reject the conclusions. If accepted, the manuscript is published and presented to the public in scientific and then trade journals.

As you can see, understanding the principles of scientific study is important to plant scientists, who must be trained in these principles. However, it is equally important that others understand the principles. Anyone who works with plants for a living has to be able to read and interpret the scientific and trade literature of his or her discipline. Without this ability, it is likely that decisions will not be based on sound scientific evidence.

SUMMARY AND REVIEW

Humans and cultivated plants are mutually dependent on one another. Cultivated plants require attention from humans to survive. Humans need the plants to fill basic nutritional needs and to add quality and enjoyment to their lives. Early plant scientists studied ways to improve crop productivity to meet the demands of a growing population. Plant scientists were successful at increasing production and today we are capable of feeding everyone on earth; however, problems of starvation and uneven supply and distribution of crop commodities continue to plague the world. In addition, the population continues to grow, placing higher and higher demands on our farms, which are shrinking in number.

Complicating the situation is the fact that many improvements in production were shown in time to be detrimental to the global ecosystem. Plant scientists and growers had to find ways to grow crops without creating undue risk to the global ecosystem. Because of past mistakes, however, new production practices, such as the use of GMOs to reduce pesticide use or improved shipping quality of produce, are met with suspicion because of the fear that the new methods will also have negative effects. Public opinion is proving to be a powerful force in plant science. The difficulty is exacerbated by the fact that much of the population in many countries resides in urban areas and has little understanding of how food and other plants are produced.

Today's plant scientist and grower must have a firm understanding of the relationship among production efficiency, economic viability, environmental compatibility, and social responsibility when studying ways to improve productivity. Integrating that understanding with a sound scientific approach to research in plant science will help restore public confidence by reducing the chance that a procedure will have an undesirable side effect. A sound approach begins with the formation of a hypothesis, designing the proper experiments to test that hypothesis, and finally analyzing and interpreting the data gathered correctly. Randomization and replication in experiments are important to reduce the chance of reaching a wrong conclusion.

KNOWLEDGE CHECK

1. In what group of plants do grasses, flowers, fruits, vegetables, trees, and shrubs belong?
2. What is cultivation and when did it start?
3. When did the rural/urban interface start and what problems for farmers does it cause?
4. What is agronomy, what is horticulture? Give an example crop of each and one that could fall in either category.
5. Money value and ecological value are mismatched in agriculture. What do you think would happen to the price of food if the cost of cleanup from pesticide or fertilizer runoff was added to the production cost?
6. How has our growing understanding of ecology changed plant science research and education?
7. How has the reduction in the number of farms affected the vitality of many rural communities? What has helped those communities survive in states with large metropolitan areas?
8. How was the famine predicted to be caused by diminishing farmland averted in the 1970s?
9. The ability to feed the world on 0.2 hectares of land per person (the amount of farmland predicted to be available then) when the population reaches 8 billion will require that all that land be farmed using the production techniques of what countries? How will that affect global resources, especially fossil fuels?
10. How does globalization of marketing affect the spread of pests and diseases?
11. What caused negative public opinion and close scrutiny of agriculture to develop?
12. What kind of environmental impact does the demand for perfect plants usually create?
13. What are some concerns with GMO plants and crops?
14. What are the four considerations that are being included in plant science research by many research institutions now?
15. How do randomization and replication improve the reliability of the results of an experiment?
16. How does research of a complex ecological problem differ from a controlled experiment?

FOOD FOR THOUGHT

1. There is great concern that the number of people dying of starvation will increase dramatically when the world's population exceeds 8 billion. This is predicted to happen in the near future. What do you think could be the consequences of that increase in death and how can it be prevented?
2. Sustainable farming takes into account many more factors (e.g., social issues, more environmental than just the use of chemicals) than organic farming and is not as strict in the use of chemicals. Which practice do you favor and why? How would you explain to a shopper who demands blemish-free produce, a homeowner who wants a perfect yard, or a golfer who wants a perfect fairway that their demands have tremendous ecological consequences?

FURTHER EXPLORATION

Altieri, Miguel A. 2018. *Agroecology: The science of sustainable agriculture*. Boca Raton, FL: CRC press.

Food and Agriculture Organization of the United Nations (FAO). *The state of food and agriculture*. Rome. Available online at **http://www.fao.org/publications/sofa/the-state-of-food-and-agriculture/en/**

National Research Council. 2005. *Valuing ecosystem services: Toward better environmental decision-making*. Washington, DC: National Academy Press.

Smith, B. D. 1998. *The emergence of agriculture*. New York: Freeman.

United States Department of Agriculture Sustainable. 2007. Agriculture: Definitions and Terms Available online at **https://www.nal.usda.gov/afsic/sustainable-agriculture-definitions-and-terms**

United States Department of Agriculture. National Agriculture Statistics Service (NASS) Publications. Available online at **https://www.nass.usda.gov**

2

Terrestrial Ecosystems and Their Relationship to Cultivating Plants

INTRODUCTION

Terrestrial ecosystems are a collection of organisms (plants, animals, fungi, bacteria) in an area that have over time developed intricate relationships that involve the sharing of energy and resources such as water and nutrients. The populations of the various organisms remain stable and the ecosystem is self-sustaining because of those relationships. To maintain sustainable relationships all ecosystems require a source of energy. In most cases plants provide that energy through photosynthesis. They convert solar energy to chemical energy and store it in their structures and store biochemical energy in complex carbon-based **molecules**. When other organisms consume the plant or its parts, the energy in the plant is transferred to that organism. In turn as those organisms are consumed, the energy is passed on. The greater the amount of carbon molecules created (**photosynthetic productivity**), the more the energy that is available to support the system. As the organisms grow, they use the energy to utilize other resources to develop and maintain their bodies. A crop ecosystem is, however, usually very different from the natural one it replaced. Most often it is not there long enough for stable organismal relationships to develop. The crop may not be best suited biologically for the area, especially if it evolved in a different type of biome. Generally, the more a crop ecosystem differs from the ecosystem that would occur naturally in an area, the lower its photosynthetic productivity, sustainability, and potential yield of the crop. This then requires more inputs to get the desired productivity and sustainability. By understanding the natural ecosystem that a crop system is replacing we can understand the ecological relationships and ecosystem processes that would naturally occur and attempt to mimic those as much as possible to achieve the desired productivity while reducing inputs. This chapter will help you start to develop your understanding of ecosystems.

Learning Outcomes

After reading this chapter, you should be able to:

1. Describe the components of ecosystems and their relationship to each other.
2. Define biome and be able to describe the factors that create biomes.
3. List the major biomes of the world and describe the potential of each one to support sustainable crop ecosystems.
4. Describe how succession relates to the development of ecosystems and how succession is a consideration in crop ecosystems.
5. Describe the concept of human footprint and how cultivating plants has impacted natural ecosystems.

ECOSYSTEM COMPONENTS

An **ecosystem** consists of a community of organisms in a physical environment (**Fig. 2–1**) that share the resources in that environment. The community consists of populations of individual species; different kinds of plants, animals, fungi, bacteria, and so on. A **population** can be defined as all of the individuals of a species that inhabit a particular environment. The way that we define the environment determines the boundaries of the population. Often we are thinking of a limited area in which the individuals share the available resources. In an isolated area of woodland, a field, or a greenhouse, the plants may be competing for light, water, or nutrients available in that specific area. However, ecological relationships may extend over larger areas, particularly for animals that can roam from one place to another. Even for plants, pollination may occur between individuals in physically separate environments many miles apart.

Almost all terrestrial ecosystems depend on the ability of plants to capture energy from the sun through photosynthesis and store it in complex, carbon-based organic molecules (**carbon fixation** or **carbon sequestering**). These molecules constitute most of the plant's **biomass**. How much biomass is produced is called **photosynthetic productivity**. Other organisms feed on the plants and get the energy stored in the plant, enabling them to live. An ecosystem is formed and then becomes stable when the relationship between the organisms does not change much over time. The greater the photosynthetic productivity, the more energy is available to support and maintain the ecosystem. The energy in the plant is utilized by other ecosystem organisms and the carbon and other plant components such as nutritional elements, for example nitrogen and phosphorus, are recycled back into the system. The amount of carbon fixed is called photosynthetic productivity. All the other organisms in the ecosystem depend on the plant productivity in one way or another to survive.

We tend to think of ecosystems in terms of the plants and animals that we might see on a visit to a "natural" area in a state park or wilderness location. However, anywhere organisms exist is, in a strict sense, an ecosystem. Many of the most important organisms and ecological processes in all ecosystems are invisible to us because the organisms are small or because they and the processes occur in the soil. A "cultivated ecosystem" such as a cornfield or an area of turfgrass may look too simple to qualify as an ecosystem, but a whole **community** of organisms interacts with the single species of plant, both above and below the ground. Ecology does not disappear when we grow plants in a home or a greenhouse. The physical environment, including the **growing medium**, may be artificial, but it is colonized by other organisms, some harmful and some beneficial. Although books and television programs about nature may focus on the animals and birds that enliven natural ecosystems, many of the functions and ecological interactions that sustain the ecosystems are carried out by small invertebrate animals, fungi, and bacteria (**microflora** and **microfauna**), and many of these organisms are in the soil. The microflora and fauna are, relatively speaking, even more important in crop ecosystems, where we deliberately try to exclude macrofauna (birds and mammals) and noncrop macroflora (in other words, weeds). What distinguishes these cultivated ecosystems is that some of the organisms, processes, and interactions that would sustain a natural ecosystem are absent or heavily modified by human intervention. For example, inputs of nutrients are necessary to promote crop growth, or chemicals are needed to suppress disease and insects. We can describe crop production in terms of these inputs only and ignore the ecological processes and interactions. However, the goal of sustainable production requires that we minimize the inputs and maximize the

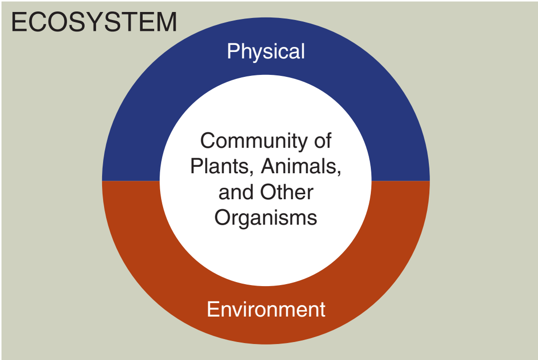

Figure 2–1
An ecosystem consists of a community of organisms in a physical environment (consisting of soil and atmosphere in the case of a terrestrial ecosystem). Source: Michael Knee.

contribution of natural ecosystem processes. By observing the full range of interactions and processes in natural ecosystems, we can learn how to manage crop ecosystems to help achieve the goal of sustainable and profitable crop production.

The organisms in an ecosystem interact according to the nature of the species and their role in the ecosystem. Each individual organism draws on the resources of the ecosystem to meet its requirements. Plants require light, water, and nutrients for growth and may require pollinators and dispersal agents for reproduction. **Competition** occurs when more than one organism draws on a resource that is in short supply (**Fig. 2–2**). The resource might be required for growth or the reproduction of the organism. In a competing system, one or more of the organisms needing the common resource usually does not get enough so its numbers are reduced or it disappears altogether.

In ecosystems with a complete cover of **vegetation**, the most intense competition among plants is likely to be for light. A plant with a greater leaf area is likely to capture more light, particularly if the leaves are positioned above those of another plant. Trees can capture most of the light and are the dominant vegetation in many parts of the world. However, they have to invest considerable resources in the trunk and branches that support their leaves, which is one factor that limits the size of trees. Vines such as Virginia creeper, English ivy, and poison ivy can compete for light with less structural investment by using the support provided by the trees to grow tall enough to reach sunlight.

Usually a single species cannot utilize all of the resources or the whole of any one resource in the environment. For example, some light does penetrate the **canopy** in most forests, and **herbaceous** plants, such as ferns, are adapted to growth in the low-light environment of the forest floor. Many of the trees in temperate forests are **deciduous**, and for a period in the spring, light is available for herbaceous flowering plants such as bloodroot, *Trillium,* and *Hepatica* to grow, flower, and set seed before the trees develop their full canopy. These kinds of plants are called spring ephemerals. The shade-adapted plants and spring ephemerals occupy niches. Niches exist when a resource is partitioned so that different portions of it are accessible to only certain species (**Fig. 2–3**).

Although a critical environmental resource may be required for a species to find its place or **niche** in an ecosystem, each species has more or less strict requirements from a long list of environmental resources. In the fullest sense, the niche includes everything that is required for an organism to flourish in the environment. For a plant, this list can include light intensity, availability of water, nutrient concentrations, and the presence of the right **pollinators**. If two plants have identical environmental requirements and they are trying to occupy the same niche, the competition will be more severe than it is for two plants with different requirements. Competition is thus more intense between plants of the same species than it is between plants of different species. For species to coexist in an ecosystem,

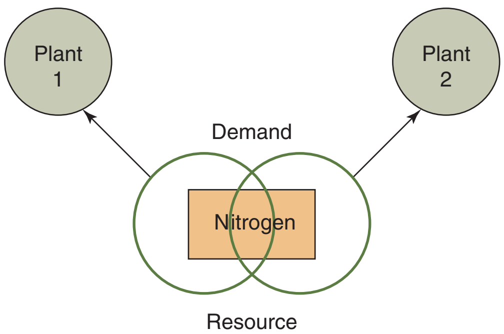

Figure 2–2

Competition occurs when plants of the same or different species attempt to use a resource that is in limited supply. Source: Michael Knee.

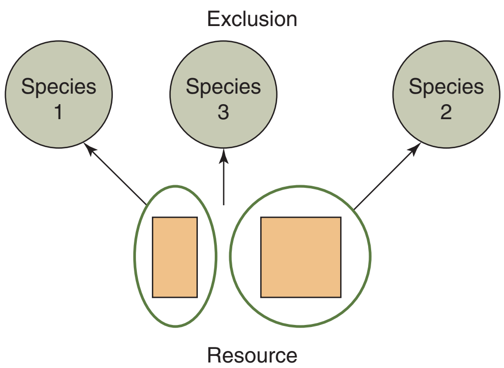

Figure 2–3

Species 1 is able to occupy a niche because species 2 does not use all of the resources. However, species 3 is subject to exclusion because it also needs the resources, but none remain. Source: Michael Knee.

they must occupy different niches. It can be difficult to see how species requirements differ, for example, when looking at different species of deciduous trees that make up the forest canopy. However, species are separated by their physiological requirements as much as by their more obvious morphological differences.

In healthy, natural ecosystems, every available niche tends to be filled, and consequently resources are fully exploited. It is difficult for new species to colonize the environment because it lacks open niches or unexploited resources, and the result is called exclusion (Fig. 2–3). Thus, annual herbaceous plants cannot colonize mature woodland. If seeds blow in and germinate, the development of the foliage in the canopy during the spring will close off the light before the annual plants can flower and set seed. On the other hand, if some trees come down in a storm, annual plants may be able to colonize the open area or gap until new trees grow and the canopy closes.

Crop ecosystems have one or a few species that do not exploit all of the resources of the environment. Thus, niches tend to be available for other plants to colonize. We call the other plants weeds, and their presence is a problem to the extent that their resource requirements overlap those of the crop species. One of the strategies in weed control is to plant additional, noncompetitive crop or noncrop plants with the main crop to occupy niches that would otherwise be occupied by weeds.

Resources captured by plants may be transferred through consumption to other organisms by **predators** or **parasites**. Predation occurs when plants are consumed by a wide range of animals, which we call **herbivores**. (We use the term predator for animals that consume other animals.) Herbivores include mollusks (slugs and snails), arthropods (insects and mites), mammals, and birds. The diversity and large numbers of herbivores emphasize the importance of plants as a food source in terrestrial ecosystems. Many believe that herbivores do not compete with each other or come close to consuming all of the plant food resources of natural ecosystems because their numbers are kept in check by their own predators. There is a wide range of small predators among the arthropods, and there are many insect-eating birds and mammals. Large predators that feed on birds and mammals are less common because ecosystems cannot support many of them. As the number of herbivores increases, they become easy prey for the predators. Crop ecosystems are usually more vulnerable to herbivory because the number of predators is low or nonexistent. Thus, it may be necessary to use chemicals, introduced predators and **parasites** (biocontrols), or other means to control slugs, insects, rodents, birds, or deer.

Parasites are organisms that derive their nutrition by living in or on the **tissues** of another organism, often producing symptoms of disease such as swellings or discolored tissue. Plant parasites include many kinds of **viruses**, bacteria, and fungi. Some parasites can grow only in the host and are called obligate. Other parasites can grow outside the plant and are called facultative. All viruses are obligate parasites, whereas fungi and bacteria may be obligate parasites or facultative (as when they commonly exist outside the plant in the soil). A few parasitic plants, such as dodders and mistletoes, can infect plants in natural and crop ecosystems. Other classes of plant parasites include nematodes and some insects and mites, particularly those that form galls on leaves and stems.

Parasites differ from herbivores because they cause a disease rather than simply eating their way through the tissue. In a disease, the **physiology** and often the morphology of the host is altered as its resources are redirected toward the pathogen or disease-causing organism. Parasitism is a long-term relationship between a host and a pathogen, in which the host does not usually die because this would also entail the death of the pathogen. Although the host may not die, it is usually weakened making it vulnerable to attacks by other (secondary) organisms. **Parasitoids** are animals, often insects, which spend the juvenile phase of their lifecycle in the tissues of another insect. When they emerge as adults, the host is killed. Parasitoids can be helpful in crop ecosystems when they infect herbivorous insects such as caterpillars. Some biological pest control such as parasitic wasps that are used commercially to control plant pests are parasitoids.

Some associations between organisms are mutually beneficial rather than antagonistic. In natural ecosystems, the roots of most plants are colonized by fungi that draw nutrients from the soil and pass some of them on to the plant. In return, the plant passes sugar and other organic

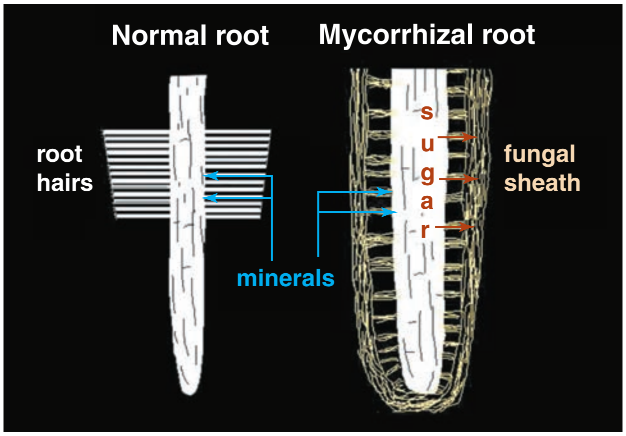

Figure 2–4

Many plant roots form a symbiosis with fungi, a relationship in which the plant supplies sugar to the fungus and the fungus draws mineral nutrients from the soil, which it passes on to the plant. Source: Michael Knee.

Figure 2–5

Recycling is essential for maintaining the supply of nutrients in natural ecosystems, and soil microorganisms are the primary agents in this process. By decomposing the leaf litter and tree trunk in this picture, saprophytes and detritivores are recycling the nutrients in those items. Source: Margaret McMahon, The Ohio State University.

molecules to the fungus. The fungi are known as **mycorrhizae** and can either live on the surface of the root (ectomycorrhizae) or invade the root tissue (endomycorrhizae) (**Fig. 2–4**). This relationship is an example of **symbiosis**, which involves a permanent and close association between two organisms that are known as symbionts. Mycorrhizae are less common in crop ecosystems, particularly on herbaceous plants, than in the wild. The nutritional requirements of crops are often supplied by fertilizers and fungi are not needed to scavenge for them. However, mycorrhizae are now being supplied to several crops to reduce the need for chemical fertilizers. Lichens that are found on tree trunks, rocks, and the soil surface are formed by the symbiosis of a fungus with an algae species. Another kind of plant symbiosis involves a bacterial symbiont, ***Rhizobium***, that forms the **nitrogen-fixing** nodules on the roots of many species in the legume family, or *Fabaceae* and a few other families. Nitrogen-fixing bacteria take nitrogen from the air and convert it to a form that can be used by plants. They are important for maintaining the nitrogen supply in natural ecosystems. The legume family includes many important crops such as beans, peas, and alfalfa. Rotating a nitrogen-fixing legume crop such as soybean or alfalfa with a nonlegume on a regular basis is a common farming practice to keep nitrogen levels up in a field. A more general term for a mutually beneficial association between organisms is **commensalism**. In addition to symbiosis, commensalism includes looser and less permanent associations such as that between a plant and its pollinating insect.

Although parasitic organisms may be the most conspicuous fungi and bacteria in crop ecosystems, most microorganisms are **saprophytes** that digest dead plant and animal material at or below the soil surface (**Fig. 2–5**). Saprophytes are essential to the survival of the ecosystem because they recycle nutrients that would otherwise be tied up in dead organisms. In natural ecosystems, a few plant species are saprophytic. Saprophytes are aided in their activity by **detritivores** that break up large pieces of organic matter as they consume it. Earthworms are an important part of this group, which also includes other kinds of worms, many insects, and small mammals. Detritivores and saprophytes may be less important in crop ecosystems than in nature because crops and crop residues are removed and the nutrients are replaced by synthetic fertilizers. They become more important, however, as we try to recycle crop waste and minimize fertilizer inputs to develop more sustainable production systems.

Primary producers (mainly plants), herbivores, parasites, commensals, detritivores, and saprophytes exist in all terrestrial ecosystems. In a natural ecosystem, each of these roles is filled by many species of organisms that exist in a complex web of relationships (**Fig. 2–6**).

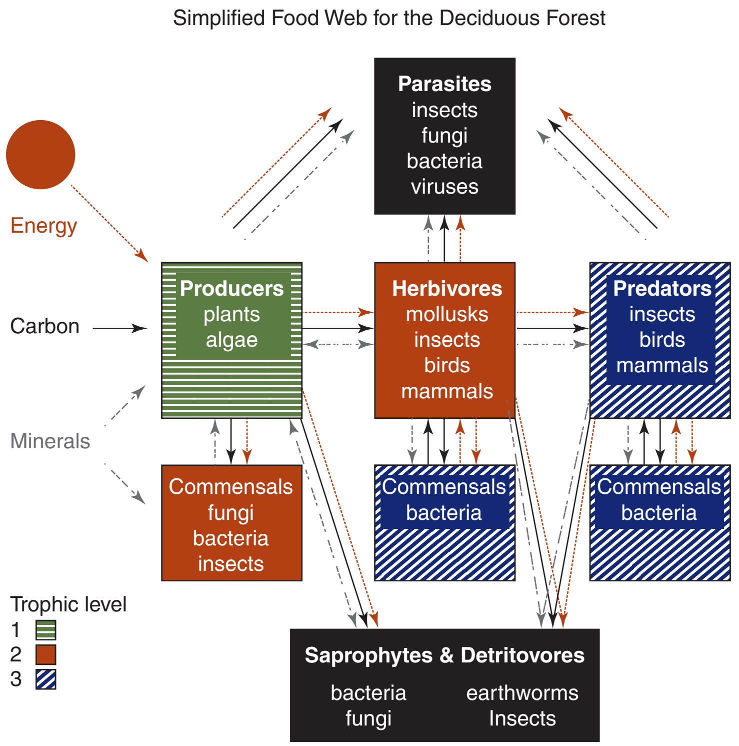

Figure 2–6

Natural ecosystems operate with inputs of carbon, energy, and water and are highly conservative of nutrients because of a complex web of ecological relationships. Source: Michael Knee.

Nutrients are passed continuously from one organism to another along with the energy and carbon compounds that sustain the whole ecosystem and that originally came from the primary producers. The system tends to be highly conserved. Many organisms compete for the resources available at any level in the **food chain**. If there is any gap in the utilization of resources, species are "recruited" to fill it. Crop ecosystems are based on one or a few plant species, which are usually intended to be harvested rather than allowing resources to be consumed by other species. While the crop is growing, however, surplus resources exist that could be exploited by competitors, herbivores, and parasites. We have attempted to manage these problems by mechanical and chemical means. By eliminating species, we attempt to simplify the ecosystem and minimize ecological interactions. More recently, however, we have begun to introduce species that help control some of the problems, for example, **cover crops**, predators, parasitoids, and so on.

BIOMES

We often like to go to different climatic zones for vacations, but if you get the chance to travel to a similar one, say, from eastern North America to northern Europe, you may be struck by the fact that similar but not identical trees are present in the forests. You might see oak, maple, beech, and ash but not the same species that you would see in the United States. The explorer Alexander von Humboldt noticed that there was a similar progression of vegetation types as he moved north or south from the equator or ascended in altitude in different parts of the world. He realized that the same kind of vegetation tended to occur in similar climatic conditions around the globe. The vegetation appears similar because the plants are functionally similar but not necessarily the same species. The functional groups include deciduous broad-leaved trees, coniferous evergreens, succulent plants, tall and short grasses, spring-flowering **bulbs**, and so on. Today we call the recurrent vegetation types biomes; a **biome** is a collection of ecosystems with similar climate, soil, and plant composition. Understanding what constitutes a biome and how that relates to the plants growing in it is very important to growers of plants because quite often we are trying to grow plants in areas very different from the biome in which they evolved. For that reason the next section will give you an understanding of climate, microclimates, and biomes that can be used to help determine strategies for growing plants.

Climate is the main influence on the type of vegetation that develops. The most important climatic variables are temperature, rainfall (or, more correctly, precipitation), and any seasonal variation in both. A key component in the relationship between climate and vegetation is soil. As we will see in Chapter 5, soils are produced from parent material, such as rock, by the interaction of climate and organisms. Plants are key components of the soil ecosystem and influence all of the other organisms present. Although a world map may show the natural distribution of the different biomes across all of the continents, many of these areas have now been converted to agriculture or urban development. The soils that developed in the biomes differ greatly in their suitability for crop production. In general, the greater the difference between a crop production system and the preexisting biome, the more difficult it is to sustain that system. Sometimes it may even prove to be impossible.

Temperature is primarily influenced by latitude, and within latitudes, it is also influenced by the elevation of the land above sea level (altitude). The other factor, moisture availability, is affected by patterns of air circulation around the globe. Air moves in one direction in the winds that we experience at ground level and then rises to the upper atmosphere to flow in the opposite direction, before returning to ground level. This circulation is rather like a donut-shaped mass of air, with the wind moving around it from the hole in the middle to the outside and back. A series of three such systems operates between the equator and each pole (**Fig. 2–7**).

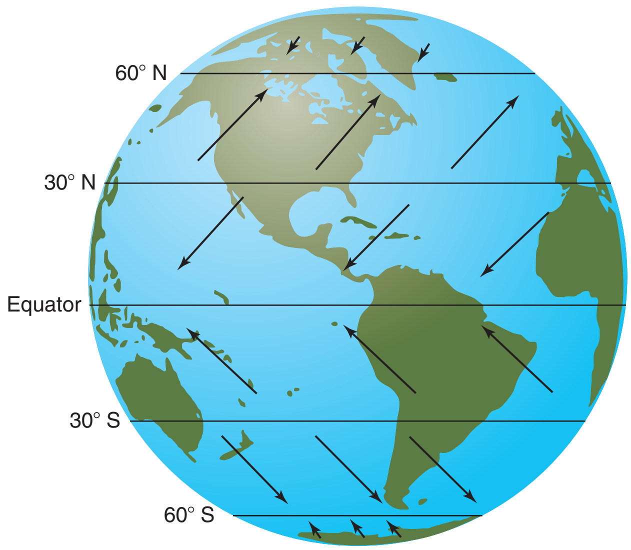

Figure 2–7
Three main belts of surface winds exist in each hemisphere. Each one determines patterns of precipitation and the vegetation that develops. Source: Margaret McMahon, The Ohio State University.

At the equator, temperatures are high throughout the year. The trade winds from the north and south carry moisture from the oceans and converge in this region. The warm, moisture-laden air rises and cools down so that the moisture condenses as rain. The warmth and readily available water are favorable for plant growth throughout the year, and all kinds of other organisms can benefit from the high productivity of the plants. The tropical rainforests of South America, Africa, India, and southern Asia developed under these conditions and make up the most productive biome, with the greatest range of biological diversity on earth.

The tropical rainforest is dominated by broad-leaved and **evergreen** trees whose dense canopy captures most of the light. Rainforest trees include kapok, mahogany, and rosewood. Rainforest soils are shallow, and the tree roots spread outward rather than down. The trees gain stability from their shallow root systems by forming buttress roots. Because of the low-light levels, only a few shade-tolerant plants grow under the canopy; however, the trees provide support to many **lianes**. Also many **herbaceous** plants called **epiphytes** grow on the trunks and branches of the trees. The roots of these epiphytes never reach the soil; they catch their water as it runs down the surface of the tree or from the air itself with specialized aerial roots. Many orchids and bromeliads are rainforest epiphytes.

Much of the life of the forest occurs in the canopy, unseen by humans and other groundlings. Most of the nutrients in the ecosystem are also in the canopy and are cycled from one organism to another without passing through the soil. This occurs because nutrients are rapidly taken up by plants and rapidly recycled from dead organisms, so rainforest soils contain little in the way of free nutrients. After the forest is cleared, good crops can be raised for a year or two, but the nutrients are soon exhausted. To make matters worse, nutrients are washed out by the rains, and the soils themselves are unstable in the absence of vegetation. So production of annual crops is not easily sustainable in this region.

About 30° north and south of the equator are bands of divergence in the global air circulation. Air moves away from these latitudes in the trade winds toward the equator and in the westerlies toward the temperate latitudes. This movement is powered by a downdraft of air that carries moisture away, and it is most pronounced over large land masses. It gives rise to the deserts of North and South America, Africa, Asia, and Australia, which make up the largest biome on the planet. By day, temperatures are warm, but at night the absence of moisture in the air permits rapid loss of heat so that it can be surprisingly cold. The plants of this environment are highly specialized and grow slowly or intermittently. They can be slow-growing perennials with succulent stems or leaves that help conserve water. Cacti and yucca are an example of these kinds of plants. They can also be fast-growing annuals such as the ghost flower (*Mohavea confertiflora*) and desert sunflower (*Gerea canescens*) that take advantage of occasional rains to complete their life cycles while the moisture is available. Because of slow growth, there is little accumulation of organic matter that can be recycled to build up soil fertility in these ecosystems. Because temperatures can be favorable to plant growth and deserts occupy about two-fifths of the land surface, many people have had the dream of "making the desert bloom." This requires massive amounts of water that can be economically transported or diverted to the desert region. Fertilizers must be used to compensate for the low fertility of the soils. All water sources contain small amounts of salts, even if they are so-called fresh water. The salt level increases when fertilizers are added. When the desert is irrigated, the salts are left behind after the water evaporates from the soil or through plant transpiration. Desert soils are difficult to manage in the long term because the salts tend to accumulate to levels that inhibit the growth of plants.

Moving north or south away from the deserts, the climate becomes moister but temperatures are not continuously favorable for plant growth. In latitudes between 40° and 50° and when there is more than about 75 cm of rainfall, temperate deciduous forest develops (**Fig. 2–8**). Ash, oak, maple, hickory, and beech are some of the hardwood species found in temperate forests. These forests develop all of the land masses in the northern hemisphere, but there is little land area in these latitudes in the southern hemisphere so temperate deciduous forest is nearly absent south of the equator. During the summer, the trees in these forests can be almost as productive as those in the tropical rainforests. However, growth nearly ceases in the winter, when most of the trees have lost their leaves. Although lianes, more commonly called vines in this biome, are present in old-growth forests of this type, the canopy is not as favorable a habitat for epiphytes as in the rainforest. However, **spring ephemerals** which are **understory** shrubs and herbaceous plants such as trillium (*Trillium grandiflorum*), dogtooth violet (*Erythronium dens-canis*), and bloodroot (*Sanguinaria canadensis*) can exploit the light that comes through the canopy in the spring before the new leaves are fully formed. (The understory is composed of the plants that grow under the canopy of other taller plants.) The botanical diversity of the Appalachian forests of North America is a distant second to the rainforest, but it is more readily apparent to a wanderer in the sunlit carpets of spring ephemerals than it is to a ground-based visitor in the comparative (and permanent) gloom of the rainforest.

Figure 2–8

A clear area under the canopy of a mature temperate forest where other plants cannot grow in the low light. In the spring, however, it is filled with spring ephemerals. Source: Margaret McMahon, The Ohio State University.

The annual leaf fall adds a certain amount of nutrients to the litter layer of the temperate deciduous forest. However, the leaves contain only a fraction of the nutrients locked up in the permanent structure of the tree, and trees manage to withdraw much of the nitrogen and phosphorus from their leaves before they are shed. So forest soils develop slowly and tend to have only a thin organic-rich layer. As with the rainforest soils, fertility can be soon exhausted if not managed properly when crops are grown after the forest is cleared.

The area between the deserts and the forests consist of **grasslands** and **savannas** (**Fig. 2–9**). Tree growth in grassland and savanna is limited to some extent by lack of water, but fire and grazing animals are also important in maintaining these ecosystems. Grassland vegetation survives and may even benefit from a certain level of grazing that woody plants cannot tolerate. Also dead grass is readily ignited by lightning strikes. When fires sweep through grassland, most trees are killed, but grasses and herbaceous perennials, which have their growing points at or below the soil surface, typically survive. Grasslands and savannas were favored by early people and our first efforts at land management may have been to set fires to provide habitat for animals that we were trying to encourage into or deliberately keep in herds. We still find prairies, meadows, and forest glades attractive but may not fully realize our own role in their ecology.

Grassland plants accumulate nutrients in the roots and stems that are renewed from year to year. In temperate climates, the old stems and roots are not fully recycled each year and organic matter builds up over time. This organic matter contains reserves of nutrients and makes up a large part of the black earths that are characteristic of moist grasslands around the world. The nutrients in such soils can sustain crop production for many years, and the former grasslands of North America, Europe, and Asia have proved to be the world's most productive agricultural land. Agriculture itself originated in such a region, the so-called "fertile crescent" that occupied river valleys from present-day Egypt to Turkey and Iran. Grassland becomes less productive as it merges with drier regions on its margin. In the United States, for example, the tall grass prairie of the central states gives way to short grass prairie to the west. Attempts to raise productivity with **irrigation** can meet the same problems of salinization as in the desert. Arid lands can all too easily be turned to desert by overgrazing, and soil erosion can be a devastating consequence of attempted cultivation. The extent to which human beings are responsible for the spread of deserts throughout the world is debatable. Climatic changes, such as unusual and persistent droughts, are

Figure 2–9

The prairie in Kansas is characterized by expanses of grassland interspersed with a few trees and shrubs. Source: Kimberly Williams, Kansas State University.

certainly involved in the process, but questionable agricultural practices can increase the risk of degradation. This interaction contributed to the US dust bowl of the 1930s, and recovery from it required massive changes in land management. Arid lands are generally sparsely populated, but the quarter billion or so people who live in such areas around the world are among the most vulnerable to climatic change.

At about 60°N, the convergence of arctic winds and the westerlies from lower latitudes creates an upcurrent leading to precipitation, just as at the equator. Of course, it is much colder at this latitude than at the equator, and the long winter allows for only a short season of plant growth each year. Coniferous trees make up the dominant vegetation in this **boreal forest**, or **taiga**, and plant diversity is much lower than in the temperate and tropical forests. Because the conifers are mostly slow-growing evergreens, recycling and the availability of nutrients is lower than in the deciduous forest. Nutrients are also depleted as water drains through soils that are wet for most of the year. This type of vegetation is almost absent from the southern hemisphere because there is little land around 60°S. However, taiga occurs in a band from North America through northern Europe and Asia, making it the second largest biome after the desert. Of course, coniferous trees are a valuable crop for lumber and paper making, but there is little prospect for large-scale production of other kinds of crops in this area (**Fig. 2–10**).

In the tundra, north of the taiga, the ground is permanently frozen (**permafrost**) except for a surface layer throughout the year. The short melt period in the summer allows only a low vegetation of dwarf shrubs, sedges, and grasses to develop. Similar vegetation occurs in high mountains. Some of the plants have showy flowers that make the tundra briefly more colorful than the taiga. Alpine plants are attractive for specialist collectors, but there is almost no prospect for crop production in the tundra itself. Recently there is increased concern because as global temperatures rise, the arctic permafrost has begun melting causing the ground to become unstable and decomposing organic material to release large quantities of carbon dioxide and methane into the air.

The biomes are described in terms of the vegetation that existed before human interference, which began several thousand years ago to change the vegetation to provide food directly for humans or for animals that could be eaten by humans. At this stage, almost all the biomes have been influenced by human activity and some have been almost destroyed. Grasslands have been the most extensively modified because of their value for agriculture. In the United States, only 2 percent of the tallgrass prairie remains. Temperate forest has nearly all been harvested at some time and much was converted to farmland, although small areas have returned to woodland in many parts of the United States and Europe over the past fifty years (see Fig. 1–4 on page 5). These historic changes have been followed by clearance

A B

Figure 2–10

In the taiga, farming is done on a very small scale. (A) Hay making in the taiga. (B) A small farm producing fruits and vegetables in the taiga. Source: Margaret McMahon, The Ohio State University.

of the tropical forests in the twentieth century. This development is widely regarded as an ecological catastrophe, but it is not clear whether we can prevent it or have the right to act to expect it to stop.

Even when small areas of ecosystems are allowed to remain in or return to their natural state, they do not function in the original way because of changes made to the area. One of the most pervasive causes of change has been the widespread practice of land drainage. All of the kinds of ecosystems that made up the biomes contained wet areas or wetlands (**Fig. 2–11**), which were often the most productive areas because water was permanently available. Wetlands also acted as ecological buffer zones, providing refuge for animals and sources of moisture for plant life during dry seasons. Drainage proved necessary for most kinds of crop production in moist temperate areas, but this practice left remaining natural areas more vulnerable to periods of drought. Because we now understand the benefits of wetlands, the creation or restoration of wetlands has become common on farms, golf courses, housing developments, and other land use projects.

Crop production has displaced many preexisting ecosystems, and it is more realistic to describe global ecology in terms that include new biomes such as farm fields, rice paddies, or pasture. Just about all of the land that can be cultivated easily is now used for the production of crops. With the pressure of world population, we need to produce more food. It is also desirable to increase the diversity of food available to many people who currently depend on one or two staple crops. Is it realistic to increase the land area available for crops? Substantial gains could be made only from biomes that have not been exploited so far. But these biomes present serious limitations to crop production. Although tomatoes can be grown in greenhouses in Alaska, the temperature limitations on crop production in the taiga and tundra cannot yet be overcome on a large scale. Lack of water can be overcome more easily and irrigation will continue to be important for crops in many parts of the world. However, fresh water is a limited resource in all parts of the world where irrigation could be most useful, and it is not realistic to contemplate massive conversion of desert areas to any kind of large-scale crop production. In addition, marginal areas are often the most vulnerable to environmental degradation. When plant growth is slow, recovery from disturbance is also slow, and other organisms that depend on plant life can easily lose their place in the ecosystem. The low productivity of the ecosystems limits the earnings of people that depend on them and can encourage overexploitation. Many argue that we should focus on increasing the productivity of existing crop areas rather than expand into currently unproductive land.

Figure 2–11

Wetlands provide many important ecological benefits. Source: Margaret McMahon, The Ohio State University.

Within every biome and major climate area there are innumerable **microclimates**. These are determined by hills and valleys or even small depressions in a field, proximity to large and small bodies of water, presence of large land masses or buildings. Hills, valleys, and depressions create microclimates that can be warmer or colder than the climate in general. Bodies of water can delay spring warm-up and fall cool-down. Buildings that have been warmed by the sun can provide a source of heat, at least temporarily. Often, a microclimate is more important than the biome or climate in determining what plants can survive or thrive there. People who grow plants can take advantage of these areas to grow plants that may not do well in the regional climate or protect the plants that may be harmed by it. For example, a landscaper can put tender plants close to a building to prolong their growing season in the autumn. The heat from the building may provide enough warmth to allow the plants to live a few weeks beyond what similar plants would live if not near the building. Farmers can avoid planting too early in parts of their fields that are known as "**frost pockets**," which are depressions where cold air collects and temperatures are lower than in the surrounding area.

Microclimates are also influenced by elevation or altitude. Elevation is very similar to latitude. An increase in elevation is similar to increasing distance from the equator, especially in regard to average temperature. Plant cultivation strategies often take advantage of this to produce temperate region crops at the equator by growing them at higher, cooler elevations in equatorial mountains.

Another important consideration of natural and crop ecosystems is their ability to influence atmospheric carbon dioxide levels. Rising carbon dioxide levels are considered to be a major cause of climate change. During photosynthesis atmospheric carbon dioxide is removed from the air and much of it is incorporated into the plant biomass. As you have already learned, this incorporation of carbon dioxide into biomass is also called photosynthetic productivity. However, not all of the carbon stays in the biomass; some is returned to the atmosphere through **respiration**. When the loss of carbon dioxide through respiration is also considered, it is called **net photosynthetic productivity** (**NPP**).

SUCCESSION

Descriptions of biomes can leave the impression that they consist of communities of plants and other organisms that would always be there in the absence of human interference. However, we know that organisms have evolved, landforms have changed, and climate has varied over time. The change in plant communities over time is known as **succession**. It is often described in terms of the development of vegetation from a blank-slate situation such as a rock surface, a pool of water, or bare soil (**Fig. 2–12**). These situations may have arisen because of natural causes (an earthquake, volcanic eruption, or the passage of a glacier) or because of human interference.

If there is no soil, succession must begin with soil formation. A rock surface can be colonized by lichens, which trap windblown dust particles and eventually decompose to form a thin layer of soil that can be colonized by mosses. Further soil accumulation allows herbaceous plants to move in. Water might be colonized by floating plants, which decompose and sink to the bottom of a pond that may also be receiving sediment from streams. As the pond becomes shallower, bottom-rooting plants with emergent leaves can colonize, followed by wetland plants. If some kind of soil is already present, fast growing herbaceous plants will exploit the space but will give way to slower-growing plants that can use resources more efficiently. The composition of the ecosystem is always evolving toward the group of organisms that can best exploit the available resources at that time. Succession begins with **pioneer species** that can survive under special conditions and tend to get displaced as the ecosystem develops. As niches become available in the ecosystem, they are filled by the best available candidates.

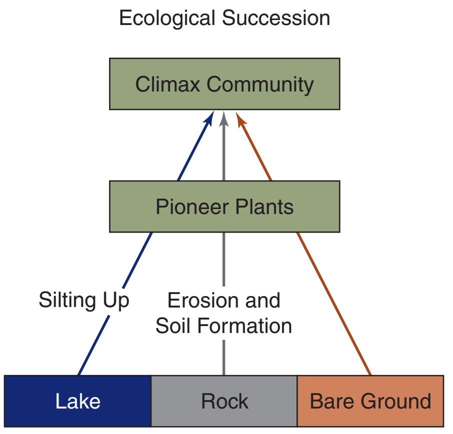

Figure 2–12

All locations in a geographic area tend to develop the same kind of vegetation over time. Source: Michael Knee.

The theoretical end point of succession is known as the **climax community**. At one time, this point was thought of as a permanent assembly of species that were linked together and would always return after any kind of disturbance. Now it is clear that there is no end point to succession and that species just happen to occur together, not because of necessary associations. The climax community can be seen as a group of species within the broad structure of the biome that is appropriate to the climatic conditions of the area. Over much of the eastern United States, this would be temperate deciduous forest with a mix of forest trees, shrubs, and herbaceous plants. Although we can characterize typical associations such as oak-hickory forest, the makeup of the ecosystem varies with location and has changed over time.

In spite of the difficulties inherent in the idea of a climax community, the broad idea of succession is sound and has implications for crop production. Many crop ecosystems are maintained at an early successional stage where they invite colonization by pioneer species, which we also know as weeds. It is easy to see that without cultivation, weeds would move in, followed by a thicket of woody plants, and the process would culminate in a forest of the longer-lived tree species. The further from the climax community we try to stay, the more work and inputs are required to maintain the ecosystem. The success of the corn belt in part can be explained by the fact that a mix of tallgrass species in the original prairie was replaced by another tallgrass that happens to be physiologically similar. In the temperate zone, we have often been lucky to be able to make drastic changes in the vegetation without suffering excessive losses of soil fertility and structure. In more difficult climates, the consequences have not been so positive, and it can be a good idea to model crop ecosystems on the broad structure of the **climax vegetation**.

Once a climax community is established, no other species can easily invade because all the niches in the ecosystem are filled and no surplus resources are available to exploit. This outcome is related to the idea of the climax community as a well-defined group of mutually dependent species. However, alien species do invade natural ecosystems, often with quite disastrous consequences, and this outcome is part of the evidence that no unchangeable association exists between the species in a climax community. Long-standing species may be well-adapted to secure the resources that they need from the environment, but they are also vulnerable to pathogens and herbivores, which are equally well-established in the environment. While an alien species may not be able to exploit the resources as efficiently as natives, it may be **immune** to the diseases and unpalatable to the herbivores. These characteristics would give it a competitive advantage, at least until the pathogens and herbivores catch up with it.

Human beings have a long history of moving plants and other organisms around the world, deliberately or by accident. Many ecosystems have been irreversibly altered by introduced species that have become invasive, replacing native plants and disrupting the ecosystem. For example kudzu was introduced into the American south to control erosion and has taken over many areas. Likewise multiflora rose and Japanese honeysuckle are invasive in several parts of the United States. In many areas extensive effort has gone into eradicating the invasives and trying to restore native populations. In recent years, the movement of organisms across national and state borders has become much more highly regulated and actively policed. Travel and trade have also increased greatly, however, and there is no guarantee that the flow of potentially damaging organisms has decreased.

IMPACT OF CULTIVATING PLANTS ON ECOSYSTEMS AND THE HUMAN FOOTPRINT

Human impact on natural ecosystems is both physical and biological. Worldwide we now deliberately choose or influence the organisms that inhabit about 35 percent of the land surface of the earth. Much of the remaining area is desert or tundra, with low productivity and biological diversity (**Fig. 2–13**). Thus, we exclude or even

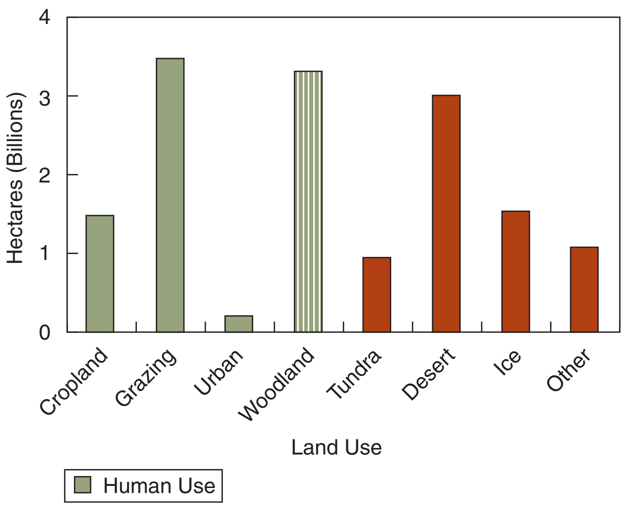

Figure 2–13

Global land use. The shaded columns indicate land used by people. Woodland is striped because it includes areas that are natural and unexploited, natural but managed or harvested, and planted purely for economic use. In a sense, all areas are used for carbon dioxide absorption, if nothing else. Source: US Global Change Research Program, http://www.globalchange.gov/

deliberately exterminate organisms in many of the most diverse and productive regions of the earth. Some ecologists allege that we have started an era of mass extinction of species like those that have occurred in geological history from meteoric impacts or other physical causes. This proposition is somewhat controversial, and people often argue about the value of preserving individual species or populations of species. However, we cannot escape the fact that we are increasingly presented with the choice about whether to try to preserve plants and animals from extinction or to allow them to disappear. Having admitted the existence of this debate, we will spend the rest of the chapter focusing on the physical cost of providing the crop plants that we utilize or consume. The physical cost comprises the land and energy inputs required in crop production.

Energy requirements and land use are the basis for two ways of evaluating the environmental impact of human activity. Accounting for energy inputs enables us to evaluate the efficiency of technological systems such as crop production, and we can look at energy demand in relation to availability on a national or global level. The land area required for the same activities is a measure of their contribution to the **human footprint**. The total human footprint is an estimate of the land area required by an individual, a geographic area, a sociopolitical group, or the world population taken as a whole. It accounts for the space required to provide all of the items we use in our lives and to absorb all of the wastes that we generate. Thus, crop production contributes to our footprint not just through the area required to grow crops, but also the areas required to provide inputs of fuel and chemicals, to transport the produce, and to absorb the wastes produced.

A footprint analysis often takes account of the area of land without regard for the intensity of use. Thus, a square meter of land occupied by a home is not differentiated from a square meter of forest that provides lumber or pasture that provides meat or dairy products. But the home uses the area almost entirely for human purposes, whereas the forest or pasture can support many other organisms. A more sophisticated equation is:

$$\text{Footprint} = \text{Area used} \times \text{Intensity of use}$$

This equation implies that we can reduce our footprint by reducing the area or the intensity of our activities. This calculation is particularly relevant to agriculture and horticulture, including landscape installation and maintenance. For many industries, the intensity of land use is 1, implying that they use 100 percent of the resource area. However, crop production need not completely displace various plants and animals from the space that is used. The global human footprint is said to exceed the area available by 20 percent. While it is desirable that some wilderness areas should remain comparatively free from human activity, it is unrealistic to expect that people withdraw from many of the areas of the globe that they now occupy. Although governments have generally supported the maximum intensity of crop production, they can begin to support greater biodiversity in crop production systems. This kind of policy would be consistent with attempts to rely on ecological processes rather than manufactured inputs to achieve production goals, such as maintenance of soil fertility or reduction in pests.

Much of our footprint on the planet is related to energy use. Most of our energy consumption is based on fossil fuels, and a footprint is associated with extraction, processing, and distribution of these fuels. However, a far greater footprint arises from the carbon dioxide produced as the fuel is burned to generate energy. This requires 8 hectares of forest for each person in the United States. Cropland makes a smaller contribution to carbon absorption because much of the carbon is returned to the atmosphere as the crop is consumed. The maintenance of forest for carbon fixation is a low-intensity component of our total footprint because we can allow natural ecosystems to perform this function. It is important that the most productive forests in equatorial Asia, Africa, and South America should not be converted to farmland. It has been said that we should probably pay for them to be maintained because we use their services. In fact, in 2008, the World Bank had committed $165 million to offer to tropical countries for "**carbon offset credits**" or "**carbon credits**" for preserving their forests. Carbon credits can be bought by countries that emit large amounts of carbon di oxide, essentially allowing them to buy a place to sequester the carbon. Other organizations, such as Carbon Conservation and Merrill Lynch, are also involved in "payment for preservation" programs. Some plant and soil scientists are now investigating how more permanent carbon sequestering can be made to occur in crop land.

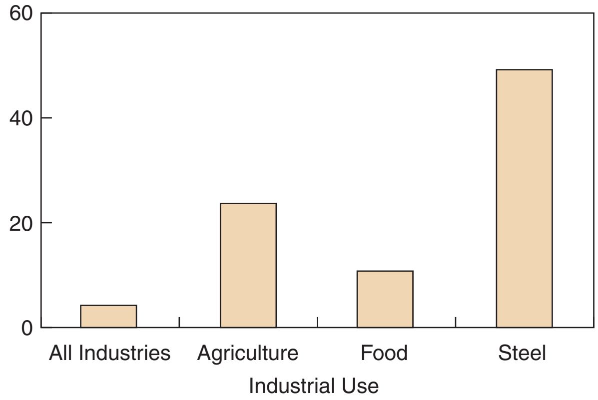

Figure 2–14

Comparative energy use by US industries in relation to contribution to gross domestic product. Agriculture appears to be energy intensive partly because profit margins are low. Food manufacture adds value to its raw materials and appears more energy efficient. Source: Earth Observing System Data and Information System, http://esdis.eosdis.nasa.gov/

Figure 2–15

Energy used in the food system includes production, transportation, processing, and storage. Source: Margaret McMahon, The Ohio State University.

Agriculture accounts for only about 2 percent of US energy use, so it can make only a minor contribution to energy conservation. However, because it accounts for less than 1 percent of gross domestic product, it is using above average amounts of energy and has to be regarded as an energy intensive industry (**Fig. 2–14**). Production of fertilizer accounts for nearly half of agricultural energy use in the United States. If the whole world adopted a similar mechanized and high-input agriculture, it would require about 10 percent of current global energy consumption. Most of the energy used for our food supply is consumed after produce leaves the farm for transportation, processing, and storage. It is difficult to account for all of the energy inputs between the farm and the dinner table, but the food sector has been estimated to account for up to 10 percent of total energy consumption. Surprisingly, less than 10 percent of this energy, or 1 percent of total energy consumption, is used in transport. Much of the energy is consumed in food marketing and preparation in the home (**Fig. 2–15**). If the rest of the world adopted this aspect of our lifestyle, it would use up about half of the world's energy supply.

Footprint and energy accounting are complementary and related to each other, although no simple equivalence exists between the two. As we saw, use of fossil fuels entails land use both on the supply and consumption side. In terms of supply, these fuels minimize our present-day footprint by using the long-ago photosynthetic productivity of the earth to meet our needs now. But they also increase our footprint by increasing atmospheric carbon. A decision to use renewable energy to reduce our carbon footprint, often enlarges our land use footprint by increasing the need for land devoted to wind farms, solar panels, or biomass production.

SUMMARY AND REVIEW

Plants provide the energy that drives almost all terrestrial ecosystems. Photosynthetic productivity is a measure of how much solar energy is converted to biomass in natural or crop ecosystems. An ecosystem consists of populations of different species of organisms in a physical environment. Crop ecosystems require inputs because they usually lack some of the organisms and processes that sustain natural ecosystems. Ecosystem organisms can interact in several ways to exploit the resources of the environment. Competition for resources is more likely to occur between individuals of the same species or closely related species. A single species cannot fully exploit all the resources in an environment. Resources are partitioned to provide niches that are occupied by different species. A natural ecosystem may not have any unoccupied niches, but crop ecosystems often provide niches that can be occupied by other plants are usually weeds. Small animals, fungi, and bacteria help to recycle nutrients in natural ecosystems and make them available to plants. In crop ecosystems nutrients are often withdrawn from crop ecosystems when the crop is harvested and not recycled naturally back into the system necessitating the inputs of fertilizer and fuels. The more a crop ecosystem mimics the one it replaced, the less inputs are needed.

The natural ecosystems that occur in different parts of the world can be grouped together in biomes. Each biome is a collection of ecosystems with similar climate, **soil type**, and vegetation, and these three elements are interrelated. Temperature and precipitation are the main climatic factors. Temperature is determined mainly by latitude and height above sea level. Precipitation patterns are related to the predominant wind patterns that occur in three bands in the northern and southern hemispheres. Temperature and precipitation are consistently high in the equatorial region, leading to continuously high rates of growth and low nutrient availability in the soil for the tropical rainforest. The divergence of wind systems north and south of the equatorial zone leads to dry conditions and the low productivity of the desert biome. In the northern hemisphere, the moist temperate zone is occupied by deciduous hardwood forest, which is highly productive in summer but dormant in winter. On the major continental land masses, the region between forest and desert was naturally occupied by grasslands. While these areas were not as productive as forests, highly fertile soils developed, and they became some of the world's most productive agricultural areas. To the north of the temperate deciduous forest, coniferous trees predominate in the taiga, or boreal forest; further north still, the subsoil is permanently frozen and trees cannot grow.

Microclimates exist everywhere and vary from the prevailing climate because of a feature such as body of water, land mass, building, altitude, and other features. The environment in a microclimate may be more favorable or less favorable to plant growth than the general climate in the area. Growers can use growing strategies that account for microclimate effects.

Soils and ecosystems develop over time in a process known as succession to a stable climax community. Most crop ecosystems are maintained at an early, unstable successional stage that requires significant energy input to maintain.

Agricultural and other human uses now dominate the ecology of nearly all of the most photosynthetically productive terrestrial areas of the earth. Crop plants and farm animals have replaced the organisms that inhabited these areas, even to the extent that we are causing extinction of other species. We can summarize our impact on global ecology in terms of the land or the energy that is used for human purposes, including crop production through the concept of the human footprint. While crop production represents a small fraction of total footprint and energy use, the intensity of land and energy use for crops is higher than for other industries. The food supply system (processing, transportation, and storage) uses much more energy after it leaves the farm than was used in production.

KNOWLEDGE CHECK

1. Briefly describe the parts of an ecosystem.
2. What distinguishes the ecosystem created by cultivating plants from natural ecosystems?
3. What is meant by a niche in ecosystems?
4. Why is it usually easy for weeds to get established among cultivated plants?
5. Although disease parasites often do not directly kill a plant they infect, the plant will often die. Why?
6. What is the beneficial relationship that mycorrhizae have with plants? What is the relationship that *Rhizobium* has with plants?
7. What role do saprophytes and detritivores have in ecosystems? When do they become most important in plant cultivation systems?
8. What is a biome?
9. How do global wind patterns affect the creation of the major biomes?

10. What types of plants are found in tropical rainforest, desert, temperate forests, grasslands and savannas, taiga, and tundra?
11. What is a microclimate?
12. Describe two ways cultivating plants has impacted biomes.
13. Of the major biomes, which are the most photosynthetically productive?
14. Are crop systems usually more or less photosynthetically productive than the native plants they replaced?
15. Describe ecosystem succession. In terms of succession, what is the difficulty with maintaining many of our crops?
16. How does cultivating crops impact our carbon footprint?
17. What is the concept of "carbon credits"?
18. Give two reasons why the United States uses so much energy for its food supply.

FOOD FOR THOUGHT

1. Decide if you think it would be better for countries with tropical rainforests to convert the forests to crop land or sell them for carbon credits instead. Then, give the reasons for your decision.
2. Think about the biome in which you live. How do the plants growing in the landscape of your college or at your home compare to those that would be growing there naturally? What, if anything, has to be done to alter the environment so that the landscape plants thrive? How would these practices affect the carbon footprint?

FURTHER EXPLORATION

Hunter, M., D. Lindenmayer, and A. Calhoun. 2007. *Saving the earth as a career*. Hoboken, NJ: Wiley-Blackwell.

National Research Council. 2005. *Valuing ecosystem services: Toward better environmental decision-making*. Washington, DC: National Academy Press.

Schmitz, O. J. 2013. *Ecology and ecosystem conservation*, e-edition. Washington, DC: Island Press.

Food and Agriculture Organization of the United Nations. 2010. An ecosystem approach to sustainable crop production intensification—A conceptual framework. Available online at **http://www.fao.org/fileadmin/templates/agphome/scpi/SCPI_Compendium/SCPIConceptual_framework.pdf**

Global Footprint Network. Ecological footprint (interactive). Available online at **https://www.footprintnetwork.org/our-work/ecological-footprint/**

3

Growing Plants for Human Use

Michael Knee

Learning Outcomes

After reading this chapter, you should be able to:

1. Describe how plants are used to meet human nutritional needs.
2. Describe the many ways plants are needed and used by humans in addition to nutrition.
3. Discuss how growing plants impacts our energy use and carbon footprint.

The previous chapter looked at ecosystems and the impact humans have on them. You learned about our energy footprint. Now let's look at why we grow plants and take a closer look at how our need for plants and the way we grow them influences ecosystems, the energy footprint, and society.

PLANTS FOR HUMAN USE

Nutrition

A healthy diet requires an energy source from organic carbon molecules (**carbohydrates**, **fatty acids**, **lipids, fats, and oils**). The diet also requires other components: **amino acids from proteins** and various vitamins, minerals, and water. Apart from the minerals and water, these requirements are met through a series of processes that start with photosynthesis and the creation of organic molecules. Though the definition can vary, for this section organic molecules will be considered to be molecules containing carbon bonded with hydrogen, though other elements may also be a part of it.

To help with understanding this section, here are brief definitions of the different organic carbon molecules as well as amino acid and protein.

1. Carbohydrates are chains of carbons linked together with hydrogen and oxygen atoms also attached. The number of the carbons and the number of hydrogen and oxygen atoms in the molecules determine the characteristics of carbohydrates.
2. Fatty acids are carbon chains with hydrogen but no oxygen attached along the chain except at one end where a carboxyl (one carbon and two oxygen and one hydrogen atoms, -COOH) is attached. Fatty acids can be **saturated** or **unsaturated**. Saturated acids have single bonds between all carbons, and hydrogen is attached to all other binding sites (saturated). Unsaturated acids have a double or triple bond between some of the carbons where hydrogen could attach if the bond was single).
3. Lipids, fats, and oils are made up of fatty acids and other elements. The exact make up of each determines its characteristics. In general, fats are solid at room temperature and oils are liquid.

4. Amino acids are made from a carboxyl and an amine (NH_2) with side chains of other elements. The side chains give the amino acid its characteristics.
5. Proteins are very long and complex chains of amino acids.

Plants are essentially the only terrestrial organisms that convert inorganic carbon, oxygen, hydrogen to organic forms through photosynthesis. In other words plants incorporate the solar energy they capture into the organic forms of carbon. It is these organic forms that provide the energy for all living organisms. This ability to convert inorganic to organic is why plants are called **autotrophs** (meaning "self-feeder"), whereas humans and just about everything else that live on land are **heterotrophs** (or "other feeders") because they feed off autotrophs or other heterotrophs.

Crops When we look at cultivated plants, we see that only a small percentage of all the plant species in existence feed the world's people either directly or indirectly (through animals). The six major groups of food plants are:

1. Cereal crops—wheat, maize (corn), rice, barley, oats, sorghum, rye, and millet. (Over half the world's food supply comes from the photosynthetic activity of these crops.)
2. Roots and tubers—potatoes, sweet potatoes, and cassavas.
3. Oil crops—soybeans, corn, peanuts, palm, coconuts, sunflowers, olive, and safflower.
4. Sugar—**sucrose** from sugarcane and sugar beets, **fructose** from corn.
5. Fruit crops—bananas, oranges, apples, pears, and many others.
6. Vegetable crops—tomatoes, lettuce, carrots, melons, asparagus, and so forth.

Fruits and vegetables add to the variety and **palatability** of our daily meals and supply much-needed vitamins and minerals.

Table 3–1 shows some of the common crops ranked in relation to the **calories** and proteins produced per unit of land area. However, not all of the total production of food materials becomes available for human consumption. Much is lost during harvesting, transportation, and marketing, primarily from attacks by insects, diseases, birds, and rodents. Also, some of the production is saved to be used as seed for future plantings.

Table 3–1
Some Important Food Crops Ranked According to Calorie and Protein Production per Unit of Land Area

Rank	Calories Produced per Unit Area	Protein Produced per Unit Area
1	Sugarcane	Soybeans
2	Potato	Potato
3	Sugar beets	Corn
4	Corn	Peanuts
5	Rice	Sorghum
6	Sorghum	Peas
7	Sweet potato	Beans
8	Barley	Rice
9	Peanuts	Barley
10	Winter wheat	Winter wheat

Source: USDA, IR-1 Potato Introduction Station, Sturgeon Bay, Wisconsin.

Nutrition Requirements Adults need 2,000 to 3,000 kcal of energy per day, depending on their size and level of activity. This energy can be provided by carbohydrates, which are typically found in plant-based foods. So twenty-four to thirty-six slices of bread is one way to get our daily energy requirement. Lipids provide energy in more condensed form, and 9 to 14 ounces of vegetable oil can provide our energy for the day (**Fig. 3–1**). Fats are more characteristic of animal foods, but many health problems are associated with consumption of animal fats partly because they tend to be made from saturated fatty acids that cause more health problems than unsaturated fatty acids. Unlike animals, plants can make **polyunsaturated fatty acids** (PUFAs) such as linoleic and linolenic acids. Apart from the health benefits of PUFAs, we need linoleic acid to make hormones such as prostaglandin, and plant oils are a more direct source than animal fats. We can also derive energy from protein-rich foods such as meat. Eating only meat for our energy needs is wasteful and probably unhealthy because of the need to excrete the excess nitrogenous material. Most nutritionists believe that reliance on plant foods as an energy source is healthy because the energy-providing carbohydrates are associated with indigestible fiber, which protects us from colon disorders and other so-called diseases of affluence. Of course, these benefits come only with unrefined carbohydrates, such as whole wheat or brown, unpolished rice. Purified

Figure 3–1

Comparative amounts of bread (carbohydrate) and vegetable oil (lipid). Source: Margaret McMahon, The Ohio State University.

Figure 3–2

Grain and pulse crop combinations such as wheat and peas provide a balance of carbohydrates and protein. Source: Margaret McMahon, The Ohio State University.

carbohydrates such as refined sugar or starch are not as beneficial and carry their own health risks.

An adult needs about 70 grams of protein in a day. Plant foods, especially cereal grains and pulses (peas and beans), often provide enough protein along with the energy that they supply. However, a plant diet may not satisfy our protein requirement because it may be deficient in one or more of the amino acids that we require. The essential amino acids are leucine, isoleucine, valine, threonine, methionine, phenylalanine, tryptophan, and lysine; additionally, children require histidine. Plants make these and the rest of the twenty amino acids that make up proteins, but plant proteins often have only a low proportion of some of the essential amino acids, particularly the sulfur-containing methionine, and the basic amino acid, lysine. No common plant food provides the right balance of amino acids, so we would need to overeat to meet our dietary requirements. An exception is the so-called "miracle grain," quinoa (*Chenopodium quinoa*), which provides enough of the essential amino acids along with its energy content. Animals, being more closely related to us, have a similar amino acid composition and generally provide better-quality protein. Eggs are generally regarded as providing perfect protein and are given a protein score of 100. A balanced diet can be achieved on a plant diet supplemented with a small amount of meat or other animal food. Alternatively, the deficiencies of individual plant foods can be remedied to a large extent by combining them. Grains tend to be low in methionine, whereas pulses (legumes) are low in lysine. A mixture of a grain and a pulse provides a more balanced protein. Many cultures in different parts of the world have based their diet on such mixtures: rice and soybeans in China, wheat and chick peas in the Middle East, and corn and beans in South America (**Fig. 3–2**).

Carbohydrates, lipids (fats), and proteins are the bulk constituents of our diet. We also need small amounts of other organic molecules, called vitamins. We have some ability to make our own vitamin D, depending on the exposure of our skin to sunlight. All of the other vitamins are plant or microbial products. Most vitamins can be obtained from fruits, vegetables, or grains. Grains and grain flours are a poor source of some vitamins, particularly if they are polished or refined. Vitamin C

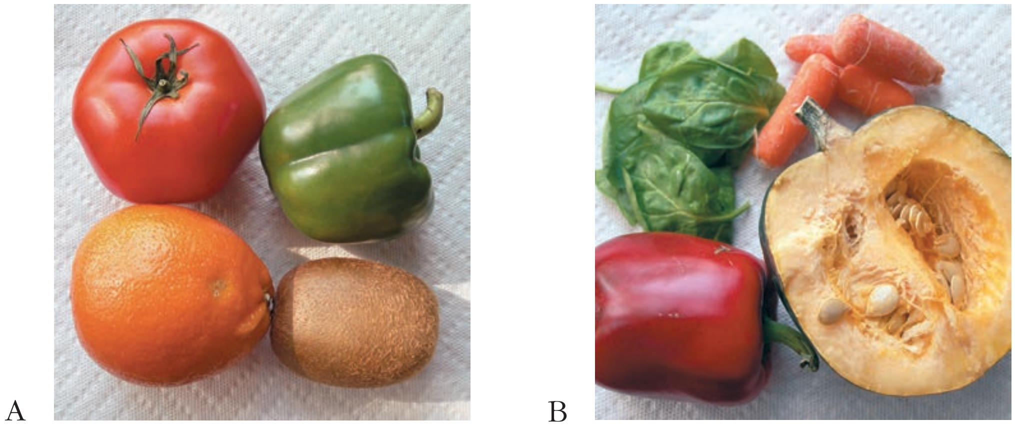

Figure 3–3

(A) Fruits and vegetables rich in vitamin C. (B) Green, yellow, orange, and red fruits, vegetables, and grain provide carotene, which is the precursor to vitamin A. Source: Margaret McMahon, The Ohio State University.

(ascorbic acid) is found only in fresh fruits and vegetables. Some of the fruits and vegetables that are high in vitamin C are: citrus fruit, pineapples, watermelon, cantaloupe, raspberries, blueberries, cranberries, the cole crops (cabbage, broccoli, etc.), peppers, tomatoes, and leafy greens (**Fig. 3–3A**). Vitamin A is derived from **carotene**, which is found in green, yellow, orange, or red fruits, vegetables, and grains (**Fig. 3–3B**). Plant foods do not provide vitamin B_{12} (cyanocobalamin), which is manufactured by bacteria, especially in the guts of ruminant organisms, so it is available to us in dairy products and meat.

In addition to the organic components, we require six major inorganic nutrients (calcium, phosphorus, magnesium, sodium, potassium, and chloride) and seven micronutrients. All can be obtained from plant foods, although they are often more abundant in animal foods. We can assume most of the time that we are getting enough of the nutrients in the food that we normally eat, but calcium, phosphorus, iron, and iodine are the most likely to be deficient and are called critical nutrients.

Nutrition Footprint If an adult needs 3,000 calories of energy per day and if average US yields can be achieved, it would take about 0.15 hectares of wheat or 0.06 hectares of corn to satisfy this dietary requirement for a year. To improve the protein quality of the diet, beans can be substituted for one-quarter of the grain intake. Again assuming average US yields of soybeans, this diet would take about 0.05 hectares. Yields of soybeans are about the same as those for wheat, so the total area required (0.16 hectares) would not change much on a diet of beans and wheat. However, corn yields are much higher, and a diet of corn and beans would take about 0.09 hectares. However, this diet would be boring, and it would lack important vitamins (particularly A and C) and minerals. The USDA recommended intakes could be supplied by about 400 grams of fruit and vegetables per day, which would require another 0.02 hectares of land (once more assuming typical US yields). So the wheat-based diet would require a total of 0.16 hectares, and the corn-based diet 0.11 hectares (**Fig. 3–4**). These figures are optimistic because cereal yields

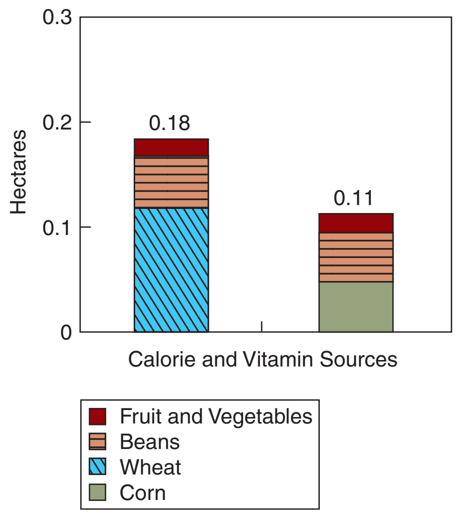

Figure 3–4

Amount of land required to provide an adult with vitamins from 400 grams fruits and vegetables, 750 kcal from soybeans, and 2,250 kcal from either wheat or corn. Source: Michael Knee.

in most countries are lower than in the United States, and soybeans are the highest yielding of the pulse crops. The peas and beans that are mostly consumed by people have much lower yields. It is questionable whether the inputs that are used to attain US yields are physically available or environmentally desirable on a worldwide scale. The United States is exceptionally fortunate in having stable and productive soils and an excess of cropland relative to its population. Worldwide there are about 0.25 hectares (0.6 acres) of cropland for each person. With realistic inputs and yields, this land is about enough to provide everyone with a vegetarian diet but would not likely support a larger population.

Though not major providers of nutrition, herbs and spices add flavor to our diets. The production of these plants contributes to our food footprint and in some areas takes a large amount of land area. The Food and Agriculture Organization of the United Nations (FAO) documented that nearly 3.5 million hectares were devoted to the production of garlic, cinnamon and other spices, and herbs, globally, in 2016. Plants also provide dyes, perfumes, and other specialized chemical ingredients. Today, many of these have been more or less replaced by synthetic materials, often produced from petrochemicals. However, there is still a viable market for products like essential oils and fragrances derived from plants.

In addition to the land required to grow crops, we should count the area needed to provide the inputs of energy and chemicals that are used in modern production systems. However, chemical inputs of fertilizers and pesticides can reduce the footprint because they increase the yield from a given area. Area is also required to absorb the wastes generated by food production. In the past, this factor tended to be ignored, with the result that **groundwater** and surface water became contaminated. Now, many crop production facilities, large and small, use fertilization and pest control practices that minimize chemicals leaching into the groundwater. Many growers provide some kind of buffer vegetation to prevent soil particles and fertilizer runoff from cropland entering into streams and lakes. Plant waste can often be recycled by **composting** or incorporation into soil or by feeding it to animals. Animal wastes are often spread on the land. Major problems still occur, however, when wastes cannot be recycled for the production of crops.

Crop production has become concentrated and specialized in regions and countries around the world. For example, California and Florida produce more than 60 percent of the fruits and vegetables grown in the United States, which means that crops are often transported thousands of miles between production and consumption points. Although some argue from an ecological perspective that we should consume local produce, the energy costs of transport are much lower than for out-of-season production in a greenhouse (**Table 3–2**). On the other hand, the nutrient flows arising from food transport do present some problems. The nutrients in the produce are removed from the area where the crop was grown. For example, several countries in Africa and South America produce high-value horticultural crops for export to Europe and North America. These crops tend to have high potassium content; so an essential plant nutrient is being exported and may not be easy to replace.

The sewerage system transporting human wastes can also be viewed as part of the agricultural footprint. Like animal manure and urine, human waste contains a high level of nutritional elements. Although some municipalities have

Table 3–2
ENERGY COSTS OF SUPPLYING FRUITS AND VEGETABLES OUT OF SEASON

Commodity	Provided by	Energy Input (kJ/kg)	Food Energy (kJ/kg)	Relative Energy Cost*
Strawberries	Road from Florida to Ohio	1,400	1,250	1.12
Broccoli	Road from California to Ohio	2,800	1,110	2.53
Lettuce	Greenhouse production	230,000	500	460

*The relative energy cost is estimated by dividing energy input by food energy value. A positive value indicates that the energy put into producing and shipping a crop is greater than its calorie value.

Source: Michael Knee.