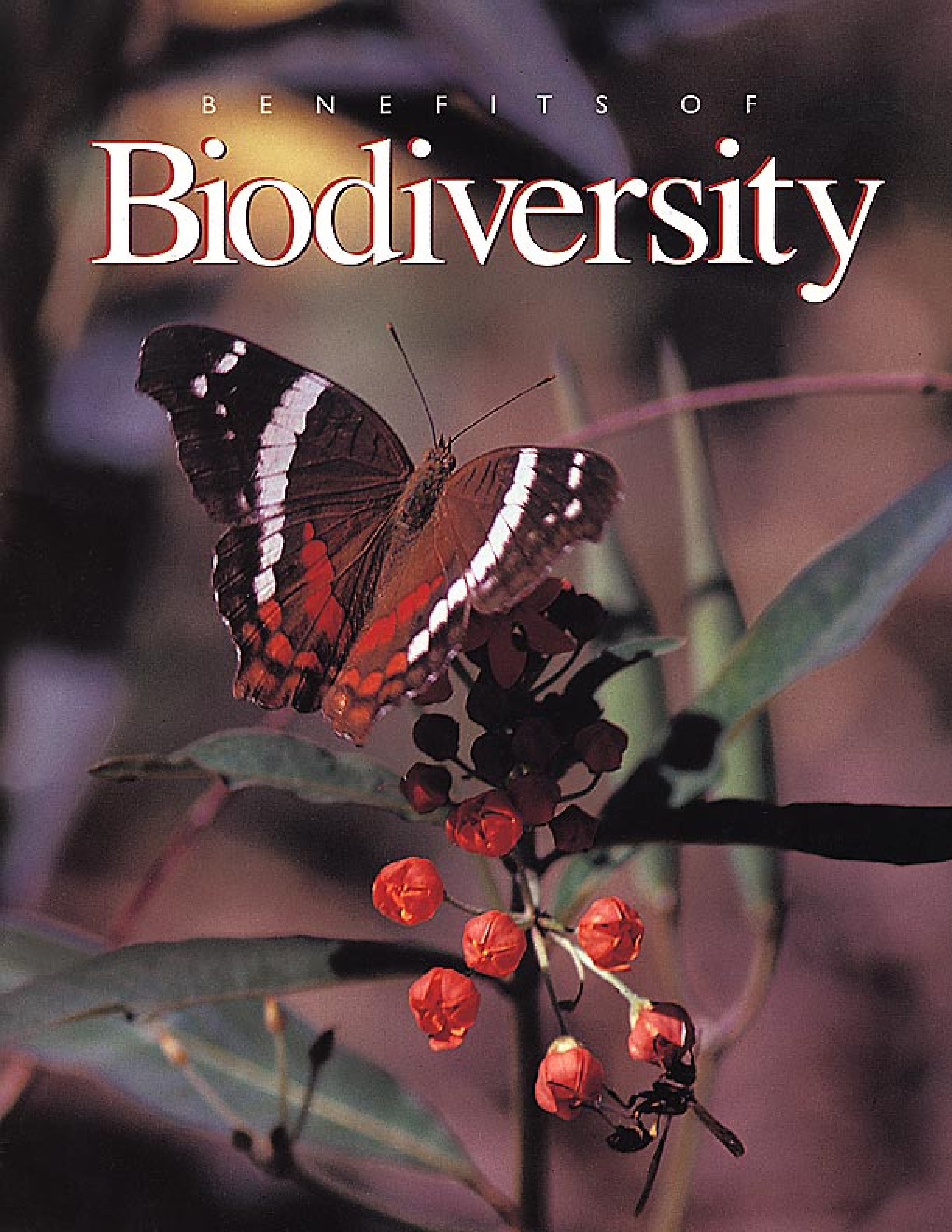
BENEFITS OF Biodiversity



Benefits of Biodiversity

Council for Agricultural Science and Technology
Printed in the United States of America
Cover design by Lynn Ekblad, Different Angles, Ames, Iowa
Cover photograph by Carl Kurtz, St. Anthony, Iowa. Fatima (*Anartia fatima*) butterfly and Vespid (Vespidae) wasp pollinating a blood flower (*Asclepias currassavica*) found in a tropical deciduous forest in the state of Nayarit, western Mexico.
ISBN 1-887383-15-8
ISSN 0194–4088
02 01 00 99 4 3 2 1

Library of Congress Cataloging in Publication Data

Benefits of biodiversity.
p. cm. — (Task force report, ISSN 0194–4088 ; no. 133)
Includes bibliographical references (p.) and index.
1. Agrobiodiversity. I. Council for Agricultural Science and Technology. II. Series: Task force report (Council for Agricultural Science and Technology) ; no. 133
S494.5.A43B45 1999
333.95'34—dc21 98–50296
CIP

Task Force Report
No. 133 February 1999

Council for Agricultural Science and Technology

Task Force Members

G. David Tilman (Cochair), Department of Ecology, Evolution, and Behavior, University of Minnesota, St. Paul

Donald N. Duvick (Cochair), Department of Agronomy, Iowa State University, Ames

Stephen B. Brush, Department of Human and Community Development, University of California, Davis

R. James Cook, Department of Plant Pathology, USDA/Agricultural Research Service, Washington State University, Pullman

Gretchen C. Daily, Department of Biological Sciences, Stanford University, Stanford, California

Geoffrey M. Heal, Graduate School of Business, Columbia University, New York

Shahid Naeem, Department of Zoology, University of Washington, Seattle

David Notter, Department of Animal and Poultry Sciences, Virginia Polytechnic Institute and State University, Blacksburg

Reviewers

Cornelia B. Flora, North Central Regional Center for Rural Development, Iowa State University, Ames

Kenneth J. Frey, Department of Agronomy, Iowa State University, Ames

Wesley Jackson, The Land Institute, Salina, Kansas

Jane Lubchenco, Department of Zoology, Oregon State University, Corvallis

Peter Raven, Missouri Botanical Garden, St. Louis

Osvaldo E. Sala, Department of Ecology, University of Buenos Aires, Buenos Aires, Argentina

Contents

Figures

Foreword

Following a recommendation by the CAST National Concerns Committee, the CAST Board of Directors authorized preparation of a report on the benefits of biodiversity.

Dr. G. David Tilman, Department of Ecology, Evolution, and Behavior, University of Minnesota, St. Paul, and Dr. Donald N. Duvick, Department of Agronomy, Iowa State University, Ames, served as cochairs for the report. A highly qualified group of scientists served as task force members and participated in the writing and review of the document. They include individuals with expertise in agronomy, animal and poultry sciences, biological sciences, botany, ecology, economics, evolution, plant pathology, rural development, and zoology.

The task force prepared an initial draft of the report. They revised all subsequent drafts of the report and the authors reviewed the proofs. The CAST Executive and Editorial Review committees reviewed the final draft. The CAST staff provided editorial and structural suggestions and published the report. The authors are responsible for the report's scientific content.

On behalf of CAST, we thank the chairs, authors, and reviewers who gave of their time and expertise to prepare this report as a contribution by the scientific community to public understanding of the issue. We also thank the employers of the scientists, who made the time of these individuals available at no cost to CAST. The members of CAST deserve special recognition because the unrestricted contributions that they have made in support of CAST also have financed the preparation and publication of this report.

This report is being distributed to members of Congress, the White House, the U.S. Department of Agriculture, the Congressional Research Service, the Food and Drug Administration, the Environmental Protection Agency, the Agency for International Development, and the Office of Management and Budget, and to media personnel and institutional members of CAST. Individual members of CAST may receive a complimentary copy upon request for a $3.00 postage and handling fee. The report may be reproduced in its entirety without permission. If copied in any manner, credit to the authors and to CAST would be appreciated.

David R. Lineback
President

Richard E. Stuckey
Executive Vice President

Kayleen A. Niyo
Managing Scientific Editor

Interpretive Summary

Productive and efficient agriculture, which is the foundation of modern successful societies, has depended on biological diversity, and will be even more dependent on it in the decades and centuries ahead. The earth's biodiversity is the source of all livestock, of all crops and pollinators of crops, of the biological agents that control crop pests, of many agricultural pesticides and pharmaceuticals, and of numerous ecosystem services essential to agriculture, including the creation of soils and the renewal of their fertility. Expanding human activities are threatening this biodiversity, and thus compromising the long-term sustainability, productivity, and stability of agriculture and society.

Biological diversity, or *biodiversity,* includes both the number of different species and the number of genetically different varieties within species on earth. Agriculture depends on both components of biodiversity. Over 130 different plant and animal species are grown as major sources of human food, thousands of additional plant and animal species are harvested, and thousands more contribute directly and indirectly to agricultural productivity. High genetic diversity within each individual crop also is required if a crop is to be viable over the long term. This high genetic diversity is essential for developing crop strains and livestock breeds that are resistant to the diseases and other pests associated with the high densities of modern crop and livestock operations. Genetic diversity allows improvements in yield and quality, and development of varieties that can be commercially feasible in different soils or regions or in response to different market pressures. Because of recent advances in biotechnology, agriculture has the potential to draw on the genetic diversity of all species, not just crop or livestock relatives. The ability to use this additional diversity will be crucial to the future productivity and stability of agriculture, making preservation of all biodiversity essential to agriculture. Biodiversity decreases risks experienced by farmers and by society, and provides options should diseases and other pests or changing climatic conditions eliminate a once-favored crop or livestock species.

The long-term viability of agriculture requires society to invest in actively maintaining high diversity within crops and their wild relatives, within natural ecosystems, and within agricultural landscapes. It is imperative that we systematically monitor and preserve the wild relatives of major crops within their centers of origin. It is critical that we also preserve livestock breeds, as well as their wild relatives, in their centers of origin. Such maintenance of biological diversity is of long-term benefit to agriculture and to society. As importantly, the development and increased use of high-diversity cropping systems, which currently are greatly underutilized, could substantially contribute to agricultural productivity, sustainability, and stability.

Most diversity must be maintained in wilderness areas and parks, which need to be expanded worldwide. However, the maintenance of diversity can be supplemented by scattered, smaller, natural or seminatural habitats in rural landscapes, and by the varieties of crops and breeds of livestock maintained by farmers and hobbyists. Because biodiversity is of direct and long-term importance to agriculture and society, it is imperative that society invest in its more complete utilization and preservation. For crop plant and livestock genetic diversity, it is essential that national and international organizations having such preservation as their goal be better supported or created.

In total, based on our review and synthesis of the scientific literature, we recommend the following:

Preserve Biodiversity by Preserving Natural Areas

Rationale:

- Land clearing, the destruction of natural habitats, nutrient pollution, and introduction of exotic species are causing an unprecedented and rapid loss of biodiversity.
- By threatening biodiversity, these expanding human activities threaten the stability and sustainability of agriculture and of vital services provided to society by natural ecosystems.

Actions:

- Substantially increase the worldwide network of biodiversity reserves, including properly managed forests and grasslands, national and regional parks, wilderness areas, and privately held lands, in order to prevent massive, human-caused extinction of species and loss of genetic diversity.
- Preserve large blocks of land in native ecosystems to preserve terrestrial diversity.
- Prevent habitat destruction worldwide because it causes large irreplaceable losses of genetic diversity of direct long-term value to crop and livestock production.
- Increase the capacity of rural landscapes to sustain biodiversity and ecosystem services by maintaining hedgerows/windbreaks; leaving tracts of land in native habitat; planting a diversity of crops; decreasing the amount of tillage; encouraging pastoral activities and mixed-species forestry; using diverse, native grasslands; matching livestock to the production environment; and using integrated pest management techniques.
- Educate policy makers and the public about the many ecosystem services that are provided by biodiversity in natural ecosystems.

Preserve Diverse Sources of Plant and Animal Germplasm for Future Agricultural Use

Rationale:

- High genetic diversity is essential for productive, stable, and sustainable crop and livestock agriculture.
- Genetic diversity of crop plants and of breeds of livestock animals is being lost forever, as farmers around the world change farming practices in response to changing demands for food and fiber, and as native habitats of the wild relatives of agricultural species are destroyed.
- Animal breeds and their wild relatives merit significantly greater conservation efforts.
- The diverse on-farm germplasm must be collected and stored in long-term storage depositories or in monitored farm and field preserves or it will be lost. If it is lost, sources of genetic diversity for future plant and animal breeding will be dangerously or even fatally constricted.
- Well-managed *ex situ* and *in situ* crop collections effectively conserve plant biodiversity for agricultural purposes.

Actions:

- Ensure that genetic diversity now found in agricultural plants is preserved in seed banks and plant collections (*ex situ*) or as growing crops (*in situ*).
- Ensure that wild crop and livestock relatives are conserved in carefully identified natural systems.
- Systems must be devised for long-term and dependable conservation of rare breeds of farm animals and of their genetic diversity.
- Provide adequate fiscal and administrative support for maintenance and utilization of germplasm collections.
- Increase support for USDA's National Plant Germplasm System and the Consultative Group on International Agricultural Research's (CGIAR) International Germplasm Centers.
- Encourage private initiatives to conserve plant, microbial, and animal germplasm; compare these initiatives with public conservation activities to evaluate the total effort in conservation of agriculturally important germplasm.

Increase the Effective Use of Diversity in Agriculture

Rationale:

- Production agriculture is one component of the complex and highly interdependent ecosystem that encompasses all aspects of nature: urban, agricultural, and "natural." Biodiversity performs vital functions at all levels of this system. Loss of biodiversity at any level of the system will adversely affect other parts.
- Biodiversity of plants and animals is essential for maintenance of the productivity of farm crops and animals.
- Biodiversity of plants, beneficial microorganisms, and animals will be essential for future increases in productivity needed to feed an increasing world population.
- Biodiversity, properly deployed, increases dependability of performance in crop plants.

Actions:

- Develop and spread understanding of the "whole ecosystem" concept, which treats production agriculture as one component in a complex and highly interdependent ecosystem encompassing all aspects of nature.
- Broaden the use of genetic diversity to protect crops against pest and weather problems by introducing multiple genetic systems for coping with

biotic and abiotic stress.

- Use biotechnology to improve and increase useful kinds of biodiversity in plants, microorganisms, and animals.
- Provide support for studies that investigate and compare new and improved procedures for effective deployment of biodiversity in crop production and in different kinds of farming systems, particularly high-yield commercial farming systems.
- Provide support for studies that investigate ways to utilize and maintain biodiversity more effectively in animal production systems, particularly intensive production systems.
- Provide support for studies that demonstrate the interactions of agriculture with the other parts of the "whole ecosystem," e.g., provide support for studies that independently manipulate diversity, species composition, and management practices related to rotational grazing, multispecies forest stands, and crop production.

1 The Importance of Agriculture

The world has at least 5 to 7 million different species of plants, animals, and microorganisms (May, 1999), many of which have contributed to one of the most dramatic changes that has occurred on earth—the emergence of humans as the dominant species (Diamond, 1997). Agriculture is the major reason for this success. During the past 10,000 years, and especially during the past century, advances in agriculture have supported ever-larger human populations enjoying higher standards of living. Agriculture has been so productive that an ever-decreasing proportion of society has been able to feed the rest, allowing more people to pursue careers in industry, medicine, science, arts, and humanities. The resulting cultural development and accumulation of knowledge has increased our ability to live at greater population densities and with higher standards of living. Thus, all of human society and most of human recorded history are intimately intertwined with and highly dependent on the successes of agriculture. With the world's population at more than 5.9 billion, and with this number likely to double within the next 50 years, the future of humanity will depend even more on the way in which we manage both the agricultural enterprise and the remaining natural and seminatural ecosystems of the world.

Figure 1.1. Farm produce in a Minneapolis Farmers' Market illustrates some of the diversity of food from crops. Photograph courtesy of G. David Tilman, University of Minnesota, St. Paul.

What has led to thousands of years of advances in agriculture? What is needed to sustain agriculture during the coming centuries? Such questions have many answers. The development of new technologies has played, and will always play, a significant role. However, another essential part of this success has been derived from biological diversity (Diamond, 1997). Humans do not produce food. Other animal and plant species produce it for us. The essence of agriculture is the harnessing of numerous species of plants and animals for human benefit. Many of the advances in agriculture have come from the selection and development of new crops and from genetic refinements in these crops. Some major crops grown in this century were rare a century or two ago. Development of more-productive crops and the replacement of old ones have occurred for millennia. Today, 80 plant crops provide about 90% of the world's food from

Figure 1.2. Many crops cannot be produced without pollinators. Honeybees are one of the hundreds of thousands of animal species essential for pollinating crops and protecting them from pests. Honeybees collecting pollen from an oilseed sunflower. Photograph courtesy of Richard L. Wilson, USDA-ARS.

plants (Food and Agriculture Organization, 1996) (Figure 1.1). Fifty animal species account for most domestic animal production of food and fiber. Thousands of other plant species are actively farmed, and tens of thousands of plant species are known to have edible parts. Hundreds of animal species are regularly harvested for food, and additional species are being domesticated. Hundreds of thousands of animal species, mainly insects, are essential for pollinating crops and protecting them from pests (Figure 1.2). Tens of thousands of microbial species, most of them living in soil and on plants, provide for nutrient cycling, crop residue decomposition, and enhanced crop growth. Humans always have been, presently are, and always will be dependent on the diversity of organisms to provide food for the growing human population. Humankind's agricultural successes have stemmed from its ability to use biological diversity to its advantage. However, expanding human activities are threatening this diversity, which threatens the stability and sustainability of society.

2 Biodiversity

Biological diversity, or *biodiversity*, refers to all forms of life, including all species and genetic variants within species and all ecosystems that contain and sustain those diverse forms of life (Figures 2.1–2.5). For millennia, when threatened with drought, insect outbreak, famine, and plague, humans have drawn upon this biodiversity to develop new crops, new varieties within these crops, new farm animal resources, and new medicines. The new crops may be ones that are more drought tolerant or disease resistant (Figure 2.6). They may be more productive on certain soil types, or especially suited to a new agricultural practice. New livestock breeds are created to fit new production environments and markets and to resist disease (Figure 2.7). These genetic resources are not invented. Rather, they are discovered by trial-and-error processes and by careful searches of the earth's biodiversity. The productivity and sustainability of ag-

Figure 2.1. Native prairie ecosystems contain a large species diversity. The most efficient way to preserve such diversity is in natural ecosystems where diversity maintains itself. Downy Phlox (*Phlox pilosa*), Canada Anemone (*Anemone canadensis*), and White Sage (*Artemisia ludoviciana*) in virgin Lawler Prairie, Hardin County, central Iowa. Photograph courtesy of Carl Kurtz, St. Anthony, Iowa.

Figure 2.2. A variety of fauna including Great Egrets (*Casmerodius albus*) and Snowy Egrets (*Egretta thula*) thrive in the Big Cypress National Preserve in southwestern Florida. Photograph courtesy of Carl Kurtz, St. Anthony, Iowa.

Figure 2.3. Native forests contain and help preserve great species diversity. This diversity increases their productivity and stability. Paper Birches (*Betula papyrifera*), White Spruces (*Picea glauca*), and Red Maples (*Acer rubrum*) near Gobler Lake, Oneida County, northern Wisconsin. Photograph courtesy of Carl Kurtz, St. Anthony, Iowa.

Figure 2.4. A variety of flora including Sabal Palms (*Sabal palmetto*), Royal Palms (*Roystonea elata*), Saw Palmetto (*Serenoa repens*), and Swamp Ferns (*Blechnum serrulatum*) occur in Collier-Seminole State Park, Collier County, southwestern Florida. Photograph courtesy of Carl Kurtz, St. Anthony, Iowa.

Figure 2.5. Common Owl Clover (*Orthocarpus purpuracens*) and Arizona Lupine (*Lupinus sparsoflorus arizonicus*), carpet the Sonoran Desert in Pima County, Arizona. Such nitrogen-fixing legumes, because they are capable of growing on dry soils, might prove to be important to agriculture. Photograph courtesy of Carl Kurtz, St. Anthony, Iowa.

Figure 2.6. Oilseed rape, *Brassica napus,* a progenitor of the relatively new crop, canola. Photograph courtesy of North Central Plant Introduction Station, Ames, Iowa.

riculture also depend on the productivity and sustainability of soils, and on a variety of services, such as pollination of crops and provision of biological control agents, that are furnished to agriculture from nearby natural or seminatural ecosystems.

The following sections will summarize the role of biodiversity and ecosystem services, both for the future of agriculture and for our quality of life. In the process, (1) the role of genetic diversity within existing crop varieties and animal breeds, (2) the need to conserve biodiversity and to develop new crops and livestock resources, and (3) the potential benefits of more diverse cropping systems for sustaining the quality of human life will be discussed.

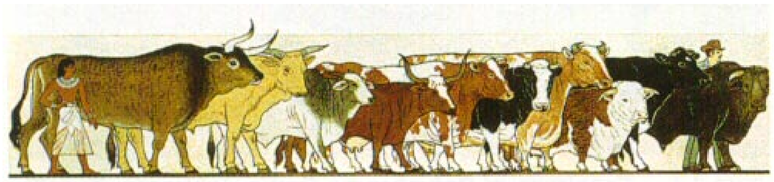


Figure 2.7. ***Evolution of Cattle,*** **Kinuko Craft. Photograph courtesy of Richard L. Willham, Iowa State University, Ames.**

3 Biodiversity in Agriculture

The diversity of crops, cropping systems, and livestock in use worldwide is one measure of the importance of biodiversity to agriculture (National Research Council, 1993a, b). These crops, livestock, and agricultural practices are the outcome of centuries of trial and error by farmers, of research on cultivation and husbandry practices, and of development of crop varieties and livestock breeds through breeding programs. This biodiversity includes different crops for different market needs. It also includes different cultivars and different mixtures of genes for pest and stress resistance, which, in turn, enable greater productivity and diversity (Buxton et al., 1993). Although the genomes of corn, sorghum, rice, wheat, barley, oats, and sugar cane, all of which are grasses, are similar, the *differences* among these genomes are of great value to agriculture. These differences can be preserved and used to the advantage of agriculture only if enough individuals of enough species are preserved, either as growing crops, in specially designed seed banks, or as wild crop relatives in native grasslands or other habitats. For instance, stem rust, which can markedly decrease wheat yields, has been controlled in the North American Great Plains since the last major epidemic in 1953 by strategic deployment of different combinations of rust-resistant genes in different cultivars (Roelfs, 1988). This control of stem rust is only possible because of the genetic diversity that has been preserved in different wheat varieties.

Diversity within each crop is essential to agriculture, as is the diversity between crops and the genetic diversity among all species on earth. Diversity within crops refers to the multitude of ancestral and domesticated forms. This diversity has two components. First are the close relatives of cultivated crops, such as the many species of wheat—einkorn, emmer, durum, spelt, goatgrass, and common wheat. Second are the different cultivated varieties of each crop, including the breeding lines that are the source of new varieties. Many of the varieties are *landraces,* which are locally used varieties of the crop developed by farmers for their own use. These landraces harbor most of the crop's genetic diversity. The world wheat collection, stored in dozens of national and international seed banks, includes 125,000 accessions (strains) that are held as an international service by the United States Department of Agriculture (USDA). Most of these strains are landraces. It is genetic diversity that has allowed wheat to be grown successfully around the world, allowing breeders to find varieties with genes that can overcome local problems such as novel diseases, insects, and climate. Genetic diversity has also been essential for maximizing and stabilizing the productivity of a crop in a given region. About half of the year-to-year increases in crop productivity result directly from genetic improvements—superior new crop varieties (Fehr, 1984). The genes that make these varieties unique come from the existing genetic variability of crops, but genetic biotechnology now potentially allows genes to be transferred to crops from any other living species.

Domestic animals of importance in the production of food, wool and other fibers, and leather are cow, sheep, pig, goat, chicken, duck, goose, salmon, trout, buffalo, yak, camel, reindeer, llama, alpaca, turkey, ostrich, game birds, and perhaps 30 more species. Each livestock species is represented by an array of genetic types known as *breeds.* Breed identity arose through regional isolation, adaptation to local stresses, genetic drift, and farmer preferences for physical or production characteristics. The Food and Agriculture Organization of the United Nations (FAO) maintains a global listing of breeds (Food and Agriculture Organization, 1995). The FAO estimates that the total number of mammalian and avian livestock breeds is between 4,000 and 5,000, approximately equal to the known number of mammal species. As with plant crops, it is these breeds, and their wild relatives, that harbor the genetic diversity on which current and future agricultural livestock production depends. Both breeds and their wild relatives merit significantly greater conservation efforts.

4 Value of Biodiversity in Crop Plants and Animals

Commercial farmers require an array of crop varieties (Duvick, 1984). Corn hybrids that perform well in Minnesota will fail in Mississippi because they lack adaptation to the shorter summer days of this southern state and have little or no resistance to Mississippi's extensive array of diseases and insect pests. Indeed, each variety of crop plant achieves its greatest yield on a particular soil type, in a region with a particular climate, in response to certain cultivation methods, or when faced with some, but not other, stresses and pests. Livestock breeds have similar differences. For instance, many Chinese landraces of pigs have evolved an enhanced ability to digest forage material, which allows them to better use crop and garden wastes as food. Genetic diversity within animal and plant crops is essential to maximize yields.

Many activities of farmers who practice subsistence or semisubsistence agriculture preserve the biodiversity of crops and livestock, indirectly demonstrating that crop diversity is of value to these farmers. Some of this value comes from the positive effects of diversity on yields and on the year-to-year stability of yields (Gliessman, 1998). For instance, farmers in Chiapas, Mexico cultivate a local maize landrace on infertile soils because modern commercial varieties do not perform well on these soils (Figures 4.1 and 4.2). Wheat farmers in Turkey continue to grow landraces of wheat because they give the highest yields on nonirrigated, hillside fields (Brush, 1991, 1995).

Diversity may help to decrease risk by decreasing the year-to-year variability of yields. For instance, landraces of wheat often have lower yield variances than many modern varieties (Brush, 1995; Food and Agriculture Organization, 1996; Jaradat, 1991). This lower variation in yields likely occurs because individual plants within a genetically variable population differ from each other. The ones favored by particular climatic and soil conditions in a given year can grow well and thus compensate for those that do poorly under those conditions. Similarly, farmers often will grow mixtures of two or more varieties as a hedge against the risk of disease or environmental stress.

These effects of diversity illustrate two general principles (Naeem and Li, 1997; Tilman et al., 1996; Tilman, 1999). First, greater diversity leads, on average, to greater productivity. This effect of diversity on productivity should occur whether the diversity comes from growing many different plant species together in a pasture or forest; from growing a mixture of genotypes (a landrace) as a crop; from growing different crops in sequence, as in crop rotation; or from maximizing the genetic diversity within each individual plant, as occurs in high-yielding crop varieties and

Figure 4.1. Hopi cornfield in September 1950 east of Moenkopi along road to Hotevilla, Arizona. Photograph courtesy of William Brown, USDA-ARS.

Figure 4.2. Ears of Hopi white landrace corn grown in 1950 in Arizona. Photograph courtesy of William Brown, USDA-ARS.

commercial hybrids. The level at which diversity is most important, and the kind of diversity that is needed, varies with the situation. For example, genetically diverse landraces are essential for farmers who must grow their crops in marginal, variable environments and who have no access to outside sources of diversity. These farmers must have plentiful diversity in their crops in the field. In contrast, commercial farmers are highly dependent on diversity in the foundation breeding pools of plant breeders who continually supply diverse new varieties to the commercial farmers, providing them with a kind of sequential diversity that has been called 'diversity in time.'

The more heterogeneous the habitat and the more that environmental conditions fluctuate during the growing season, the greater the beneficial effects of diversity. Conversely, in a spatially uniform, unchanging habitat in which a single factor always limits growth, a single strain is hypothesized to provide as great a yield as a mixture of several different strains grown together (Tilman et al., 1997). Agricultural conditions, especially climate and disease and other pests, rarely are stable and predictable. Perhaps because of this, study of maize yields and years of practical experience lead to the recommendation that a farmer's best policy is to grow several unrelated single cross hybrids with good records for stability of performance as well as high yield. Second, greater diversity leads, on average, to lower year-to-year variability in productivity; that is, to greater stability (Tilman, 1996). The ability of diversity to decrease year-to-year variability in yield means that diversity can act as crop risk insurance. Farmers may plant several different crop varieties as an additional way to decrease risk. Planting several kinds of crops, several varieties of a given crop, or a mixture of varieties as one crop increase the chance that some plants will be resistant to a disease or insect, or will perform well under existing climatic conditions. Greater crop diversity would thus decrease the odds of crop failure and may increase average yields. These features of biodiversity are greatly underutilized and merit further study and application.

Recent demonstrations of the effects of plant species diversity on productivity, stability, and sustainability (Naeem et al., 1994, 1995, 1996; Tilman, 1996; Tilman and Downing, 1994; Tilman et al., 1996, 1997) suggest that agriculture and forestry can benefit greatly from increased use of biodiversity. In particular, appropriately designed mixed-species and multispecies cropping systems have the potential to increase both long-term average yields and the stability of these yields. However, it is not clear what combination of species traits is needed for mixtures to have greater yield than that provided by the highest producing species or under what circumstances such yield gains would occur (Fukai and Trenbath, 1993; Trenbath, 1974; Vandermeer, 1989). Discovering the species traits and designs that appropriately optimize productivity, stability, and sustainability will require studies that independently manipulate diversity, species composition, and management practices, because each impacts agro-ecosystem functioning. Fruitful areas include exploration of rotational grazing of high-diversity grasslands for dairy and beef cattle production, of timber and pulp production in multispecies forest stands, of other production systems that use perennial plants, of high-diversity mixtures of a single annual crop, and of rotational diversity. In addition, precision agriculture may allow close matching of small-scale soil conditions with the crop genotypes that are optimal for them.

Biodiversity in reserve—in the form of genetically diverse breeding materials—is essential for increasing crop yields (Simmonds, 1962, 1990). Plant breeders rely on regular supplies of new material. Important breeding material comes from advanced lines, specially constructed broad-based breeding pools, and landraces. Seed banks, such as those maintained by the USDA's National Plant Germplasm System, are an important source of discontinued landraces and wild crop relatives (National Research Council, 1991).

The high rate of varietal turnover in crop plants provides strong evidence of the value of diversity in agriculture (Duvick, 1984). To be successful, new crop varieties must provide greater value than those they are to replace and they must do so repeatedly, season after season. Among crop breeders, a rule of thumb is that the less related the base-broadening germplasm is, the lower the odds of producing successful new varieties, but the higher the odds that the infrequent successes will give large advantages in yield. These large advances have had major effects on increases in agricultural production. Biodiversity is equally essential for maintaining and increasing the productivity of commercial hybrids.

Professional plant breeders use genetic diversity to protect against pest and weather problems. These problems are accentuated today because planted areas are larger and crops are more uniform, both of which contribute to the persistence and spread of disease. By using genetic diversity from anywhere in the world, breeders produce new varieties with improved pest resistance and better weather tolerance. Farmers continually experiment with new varieties, choose the best of them, and plant them extensively, often so extensively as to cause another explosive round of increased pest problems or vulnerability to unexpected weather problems. Farmers immediately switch to other varieties, if available. Thus, it is essential that crops be bred to stay ahead of (or to catch up with) continually changing and challenging disease and insect pest problems, and success depends on availability of biodiversity. Given the present massive concentration of agriculture on three crops—wheat, rice, and corn—we should be highly alert to the possibility that we could run out of ways to deal effectively with disease and insect problems of these crops. Now, more than ever, we need to apply the lessons we have learned about using biodiversity for protection against pest problems, and additionally we need more research and experimentation to find new and improved ways for use of biodiversity in the future.

Diversity is also valued in agriculture because it allows options in the future. The broader the base of crop types and of varieties within these crops, the greater are the options that farmers have available, should a current crop no longer be commercially viable. Only those farmers who have commercially viable crops that can be grown at a profit will remain in business. If a new disease, a change in climate, or a change in societal preferences eliminates a once-successful crop, farming will be able to remain in a region only if some other viable crop is on hand or can be developed quickly. This need for crop diversity, and for genetic diversity, is illustrated by the impacts of the recent scab (*Fusarium* head blight) outbreak on wheat and barley in the Red River Valley of Minnesota and North and South Dakota (McMullen et al., 1997). Wheat and barley may cease to be commercially viable in some traditional wheat and barley growing areas due to scab. Many farmers in areas where scab has been severe for 4 to 5 years are leaving agriculture because they lack alternative crops to grow profitably.

In horticultural and field crops, biodiversity has value because it can provide new traits with great economic value. For instance, wild species of tomato contributed to the cultivated tomato genes that enhanced the soluble solids and sugar content, which are traits of great commercial importance for certain tomato products (Rick and Chetelat, 1995) (Figure 4.3). Breeding organizations are selecting for, and finding, concentrations of oil in maize. In potatoes, specialized leaf hairs from a related wild species hold the promise of better insect resistance (Tingey, 1991).

Modern biotechnology has increased the value of biodiversity both within crop species and among their wild relatives because it has greatly enlarged the pool of potential sources of useful genes for crop breeding. Genes can now be moved from completely unrelated species into crop plant varieties (Tanksley and McCouch, 1997). For example, a gene that confers protection from insects was moved from bacteria to maize, cotton, and potatoes (Krattiger, 1997; Snow and Moarçn-Palma, 1997). Biotechnology thus has increased immensely the genetic biodiversity available to plant breeders, giving them the potential of using hereditary variation from the earth's vast biodiversity, not just from breeding stock or close relatives of crops. Because of biotechnology, biodiversity can contribute more than ever to agriculture. The ability to transfer to crops genes from unrelated species will clearly expand the productivity and long-term sustainability of agriculture and may well prove to be essential for the survival of modern agriculture. This means that maintaining diversity of all forms of life should be a high societal priority.

Figure 4.3. Diverse collection of fruits and flowers of wild and domesticated tomatoes. Such diversity was essential for developing tomatoes as a crop, and will be essential for it to remain a crop during the coming centuries. Photograph courtesy of North Central Regional Plant Introduction Station, Ames, Iowa.

5 Diseases, Other Pests, and Agriculture

Agriculture has transformed what were once rare plants and animals—including corn, wheat, rice, cattle, pigs, and chickens—into some of the most abundant organisms on earth. These plants and animals have, in turn, transformed humans into the dominant species on earth (Diamond, 1997). The great abundance of a few crop and animal species, though, makes these crops and livestock highly susceptible to diseases and pests. One of the best-established principles of disease dynamics is that pathogens spread more easily, and epidemics are more severe, when the hosts are more uniform and abundant. Diseases caused by fungi, bacteria, and viruses that could never be important on a rare plant host can spread epidemically through a host plant species when it is planted across hundreds of square miles. Similarly, diseases can spread epidemically through hogs, cattle, poultry, and other livestock when thousands, or tens of thousands, of individuals are grown in a single production facility. Disease problems are exacerbated if host populations have low genetic diversity in their resistance to diseases (Brown, 1983; National Research Council, 1972). Although large-scale animal production facilities can partially protect against these problems by using livestock breeds with greater disease resistance, by using a diversity of breeds, and by using procedures that minimize the chance of infection, by their very size they remain highly susceptible to catastrophic loss.

Because of the increasingly high densities and large areas over which they are grown, livestock and crop plants are continually encountering and acquiring diseases and other pests, and existing diseases and other pests are continually evolving strains that defeat the defenses of particular breeds or strains. Disease severity and occurrence are exacerbated by the accidental transport of pathogens around the world. Diseases and other pest outbreaks destabilize agricultural systems, as is currently occurring in portions of Minnesota and North and South Dakota because of *Fusarium* head blight (McMullen et al., 1997). Historically, catastrophic outbreaks of disease, invasions of insects, and climatic extremes have caused wholesale crop destruction and, at times, famines if crops had insufficient diversity to provide at least some varieties with the ability to withstand the assaults. Outbreaks of avian flu in the Chesapeake Bay area regularly result in rigorous quarantines of poultry houses due to the extremely high density of poultry farms in this region. In Hong Kong in 1998, an outbreak of a new avian flu strain to which humans seemed susceptible led to the death or destruction of hundreds of millions of chickens.

Disease problems, as old as agriculture, are recorded in myth and in written history and still exist. Red rust on wheat in Roman times, mass poisoning from ergot-tainted rye during the Middle Ages, the Irish potato famine of the nineteenth century (Figure 5.1), and the southern corn leaf blight in 1970 (Figures 5.2 and 5.3) all were caused by insufficient incorporation of biodiversity in the affected crops (Fry and Goodwin, 1997; Large, 1962; Matossian, 1989; Tatum, 1971). The severity of the 1998 Hong Kong chicken epidemic may have been exacerbated by the lack of diversity in disease resistance as well as by the high chicken densities in the production facilities.

The continual emergence of diseases can be countered only if breeders can find sufficient genetic diversity within a crop, its relatives, or some other species. Even the full complement of natural genetic variation may not be sufficient to stop some diseases. Consider, for instance, the impacts of chestnut blight, a disease caused by an introduced pathogen that devastated what was once the dominant tree of the eastern United States. Chestnut now occurs only as rare stump sprouts (Griffin, 1989). Despite the vast geographic expanse and genetic diversity of the native North American chestnut, no genetically resistant populations survived the disease. Similarly, in vast areas of West and Central Africa, livestock genetic resistance to the debilitating effects of trypanosomiasisis found only in a few unproductive local breeds. Despite massive efforts, the genetic mechanisms governing this resistance are poorly understood.

A lethal disease of corn, wheat, or rice, were it to appear and develop unchecked, could devastate agriculture and human society. The only insurance that society has against a catastrophic disease is adequate genetic variability, which comes from biodiversity. Genetic diversity within a crop plant or animal species and its relatives, or within some other organism, might allow resistant strains to be discovered and used. With genetic engineering, it may be feasible to transfer disease resistance from unrelated plants, animals, or microbes, a possibility that greatly increases the value of biodiversity to agriculture. Similarly, a broader diversity of potential food plants than currently exists might allow another species to become an effective substitute for a major crop species that was lost to disease.

Figure 5.1. Monocultures can be unstable and this can destabilize society. The engraving entitled "Searching for Potatoes in a Stubble Field" from *The Illustrated London News* illustrates the Irish potato famine tragedy caused by the fungus, *Phytophthora infestans*, during the 1840s and 1850s, which caused many deaths and the migration of many to the United States. From http://vassun.vassar.edu/~sttaylor/FAMINE/ILN/Illustrations.html

Figure 5.2. Damage to corn plants grown as a monoculture in Iowa by fungus *Helminthosporium maydis* Race T, which causes Southern Leaf Corn Blight. Photograph courtesy of Charlie A. Martinson, Iowa State University, Ames.

Figure 5.3. Stalk and leaf damage in 1970 to corn plants in Iowa by fungus *Helminthosporium maydis* Race T, which causes Southern Leaf Corn Blight. Photograph courtesy of Charlie A. Martinson, Iowa State University, Ames.

6 Factors Controlling Agricultural Diversity

Three processes have limited or decreased the genetic diversity of crops and livestock that existed at the dawn of agriculture: (1) destruction of the natural, native habitats of crops, livestock, and their relatives; (2) domestication and ensuing development of genetically uniform crop varieties and livestock breeds; and (3) farmer or consumer preferences for certain varieties and breeds of crops and animals.

Habitat destruction has caused extremely large losses of genetic diversity of direct value to crop and livestock production. Humans directly modify and use more than 40% of the earth's terrestrial ecosystems, harnessing their productivity for human benefit and modifying their composition and, often, their very existence (Vitousek et al., 1986) (Figures 6.1–6.4). Such land use practices, which are rapidly expanding, already have caused many extinctions and threaten a majority of the world's species with extinction during the coming centuries (Pimm et al., 1995). Consumer demand also has led to loss of diversity. For instance, in medieval Europe, carrots were grown with purple, yellow, white, and orange roots, but consumer demand has caused orange carrots to dominate. Thus, the loss of genetic diversity long has been a cost of agricultural development. For plants, this loss can be partially overcome by the accidental or deliberate transfer of genes from wild relatives to domesticated plants. However, as an ever-greater proportion of the earth's surface is used for agriculture and other human pursuits, the wild relatives of crop plants are becoming much rarer, decreasing both the genetic diversity preserved within the wild relatives and the chance of incorporating this diversity into crop plants. Moreover, there is no systematic monitoring of the status of important crop relatives, the persistence of which is suspected to be increasingly jeopardized in their native centers of origin.

It is possible, however, with appropriate practices, for significant genetic diversity to be maintained within some agricultural production systems, both within individual farms and among farms within a region. In the Peruvian Andes, the global center of potato diversity, a single household may grow and maintain several dozen named potato varieties from five or six different species, while many households in a valley may maintain 100 varieties (Figure 6.5). In Turkey, which is near the center of wheat diversity, an average farm household maintains two wheat varieties, with 20 or more varieties in a region. These practices occur because individual farms directly benefit from and have use for the diversity they maintain.

Genetic diversity also has been lost in livestock. The

Figure 6.1. Steep, highly erodible land plowed for growing potatoes, cabbages, and other crops near Mt. Irazu, Costa Rica. Photograph courtesy of Kayleen A. Niyo, Council for Agricultural Science and Technology, Ames, Iowa.

Figure 6.2. Farmer plowing potato field using mules; near Mt. Irazu, Costa Rica. Photograph courtesy of Erwin E. Klaas, Iowa State University, Ames.

number of breeds has markedly declined over the past half century. Up to 30% of global mammalian and avian livestock breeds (i.e., 1,200 to 1,500 breeds) are currently at risk of being lost and cannot be replaced. This declining domestic animal biodiversity has serious consequences for current livestock production and future capacity to meet unforeseen challenges and opportunities. Livestock diversity is being lost partly because of commercial production. For instance, commercial production of egg chickens, meat chickens, and turkeys is dominated by fewer than 10 multinational breeding companies. Breed-level diversity within egg- and meat-producing types is low because common breed origins and intense selection for similar production goals have promoted genetic uniformity.

Figure 6.3. Native rain forest cleared for use as pasture land, which is adjacent to a private preserve, Monteverde Cloud Forest Preserve in Costa Rica. Photograph courtesy of Kayleen A. Niyo, Council for Agricultural Science and Technology, Ames, Iowa.

Figure 6.4. A private preserve, Monteverde Cloud Forest Preserve, in Costa Rica is owned and administered by the Tropical Science Center of San Jose, Costa Rica. Photograph courtesy of Erwin E. Klaas, Iowa State University, Ames.

Similarly, China possesses at least 50, and perhaps over 100, unique pig breeds, but many of these are becoming endangered as they are replaced with western breeds.

Much of livestock's genetic diversity is maintained by hobbyists for noneconomic reasons. This is inadequate because there are no formal mechanisms to assure that the genetic diversity needed to overcome escalating disease problems in livestock will be preserved for future generations. Moreover, the luxury of hobby production of livestock does not exist in the developing nations where most livestock diversity is found. Just as importantly, habitats that sustain the wild relatives of livestock species are not adequately protected.

Commercial breeds of livestock possess greater genetic variability than most crop varieties do. This greater genetic diversity allows intensification of selection within breeds to be a fruitful approach for improving livestock productivity. However, if continued emphasis on breed replacement and increasing selection intensity come at the expense of maintenance of genetic diversity, including disease resistance and environmental adaptation, there may be significant long-term costs. For instance, Holstein cattle have become the preeminent dairy breed worldwide and have enjoyed sustained improvements in milk production potential, but only at the cost of declining genetic diversity within the breed. It is imperative that the genetic diversity of rare and endangered livestock breeds and their wild relatives and ancestral lines be preserved as insurance for future needs, especially for the genetic control of new diseases and parasites.

Figure 6.5. Diverse collection of Andean potato tubers. Such genetic diversity is continually used to help keep a crop "ahead" of its pathogens. Photograph courtesy of John Bamberg, USDA-ARS, Sturgeon Bay, Wisconsin.

7 Ecosystem Services: Other Benefits of Biodiversity

Even relatively simple natural ecosystems, such as the tallgrass prairies of the American Midwest, contain hundreds of highly variable plant species, thousands of pollinator and other insect species, and tens of thousands of species of soil bacteria, fungi, and other organisms (Figure 7.1). In comparison, agricultural systems have low diversity (Figure 7.2). People derive a wide array of important economic and life-support benefits from biodiversity. Many of these benefits are described by the term *ecosystem services*, which refers to the wide range of ways that natural ecosystems, and the species they contain, produce services that sustain and fulfill human life. In addition, natural ecosystems provide aesthetic beauty and intellectual stimulation that lift the human spirit. Natural ecosystems also yield goods, such as seafood, wild game, forage, timber, biomass fuels, and natural fibers, as well as pharmaceuticals, industrial products, and their precursors. These goods represent an important part of the economy, and their sustained production is a service provided to society at low or no cost by natural ecosystems.

Ecosystem services include many critical life-support functions on which the productivity of agricultural activities depends: (1) purification of air and water, (2) mitigation of droughts and floods, (3) generation and preservation of soils and renewal of their fertility, (4) detoxification and decomposition of wastes, (5) pollination of crops and natural vegetation, (6) cycling and movement of nutrients, (7) control of most potential agricultural pests, (8) protection from harmful ultraviolet rays, (9) partial stabilization of the climate, (10) moderation of weather extremes and their impacts, and (11) maintenance of biodiversity.

The value of these biodiversity-dependent goods and services is difficult to quantify but tremendous. A partial list of these goods and services (from Daily, 1997) includes the following.

- *Biodiversity's "genetic library"*: Accounts for about half of the annual increases in crop productivity and is key to our capacity to respond to diseases and other pests.
- *Pollination*: About half of all plant species, including food-producing crop species, are pollinated by animals. There are more than 100,000 known pollinators (bees, butterflies, beetles, birds, flies, bats) (Figures 7.3–7.7). The agricultural value of pollination services in the United States is estimated in billions of dollars per year.

Figure 7.1. A high diversity ecosystem, such as this Iowa prairie, may contain and preserve several hundred plant species. Here, compass plants (*Silphium laciniatum*) and Tall Blazing Stars (*Liatris pycnostachya*) in virgin tallgrass prairie at Doolittle Pothole Prairie, Story County, central Iowa. Photograph courtesy of Carl Kurtz, St. Anthony, Iowa.

Figure 7.2. Soybeans in early summer being grown as a monoculture in Hardin County, northwestern Iowa. Photograph courtesy of Carl Kurtz, St. Anthony, Iowa.

- *Pest control:* More than 25% of the world's crop production is destroyed by pests annually (Figures 7.8 and 7.9). More than 90% of potential crop insect pests are controlled by natural enemies that live in natural and seminatural areas adjacent to farmlands. The substitution of pesticides for natural pest control services is estimated to cost $54 billion per year.
- *Native grasslands:* Provide forage for livestock and are the original source habitat of many domestic animals and crops.
- *Pharmaceuticals:* Of the 150 most common prescription drugs used in the United States, 118 are based on compounds derived from natural sources.
- *Fisheries:* The annual world catch, worth more than $50 billion, is a major source of animal protein.

Figure 7.3. Monarch butterfly (*Danaus plexippus*) pollinating Dense Blazing Star (*Liatris spicata*) in a native Iowa prairie. Photograph courtesy of Carl Kurtz, St. Anthony, Iowa.

Figure 7.4. Craig Abel positioning a bumblebee domicile inside a cage for controlled pollination at the North Central Regional Plant Introduction Station. Photograph courtesy of Scott Bauer, USDA-ARS.

Figure 7.5. Honeybee pollinating a zinnia flower. Photograph courtesy of Scott Bauer, USDA-ARS.

Figure 7.6. Black-chinned Hummingbird (***Archilochus alexandri***) pollinating Parry's Penstemon (***Penstemon parryi***) in the Sonoran Desert in Pima County, Arizona. Photograph courtesy of Carl Kurtz, St. Anthony, Iowa.

Figure 7.7. White-lined sphinx moth (***Hyles lineata***) pollinating a tubular flower in the Iowa State University Horticulture Garden, Ames, Iowa. Photograph courtesy of Carl Kurtz, St. Anthony, Iowa.

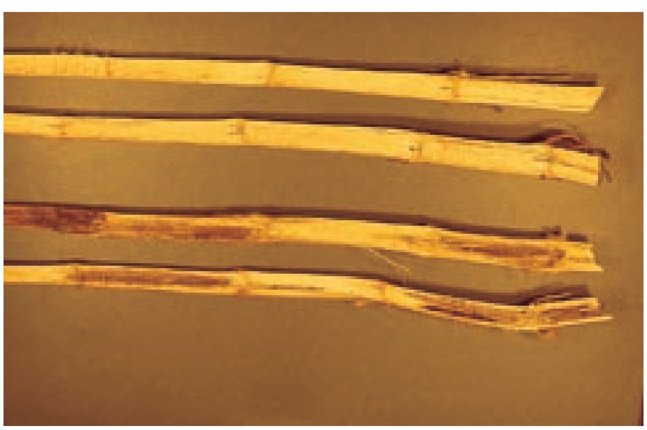


Figure 7.8. Results of stalk feeding by European Corn Borer in resistant and susceptible corn lines. Photograph courtesy of Richard L. Wilson, USDA-ARS.

Figure 7.9. Leaf feeding damage on a young corn plant by European corn borer. Photograph courtesy of Richard L. Wilson, USDA-ARS.

8 The Economic Value of Biodiversity for Agriculture and Society

Ecosystem services may be worth trillions of dollars annually (Costanza et al., 1997), but are not traded in markets and carry no price tags to alert society to changes in their supply or to deterioration of the ecological systems that generate them. Escalating human impacts on natural ecosystems imperil the delivery of these services. The services provided by biodiversity to agriculture have great current and future economic value. Biodiversity contributes to the resilience and productivity of ecosystems, including agroecosystems, by providing genetic variants of commercial crops and livestock that are resistant to diseases and emerging stresses. These variants act as "insurance" against major losses in productivity of crop plants and livestock. The insurance role of the genetic variation associated with biodiversity becomes apparent in a crisis, and in crises, its value is immense.

Biodiversity also provides inputs for agriculture without which production either would not occur or would be greatly decreased. These include soil fertility, pollination, pest control, and water for irrigation and livestock consumption. Pest control depends heavily on the mosaic of natural and seminatural ecosystems that border agricultural fields and serve as a reservoir of biological control agents. These inputs from biodiversity depend largely on the services provided by nearby natural ecosystems that, in turn, both depend on and house biodiversity. All have traditionally been provided at no cost by the natural environment, but their continuation is threatened by land use practices, especially high-intensity agriculture and forestry, conversion or destruction of natural ecosystems and ecosystem fragments, and homogenization of rural landscapes.

In economic terms, natural ecosystems may be considered capital assets—a form of "natural capital." Like other forms of capital, if properly nurtured, ecosystems provide a flow of valuable goods and services over time. Compared to record-keeping of human, financial, and physical capital, little account has been taken of the natural capital stocks (ecosystems and their biodiversity) that supply ecosystem services.

9 Preservation of Agricultural Biodiversity in Germplasm Collections

The genetic diversity of a species is called its *germplasm*. Farmers have always conserved germplasm by the act of saving seed to replant their local crop varieties, or *landraces*, and by maintaining breeding stock for livestock species. This is called *in situ*, or on the farm, conservation. During the 1900s, a system of specially designed seed storage facilities (seed banks) has been developed to better ensure long-term conservation of crop plant germplasm from many parts of the world. Seed bank conservation is often called *ex situ* conservation. The seed banks hold large collections of landraces and wild relatives of crop species, as well as modern crop varieties and special breeding stocks. Professional plant breeders at first collected landraces for use in new locations or for use as breeding materials to develop new varieties. But when the new professionally bred varieties began to displace landraces on a large scale, breeders realized that their landrace collections must be enlarged and preserved indefinitely as sources of genetic diversity for future breeding operations.

In the 1920s, N. I. Vavilov in the Soviet Union established one of the first formally organized seed banks. The USDA began the National Plant Germplasm System (NPGS) in the 1940s with the establishment of Regional Plant Introduction Stations (seed banks) (Figures 9.1 and 9.2). The National Seed Storage Laboratory (NSSL) in Fort Collins, Colorado opened in 1958 (National Research Council, 1993a). Soon thereafter, many other nations organized seed banks, and several research centers of the Consultative Group on International Agricultural Research (CGIAR) organized their own collections.

Major national or international collections occur in the United States, China, Russia, Japan, India, Mexico, the Philippines, Peru, and other nations. The five largest national collections totaled 1,418,800 accessions in 1993. (An accession is a distinct, identifiable sample of seed, such as an individual landrace.) The seven largest international center collections totaled 480,500 accessions (National Research Council, 1993a). Large collections now exist for wheat, rice, maize, soybean, potato, tomato, sorghum, legumes and many more of the world's grain, fruit, vegetable, fiber, forest, and industrial crops. Global accession totals for wheat, rice, maize, and soybean were 125,000, 250,000, 100,000, and 100,000, respectively (National Research Council, 1993a).

The total number of accessions unfortunately is not an indication that the collections are adequate, or that

Figure 9.1. A seed bank in action: Lisa Burke filling a seed order in cold storage at the North Central Regional Plant Introduction Station, Ames, Iowa.

Figure 9.2. Maintaining genetic diversity in a seed bank: Mark Widrlechner and Charles Block inspecting field cages for controlled pollination of cucurbit germplasm by honeybees at the North Central Regional Plant Introduction Station, Ames, Iowa. Photograph courtesy of Scott Bauer, USDA-ARS.

they can be maintained in good condition. During the past decade, funding for many seed banks has declined precipitously and, for others, has not been sufficient for proper maintenance and use of the collections (Raeburn, 1995). The United States is among the nations that have not provided enough funding for their national germplasm collections. Repeated statements of need, often from committees of distinguished outside experts, have elicited meager or no results.

The second essential form of germplasm conservation, on-farm (*in situ*) conservation, is in even poorer condition than the seed banks. The concept of systematic on-farm conservation is relatively new, its organization is almost nonexistent, and practical methods of cataloguing or accessing such diversity are not yet developed. Interest in on-farm conservation is increasing, however. If funding were available, *in situ* conservation could develop into a viable complement to *ex situ* conservation (Altieri and Merrick, 1987; Bretting and Duvick, 1997; Brush, 1995).

A few private, not-for-profit seed banks have been founded but they tend to be ephemeral, due primarily to funding problems. An exception to this rule is the Seed Savers Exchange, Inc. of Decorah, Iowa, now in its fourteenth year, and with about 11,000 varieties of vegetable and horticultural accessions in its collections. There is potential for complementary activity between private seed banks and the NPGS.

Much less attention has been paid to conserving the genetic diversity of livestock species, despite the importance of this genetic diversity for livestock production and its sustainability and stability. The current dependence on *in situ* conservation by hobbyists is inadequate. Formal government-sponsored international programs for *in situ* and *ex situ* preservation of livestock genetic diversity must be established. In addition, the native habitats of the wild relatives of livestock species must be preserved.

Likewise, too little attention has been paid to conserving microbial germplasm, yet microorganisms represent an enormous genetic resource for use in agriculture. Agricultural productivity and sustainability benefit from microorganisms in many ways, including the *Rhizobium* symbionts that convert atmospheric nitrogen into ammonium for use by plants, the mycorrhizal fungi that help plants take up phosphorus and other relatively immobile nutrients, the many microbial pathogens that provide biological control of insect pests and weeds, and the plant-associated microorganisms that provide plant growth factors or help defend plants against diseases and insect attack. The great diversity of these and the many other kinds of beneficial microorganisms offers numerous opportunities for improvements in their performance, either through natural selection or genetic modifications. Equally importantly, these microorganisms represent a great diversity of novel genes for plant improvement, such as the Bt genes already transferred from strains of the insect pathogen, *Bacillum thuringiensis*, to corn, potato, and cotton for control of certain insect pests. Microbial collections are currently maintained by the USDA's Agricultural Research Service and by the public-private American Type Culture Collection. In many cases, however, valuable microbial collections representing a lifetime of work by university faculty members are lost when those faculty members retire, again due to funding problems. Public support for culture collections is essential if this biological resource is to be maintained and made widely available for use in agriculture.

10 Conclusions

Complex human societies have existed for at least five millennia. Like modern society, these civilizations have depended on agriculture. The agricultural successes and advances that sustained these societies have depended on biodiversity. So, too, will it be in the future. However, the rapid expansion of human activities is having unprecedented impacts on a global scale (Vitousek et al., 1997). Humans control, and use for their benefit, almost half of the world's land surface. Humans dominate the global cycles of nitrogen, carbon, and water, and are changing global climate. Such activities of modern societies, including the destruction of native habitats and their fragmentation into ever-smaller areas, have initiated an episode of extinctions that may prove to be the most extreme extinction event ever (Figures 10.1–10.3). Indeed, the current rate of species extinctions is at least a thousand times faster than at any time within the last 10,000 years (Pimm et al., 1995). It exceeds, by a similar factor, the rate at which new species form. Long before species are driven to extinction, decreases in the population sizes of wild relatives of crops, livestock, and other species cause loss of genetic diversity. If our current society is to provide future generations with the same opportunities that we enjoy, it is essential that we invest much more in preserving the earth's genetic, species, and ecosystem biodiversity.

This preservation of biodiversity will require three distinct programs, each of which is essential to its success. First, the current agricultural germplasm collection programs should be greatly expanded. Second, more biodiversity reserves should be established, worldwide, throughout representative samples of the

Figure 10.1. Mixed agricultural landscape with banana and coffee plants, which retains significant biodiversity, near Las Cruces, Costa Rica. Photograph courtesy of Gretchen C. Daily, Stanford University, Stanford, California.

Figure 10.2. Intensively grown banana plants in a monoculture plantation near Puerto Viejo, Costa Rica that is very low in biodiversity. Photograph courtesy of Gretchen C. Daily, Stanford University, Stanford, California.

full diversity of the world's ecosystems. Third, rural landscapes should be maintained and managed to have a mixture of agricultural and natural ecosystems that can preserve much of local biodiversity and provide ecosystem services essential to agriculture.

Existing germplasm collections are unable to fulfill their original mission because they are underfunded. Moreover, their mission needs to be expanded to include formal *in situ* (on the farm) preservation of both crops and wild crop relatives. Furthermore, both the *in situ* and *ex situ* approaches to germplasm preservation must be formally expanded to major livestock species and their wild relatives. The long-term sustainability, stability, and productivity of agriculture—and of modern society—requires, first and foremost, that the full biodiversity of plant and animal crop germplasm be preserved.

In addition to crop germplasm preservation, it is essential that society preserve the biodiversity of both natural ecosystems and agricultural landscapes. Because of advances in biotechnology, the full genetic diversity of natural ecosystems is now potentially available to help solve agricultural problems. Moreover, these ecosystems provide agriculture and society with a variety of vital, and valuable, ecosystem services, the provision of which depends on the preservation of their biodiversity.

Investments in preserving natural capital could yield net payoffs in both agricultural productivity and profitability. Such investments should be considered in any economic cost-benefit analyses of alternative production regimes. The major way to preserve terrestrial diversity is to maintain large blocks of land in native ecosystems. If such biodiversity reserves are appropriately distributed, they can save much of the biological capital upon which future generations will depend and would simultaneously provide valuable ecosystem services to society. Such reserves occur in national and regional parks, in wilderness areas, and in privately held lands that are maintained as natural ecosystems (Figures 10.4–10.10). However, a much larger network of reserves is needed, worldwide, to prevent massive, human-caused extinction of species and loss of genetic diversity (Dobson et al., 1997; Reid, 1992; Tilman et al., 1994). It is essential that this expanded network of biodiversity reserves be created soon because human activities are rapidly destroying suitable sites.

In addition, rural and agricultural landscapes, if properly designed and managed, can preserve a sig-

Figure 10.3. Banana plants grown in large-scale monoculture plantations require large amounts of water, nutrients, and pesticides to produce saleable fruit. Photograph courtesy of Gretchen C. Daily, Stanford University, Stanford, California

Figure 10.4. Preservation of natural ecosystems saves most of their biodiversity. Here, Miterwort (*Mitella diphylla*), Woodland Phlox (*Phlox divaricata*), Maidenhair Fern (*Adiantum pedatum*), and Great Solomon's Seal (*Polygonatum biflorum*) at Dolliver Memorial State Park, Webster County, north central Iowa. Photograph courtesy of Carl Kurtz, St. Anthony, Iowa.

nificant amount of biodiversity. Indeed, the conservation of some species may depend on agricultural landscapes. Biologists most often study the biodiversity of natural habitats rather than agricultural rural or urban landscapes. It is plausible that many species could be maintained in mixed agricultural landscapes of intermediate intensity, but only if they are properly managed. For instance, a coffee- and cattle-producing region of Costa Rica that retains about 25% of its original forest cover still harbors almost half of the native forest bird, butterfly, and moth fauna. The other half, though, will be kept from extinction only if it

Figure 10.5. Fireball lily (*Scadoxus multiflorus*), a member of the Amaryllis family, in open grassland of the Serengeti National Park, Tanzania, East Africa. Photograph courtesy of Carl Kurtz, St. Anthony, Iowa.

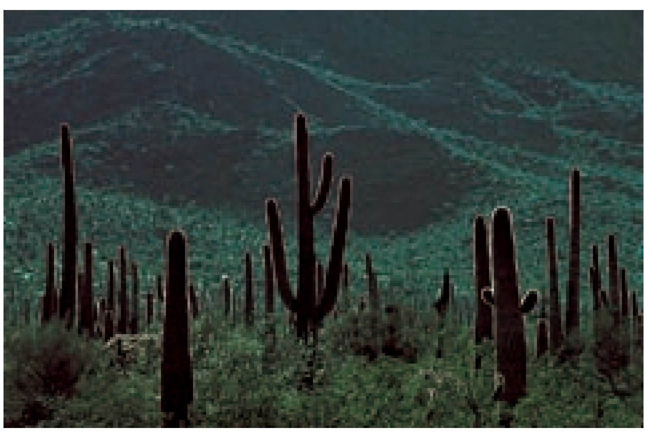


Figure 10.6. Sagauro (*Carnegiea gigantea*) forest on Ajo Mountain Drive in Organ Pipe National Monument in Arizona is a diverse ecosystem that contains many species with unique abilities to withstand drought and heat. Photograph courtesy of Carl Kurtz, St. Anthony, Iowa.

Figure 10.7. Regal Fritillary (*Speyeria idalia*) on Rough Blazing Star (*Liatris aspera*) at Kish-Ke-Kost Sand Prairie State Preserve, Jasper County, south central Iowa. Photograph courtesy of Carl Kurtz, St. Anthony, Iowa.

Figure 10.8. Stiff-leaved Wildpine (*Tillandsia fasciculata*) on Pond Cypress (*Taxodium distichum nutans*) in Corkscrew Swamp, a National Audubon Society sanctuary in southwestern Florida. Photograph courtesy of Carl Kurtz, St. Anthony, Iowa.

is retained in larger nature reserves. The capacity of rural landscapes to sustain biodiversity and ecosystem services depends on maintaining hedgerows/windbreaks; leaving tracts of land in native habitat; planting a diversity of crops; decreasing the amount of tillage; pastoral activities; mixed-species forestry; using diverse, native grasslands; matching livestock to the production environment; and using integrated pest management techniques.

In total, it is imperative that society significantly increase its investments in preserving the full range of biodiversity. The productivity, stability, and sustainability of agriculture and of ecosystem services vital to society depend on biodiversity. Once lost, biodiversity can never be recreated. Rapidly expanding human activities are causing the permanent and irreversible loss of the biological capital—biodiversity—upon which modern human society is based. The stewardship of biodiversity is an unavoidable permanent obligation of modern society.

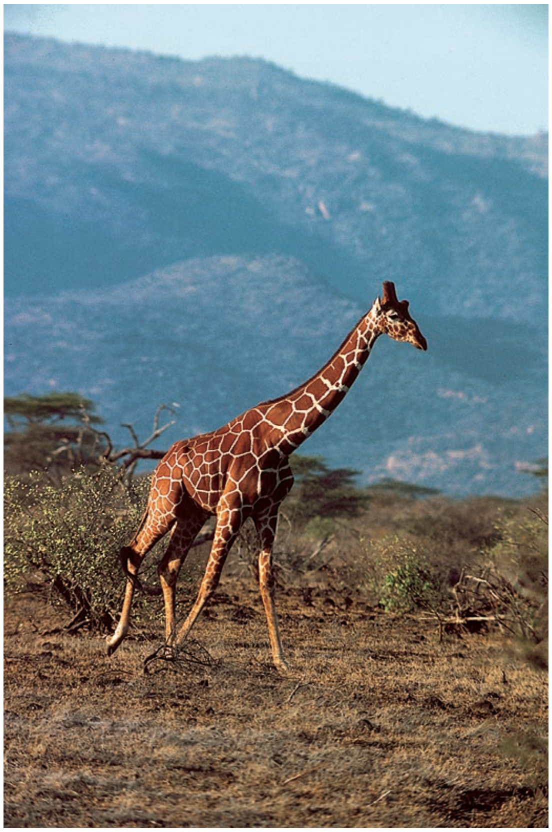


Figure 10.9. A reticulated giraffe (*Giraffa reticulata*) on the grasslands in Samburu-Buffalo Springs-Shaba National Park, Kenya, East Africa. Photograph courtesy of Carl Kurtz, St. Anthony, Iowa.

Figure 10.10. Cabbage Groundsel (*Senecio brassica*) and broad-leafed lobelias (*Lobelia keniensis*) in alpine moorland of Mt. Kenya National Park, Kenya, East Africa. Photograph courtesy of Carl Kurtz, St. Anthony, Iowa.

Appendix A: Acronyms

CGIAR	Consultative Group on International Agricultural Research
FAO	Food and Agriculture Organization of the United Nations
FERRO	Far Eastern Regional Research Organization, New Delhi, India
ISAAA	International Service for the Acquisition of Agrobiotech Applications, Ithaca, New York
NPGS	National Plant Germplasm System
NSSL	National Seed Storage Laboratory, Fort Collins, Colorado
OICD	Office of International Cooperation and Development, USDA
USDA	United States Department of Agriculture

Appendix B: Glossary

Accessions. A distinct, identifiable sample of seed, such as an individual landrace.

Biodiversity. Biological diversity refers to all forms of life, including all species and genetic variants within species and all ecosystems that contain and sustain those diverse forms of life.

Breeds. Each livestock species that is represented by an array of genetic types known as breeds.

Centers of origin. Geographic location where species evolved and lived in natural ecosystems.

Ecosystem services. A wide range of ways that ecosystems, and the species they contain, produce services that sustain and fulfill human life.

Genetic drift. A change in gene frequency in a population caused by its small size and random birth and death processes.

Germplasm. The genetic diversity of a species.

Landraces. Locally used varieties of a crop developed by farmers for their own use.

Literature Cited

Altieri, M. A. and L. C. Merrick. 1987. *In situ* conservation of crop genetic resources through maintenance of traditional farming systems. *Econ Botany* 41:86–96.

Bretting, P. K. and D. N. Duvick. 1997. Dynamic Conservation of Plant Genetic Resources. Pp. 2–51. In D. N. Sparks (Ed.). *Advances in Agronomy*. Vol. 61. Academic Press, San Diego.

Brown, W. L. 1983. Genetic diversity and genetic vulnerability—An appraisal. *Econ Botany* 37:1–12.

Brush, S. B. 1991. A farmer-based approach to conserving crop germplasm. *Econ Botany* 45:153–165.

Brush, S. B. 1995. *In situ* conservation of landraces in centers of crop diversity. *Crop Sci* 35:346–354.

Buxton, D. R., R. Shibles, R. A. Forsberg, B. L. Blad, K. H. Asay, G. M. Paulsen, and R. F. Wilson (Eds.). 1993. *International Crop Science I.* Vol. I. Pp. 1–895. Crop Science Society of America, Inc., Madison, Wisconsin.

Costanza, R., R. d'Arge, R. de Groot, S. Farber, M. Grasso, B. Hannon, K. Limburg, S. Naeem, R. V. O'Neill, J. Paruelo, R. G. Raskin, P. Sutton, and M. van den Belt. 1997. The value of the world's ecosystem services and natural capital. *Nature* 387:253–260.

Daily, G. C. 1997. *Nature's Services: Societal Dependence on Natural Ecosystems.* Island Press, Washington, D.C., Covelo, California.

Diamond, J. 1997. Location, location, location: The first farmers. *Science* 278:1243–1244.

Dobson, A. P., A. D. Bradshaw, and A. J. M. Baker. 1997. Hopes for the future: Restoration ecology and conservation biology. *Science* 277:515–522.

Duvick, D. N. 1984. Genetic diversity in major farm crops on the farm and in reserve. *Econ Botany* 38:161–178.

Food and Agriculture Organization of the United Nations. 1995. *World Watch List for Domestic Animal Diversity*. 2nd ed. Food and Agriculture Organization, Rome, Italy.

Food and Agriculture Organization of the United Nations. 1996. *Report on the State of the World's Plant Genetic Resources for Food and Agriculture.* Prepared for the International Technical Conference on Plant Genetic Resources, Leipzig, Germany, June 17-23, 1996. Food and Agriculture Organization, Rome, Italy.

Fehr, W. H. (Ed.). 1984. *Genetic Contributions to Yield Gains of Five Major Crop Plants*, Pp. 1–101. Crop Science Society of America, Inc., Madison, Wisconsin.

Fry, W. E. and S. B. Goodwin. 1997. Resurgence of the Irish potato famine fungus. *BioScience* 47:363–371.

Fukai, S. and B. R. Trenbath. 1993. Processes determining intercrop productivity and yields of component crops. *Field Crops Res.* 34:247–271.

Gliessman, S. 1998. *Agroecology: The Ecological Basis of Sustainable Agriculture.* Ann Arbor Press, Chelsea, Michigan.

Griffin, G. J. 1989. Incidence of chestnut blight and survival of American Chestnut in forest clearcut and neighboring understory sites. *Plant Dis* 73:123–127.

Jaradat, A. 1991. Regional assessment of sustainable landuse systems research: The Middle East and North Africa. In B. Hart (Ed.). *Proceedings of the International Workshop on Sustainable Landuse Systems Research*. USDA/Office of International Cooperation and Development (OICD)/Far Eastern Regional Research Organization (FERRO), New Delhi, India.

Krattiger, A. F. 1997. *Insect resistance in crops: A case study of Bacillus thuringiensis (Bt) and its transfer to developing countries*. Report No. 2. International Service for the Acquisition of Agri-biotech Applications (ISAAA), Ithaca, New York.

Large, E. C. 1962. *The Advance of the Fungi.* Dover Publications, New York.

Matossian, M. K. 1989. *Poisons of the Past: Molds, Epidemics, and History*. Yale University Press, New Haven, Connecticut, and London, England.

May, R. M. 1999. The dimensions of life on earth. *Proceedings of National Biodiversity Forum*. National Academy Press, Washington, D.C. In press.

McMullan, M., R. Jones and D. Gallenberg. 1997. Scab of wheat and barley: A re-emerging disease of devastating impact. *Plant Dis* 81:1340–1348.

National Research Council. 1972. *Genetic Vulnerability of Major Crops.* National Academy Press, Washington, D.C.

National Research Council, Board on Agriculture. 1991. *Managing Global Genetic Resources: The U.S. National Plant Germplasm System*. National Academy Press, Washington, D.C.

National Research Council, Board on Agriculture. 1993a. *Managing Global Genetic Resources: Agricultural Crop Issues and Policies.* National Academy Press, Washington, D.C.

National Research Council, Board on Agriculture. 1993b. *Managing Global Genetic Resources: Livestock*. National Academy Press, Washington, D.C.

Naeem, S. and S. Li. 1997. Biodiversity enhances ecosystem reliability. *Nature* 390:507–509.

Naeem, S., L. J. Thompson, S. P. Lawler, J. H. Lawton, and R. M. Woodfin. 1994. Declining biodiversity can alter the performance of ecosystems. *Nature* 368:734–737.

Naeem, S., L. J. Thompson, S. P. Lawler, J. H. Lawton, and R. M. Woodfin. 1995. Empirical evidence that declining species diversity may alter the performance of terrestrial ecosystems. *Phil. Trans R Soc Lond B* 347:249–262.

Naeem, S., K. Håkenson, J. H. Lawton, M. J. Crawley, and L. J. Thompson. 1996. Biodiversity and plant productivity in a model assemblage of plant species. *Oikos* 76:259–264.

Pimm, S. L., G. J. Russell, J. L. Gittleman, and T. M. Brooks. 1995. The future of biodiversity. *Science* 269:347–350.

Raeburn, P. 1995. *The Last Harvest*. Simon & Schuster, New York.

Reid, W. V. 1992. Pp. 55–73. In T. C. Whitmore and J. A. Sayer (Eds.). *Tropical Deforestation and Species Extinction.* Chapman & Hall, London, England.

Rick, C. M. and R. T. Chetelat. 1995. Utilization of related wild species for tomato improvement. *Acta Hortic* 412:21–38.

Roelfs, A. P. 1988. Genetic control of phenotypes in wheat stem rust. *Annu Rev Phytopathol* 26:351–367.

Simmonds, N. W. 1962. Variability in crop plants, its use and conservation. *Biol Rev* 37:422–465.

Simmonds, N. W. 1990. Uniformity and yield in hybrid crop cultivars. *Trop Agric (Trinidad)* 68:198–199.

Snow, A. A. and P. Moarçn-Palma. 1997. Commercialization of transgenic plants: Potential ecological risks. *BioScience* 47:86–96.

Tanksley, S. D. and S. R. McCouch. 1997. Seed banks and molecular maps: Unlocking genetic potential from the wild. *Science* 277:1063–1066.

Tatum, L. A. 1971. The southern corn leaf blight epidemic. *Science* 171:1113–1116.

Tilman, D. 1996. Biodiversity: Population versus ecosystem stability. *Ecology* 77(3):350–363.

Tilman, D. 1999. The Consequences of Biodiversity: A Search for General Principles. *Ecology*, in press.

Tilman, D. and J. A. Downing. 1994. Biodiversity and stability in grasslands. *Nature* 367:363–365.

Tilman, D., C. L. Lehman, and K. T. Thomson. 1997. Plant diversity and ecosystem productivity: theoretical considerations. *Proc Natl Acad Sci* 94:1857–1861.

Tilman, D., D. Wedin, and J. Knops. 1996. Productivity and sustainability influenced by biodiversity in grassland ecosystems. *Nature* 379:718–720.

Tilman, D., R. M. May, C. L. Lehman, and M. A. Nowak. 1994. Habitat destruction and the extinction debt. *Nature* 371:65–66.

Tilman, D., J. Knops, D. Wedin, P. Reich, M. Ritchie and E. Siemann. 1997. The influence of functional diversity and composition on ecosystem processes. *Science* 277:1300–1302.

Tingey, W. 1991. Potato glandular trichomes: Defensive activity against insect attack. Pp. 126–135. In P. Hedin (Ed.). *Naturally Occurring Pest Bioregulators*. American Chemical Society (ACS) Symposium Series Vol. 449. ACS Books, Washington, D.C.

Trenbath, B. R. 1974. Biomass productivity of mixtures. *Adv Agron* 26:177–210.

Vandermeer, J. 1989. *The Ecology of Intercropping*. Cambridge University Press, Cambridge, England.

Vitousek, P. M., P. R. Ehrlich, A. H. Ehrlich, and P. A. Matson. 1986. Human appropriation of the products of photosynthesis. *BioScience* 36:368–373.

Vitousek, P. M., H. A. Mooney, J. Lubchenco, and J. M. Melillo. 1997. Human domination of earth's ecosystems. *Science* 277:494–499.

Index