Animal Agriculture
AND GLOBAL FOOD SUPPLY

Animal Agriculture and Global Food Supply

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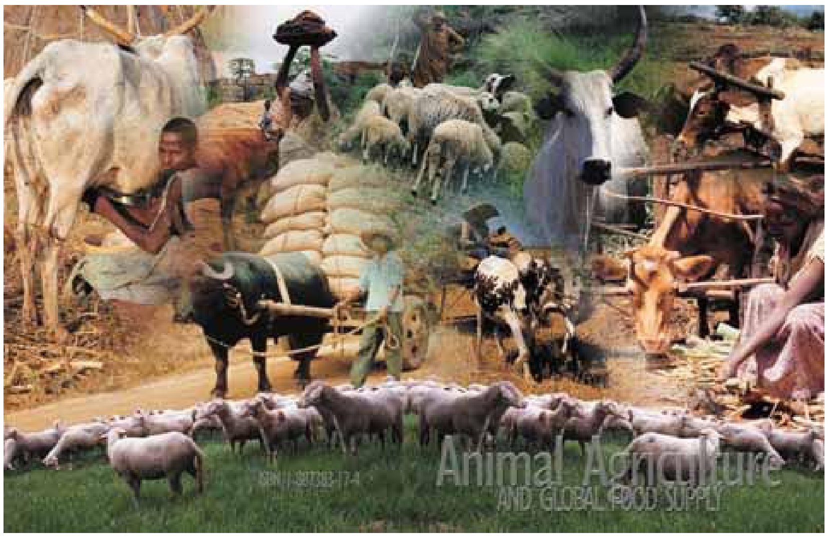
Cover



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Lower Back and Front Cover

Pastoral scene with sheep grazing in a lush pasture in the United States.

Back Cover (Left)

Upper left photograph. Milking a White Fulani cow in Nigeria. Photograph courtesy of David Elsworth, International Livestock Research Institute, Nairobi, Kenya.

Upper right photograph. Dung collection to use for fuel and land application in Nigeria. Photograph courtesy of David Elsworth, International Livestock Research Institute, Nairobi, Kenya.

Lower right photograph. Buffalo used for transportation in China. Photograph courtesy of Eric Bradford, University of California, Davis.

Front Cover (Right)

Upper left photograph. Smallholder sheep flock in the High Atlas Range in Morocco. Photograph courtesy of Eric Bradford, University of California, Davis.

Center photograph. A White Fulani cow, named after the Fulani people in Nigeria who herd them. Photograph courtesy of David Elsworth, International Livestock Research Institute, Nairobi, Kenya.

Upper right photograph. Akamba people in the Machakos District of Kenya using oxen for plowing. Photograph courtesy of David Elsworth, International Livestock Research Institute, Nairobi, Kenya.

Lower left photograph. Millet transported by oxen near Niamey in Niger. Photograph courtesy of David Elsworth, International Livestock Research Institute, Nairobi, Kenya.

Lower right photograph. Stall feeding of maize residue in a smallholder dairy in Kenya. Photograph courtesy of David Elsworth, International Livestock Research Institute, Nairobi, Kenya.

Task Force Members

Eric Bradford (Chair), Department of Animal Science, University of California, Davis

R. Lee Baldwin, Department of Animal Science, University of California, Davis

Harvey Blackburn, U.S. Sheep Experiment Station, U.S. Department of Agriculture, Agricultural Research Service, Dubois, Idaho

Kenneth G. Cassman, Agronomy Department, University of Nebraska, Lincoln

Pierre R. Crosson, Resources for the Future, Washington, D.C.

Christopher L. Delgado, International Food Policy Research Institute, Washington, D.C.

James G. Fadel, Department of Animal Science, University of California, Davis

Henry A. Fitzhugh, International Livestock Research Institute, Nairobi, Kenya

Margaret Gill, Natural Resources International, Chatham, U.K.

James W. Oltjen, Department of Animal Science, University of California, Davis

Mark W. Rosegrant, International Food Policy Research Institute, Washington, D.C.

Martin Vavra, Eastern Oregon Agricultural Research Center, Oregon State University, Burns

Robert O. Wilson, College of Veterinary Medicine, Oregon State University, Corvallis

Contents

Figures

Tables

Foreword

Following a recommendation by the CAST National Concerns Committee, the CAST Board of Directors authorized preparation of a report on animal agriculture and the food supply in the world.

Dr. G. Eric Bradford, Department of Animal Science, University of California, Davis, served as chair 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 agricultural economics, agronomy, animal sciences, environmental issues, international food policy, international livestock research, nutritional sciences, range science, and veterinary medicine.

The task force met and prepared an initial draft of the report. They revised all subsequent drafts and 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 chair and the authors 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. CAST recognizes and appreciates the financial support of the U.S. Department of Agriculture/Cooperative State Research, Education, and Extension Service (USDA/CSREES) and the USDA/Agricultural Research Service (ARS) to partially assist in the development and completion of this report. CAST thanks all members who made additional contributions to assist in the preparation of this document. 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, the Office of Science and Technology Policy, 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

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Interpretive Summary

Animal agriculture is an integral part of food-producing systems, with foods of animal origin representing about one-sixth of human food energy and one-third of the human food protein on a global basis. Animals convert forages, crop residues, and food and fiber processing by-products to high quality human food; provide draught power for about half the world's crop production; and provide manure to help maintain soil fertility. Animal production makes important contributions to agricultural economies throughout the world and to food security in developing countries.

Animals also consume one-third of the global cereal grain supply. In a world with human population forecast to reach 7.7 billion by the year 2020, a fixed or possibly shrinking quantity of arable land, and an estimated 800 million undernourished people, quantifying the net contribution of animal production to quantity and quality of the food supply is important.

Current global food supply is sufficient to provide everyone with an adequate diet. The inequitable distribution of food, which leads to hunger in some areas, is caused by inequities in income distribution, a complex issue not likely to be addressed effectively by changes in any one component of agricultural production systems.

Consumption of meat, milk, and eggs varies widely among countries, reflecting differences in food production resources, production systems, income, and cultural factors. Per capita consumption of these foods is much higher in developed countries but the current rapid increase in many developing countries is projected to continue. Total meat consumption in developing countries is projected to more than double by the year 2020, while, in developed countries, it is projected to increase no more and, in some cases, less than population growth. Because most of the world's population is in developing countries, which are experiencing the most rapid growth rates, global demand for meat is projected to increase more than 60% of current consumption by 2020.

At low levels of intake of meat, milk, and eggs, an increase in consumption of these foods is known to be nutritionally beneficial, particularly for young children. These benefits result from the higher content and nutritional availability of essential amino acids and several micronutrients, including minerals and vitamins. Thus, if achieved, projected increases in per capita intake of meat and other animal products in developing countries should improve people's nutritional status. In developed countries, on the other hand, intakes of food from animals are higher than justified by nutritional grounds alone. Opinions differ as to whether a decrease in intake of these foods would benefit the health of the general population. In all countries, the palatability and dietary diversity contributed by meat, milk, and eggs are undoubtedly important factors, in addition to nutritional content, in determining intake levels.

Conversion rates of the energy and protein in feeds consumed by animals to human food energy and protein vary, depending on species, production system, feed type, and product. Poultry and pork production are most efficient on the basis of total food produced from total feed intake but, on average, ruminants (cattle, sheep, goats) return more human food per unit of human-edible feed consumed because most of their feed is obtained from materials that cannot be consumed directly by humans. This fact has been overlooked in some assessments of the role of animals in food production.

On a global basis, less than three kilograms (kg) of grain are required to produce a kg of meat from any of the species and less than one kg of grain per kg of milk. Less grain is fed to livestock in developing than in developed countries. It has been estimated that, on a global basis, animals produce a kg of human food protein for each 1.4 kg of human-edible protein consumed. The biological value of protein in foods from animals is about 1.4 times that of foods from plants. Thus, diverting grains from animal production to direct human consumption would, in the long term, result in little increase in total food protein and would decrease average dietary quality and diversity. Also, feed grains can be and are diverted to direct human use during periods of temporary food grain shortage. An additional consideration is that maize, the principal feed grain, yields much more per hectare than wheat, the number one food grain.

Recently, conversion rates of grains to meat, milk, and eggs have improved significantly in both developed and developing countries. Applying known technologies to a larger proportion of the world's animal populations offers the potential for substantial additional improvements in efficiency and, with continued investment in research, new technologies undoubtedly will contribute to additional increases. This suggests that grain requirement per unit of animal food product should decrease. However, the largest increases in demand are forecast for poultry, pork, and aquaculture products, which are foods from species requiring relatively high human-edible content diets. The net effect on grain demand is, therefore, difficult to predict but it is estimated that an annual rate of growth in cereal production between 1.1 and 1.4%, i.e., a lower rate than in recent decades, should meet needs for both food grains and the feed grains required to meet the projected per capita demand for meat, milk, and eggs.

Livestock have both positive and negative environmental effects. Improved management of livestock grazing, better management and use of manure, and increased care in design and siting intensive production operations will be necessary to maximize beneficial effects and minimize detrimental effects of livestock. Government policies related to land use and economic development are important.

Meeting projected demand for foods of both plant and animal origin in 2020, while sustaining the productive capacity of the land, will be challenging but feasible. Animal agriculture will continue to be an important part of food-producing systems. Investment in agricultural production research and development and implementation of policies that encourage production, while protecting the environment, will be essential to achieving the goal of an adequate global food supply.

Executive Summary

Introduction

The human population is forecast to increase by 33% over the next 20 years. This report takes a global view of the consequences on the demand for human food and the current and potential contributions of animal agriculture in meeting that demand. Case studies from both the developing and developed world illustrate different types of animal agriculture and the nutrient contributions of animal products to the human diet. Predictions of the demand for and supply of food on national, regional, and global levels to the year 2020, generated by the International Food Policy Research Institute's (IFPRI) IMPACT model, are presented. The resources used in animal agriculture, based on data from the Food and Agriculture Organization (FAO) of the United Nations (UN), are examined and ways in which efficiency might be improved to meet predicted demand while limiting negative environmental consequences are discussed. Summaries of this report's key findings follow.

Food Supply and Demand

On a global basis, current food supply ought to be able to meet demand. However, inequalities in income distribution result in more than 800 million people remaining hungry. While recognizing the need for more equitable distribution, this report focuses on regional and global production figures for the year 2020.

The human population, currently increasing at 1.4% per year, is forecast to increase by an average of 1.2% per year over the period to 2020, reaching 7.7 billion. Urbanization is increasing and incomes are rising in many parts of the world, trends associated with increased per capita demand for meat, milk, and eggs. Demand for these food products is, therefore, increasing at a faster rate than population growth. Global demand for meat thus is predicted to be 63% greater in 2020 than in 1993, with 88% of the increase in developing countries and nearly 50% of that in China. However, the global economy will ensure that the consequences also will be evident in the developed world.

Demand for cereals for food and feed also will increase, at an annual rate expected to be between 1.1 and 1.4%. Historically in the developed world and currently in the developing world, animals are an integral part of food production from crops. More than 50% of cropland is cultivated by draught animal power, while the use of manure is estimated to save the purchase of fertilizer worth $700 million to $800 million per year in irrigated systems in the humid tropics alone. In addition, manure provides cooking fuel, and animals are used for transporting food to markets.

Link Between Livestock Products and Human Nutrition and Health

On a global basis, foods of animal origin, including fish, provide about 17% of the energy and more than 35% of the dietary protein; however, this average masks large variations between countries. Where intakes of animal products are low, increases in meat (in particular), milk, and eggs in the diets of toddlers and school children have resulted in marked improvements in growth, cognitive development, and health, due at least in part to the higher availability of essential amino acids, minerals, and vitamins in food of animal, compared to plant, origin. At the higher end of the range, largely in developed countries, some epidemiological studies suggest that high intakes of livestock products have adverse effects on health; however, the relationships are frequently confounded by increased longevity and variation in the intake of other dietary components. The primary problem in a number of countries seems to be excess total energy intake rather than intake of any one food group.

In the United States, during this century, per capita intake of all fats and oils has increased by 50%, despite a decreased intake of animal fats; that of sugars and sweeteners is up 65%. Intake of beef and pork has decreased by 30% from its highest level.

Analyses of diets in five case study countries (Argentina, Egypt, Mexico, South Korea, and the United States) demonstrate that humans can thrive on a variety of diets, provided their energy, protein, and micronutrient intakes are met; data from a sixth case study (Kenya) indicate suboptimal nutrition. The importance of a nutritionally balanced diet increases as total food intake decreases, particularly with young children, for whom foods of animal origin can have a significant beneficial effect.

Animal Agriculture Systems

Grassland accounts for over 30% of the global land surface. Much of this land, particularly in semi-arid and upland areas, is incapable of supporting crop production. Thus, livestock may provide the only source of local food production in regions where people have limited income for purchase of food, even for subsistence. Only about 10% of global animal protein is produced directly from grazing systems, although, in addition, animals born and reared on grass may be transferred to other systems for further feeding.

Specialized livestock farms evolved in Europe and North America only in the last 50 years; in many countries, especially in the developing world, mixed crop-livestock farms still predominate. These types of farms produce more than 50% of the meat and more than 90% of the world's milk production. In developing countries, animals provide power for cultivation and, in all countries, they provide manure for fertilization and consume crop residues and by-products that would otherwise be wasted and could have adverse environmental impacts.

The remaining proportion of livestock products are produced in intensive (industrial) systems that have been described by some as being "unnatural," inefficient in energetic terms, and unfriendly towards the environment. Yet, it is these systems that have contributed most to the relatively low-cost meat and milk enjoyed by consumers in developed countries. Such systems permit economies of scale, facilitate application of advanced production and environmental management technologies, and, in general, result in the production of meat, milk, and eggs with significantly lower total feed input per unit of production than other systems. They do use more potentially human-edible feeds than other systems and can cause pollution problems if the facilities are not well designed and managed.

Most poultry and pig production in developed countries—and an increasing percentage in developing countries—occurs in industrial systems. The largest increases in demand for food of animal origin are for poultry meat and pork and, as a result, intensive production is likely to increase. This is expected to increase global demand for feed grains.

Efficiency of Resource Use

In addition to consuming feed grains and oilseed products, viewed as being in direct competition with humans, animals consume vast quantities of human-inedible materials such as grasses and herbaceous legumes, crop residues, and by-products of food- and fiber-processing industries. The composition of animal diets varies with region and among species. Sheep, goats, and buffalo are fed very little grain, while the diets of dairy cows may include 10 to 30% of human-edible material and beef feedlot finishing rations, up to two-thirds. Pigs and poultry have limited ability to digest fibrous feeds and thus require diets high in energy content to perform well. As a result, their diets typically contain 50 to 70% of human-edible feedstuffs, with the balance consisting of milling or other by-products relatively high in energy, protein, or both.

Globally, humans still directly consume nearly two-thirds of total cereal production, while pigs consume approximately 12%, dairy cows 9%, beef cattle 5%, meat chickens 5%, and laying hens 4%. Ruminants in particular also consume by-products of crop production that are inedible by humans. For every 100 kg of human food produced from the crops considered in Fadel's analysis (1999), an average of 37 kg of by-products are produced, which can either be turned into human food by animals or be disposed of, incurring monetary, fuel, and environmental costs. However, calculation of the net cost or benefit of animal production requires data on the efficiency with which various feed sources are converted into food by different species.

Average conversion rates of feed grain to human food were calculated from global data on food production and feed grain use. For beef, pork, sheep and goat meat, poultry meat, milk, and eggs, the values (kg grain/kg product) were 2.6, 3.7, 0.8, 2.2, 0.3, and 2.2, respectively, for developed countries and 0.3, 1.8, 0.3, 1.6, 0.2, and 1.6 for developing countries. Thus, sheep, goats and dairy cattle, and beef cattle in developing countries, produce more than a kg of human food for each kg of grain consumed. For the six case study countries considered in this report, dairy cattle returned between 1 and 14 kg of protein in milk for each kg of protein in the human-edible material consumed. The very low conversion rates, which have been quoted in some assessments of animal products, e.g., 0.8 to 0.14 kg of beef per kg of grain, ignore the forage and by-products consumed and are extrapolations from the final finishing phase of beef cattle in feedlots.

Thus, they substantially underestimate actual output:input ratios for the human-edible feeds eaten.

It also should be noted that the grain fed to livestock is often of a type or quality that is not in demand, or not fit, for human consumption. The yields of grains fed to livestock, e.g., maize (corn), are greater than those for wheat, which is the leading cereal used in human diets when a choice is available. This yield advantage also needs to be factored into the assumptions when comparing the efficiency of wheat versus meat in feeding the world.

It is recognized that animals are inefficient converters of total energy relative to crops but that efficiency is not yet at a maximum. Opportunities to increase that efficiency are described in this report but successes already have been achieved. During the decade from 1983 to 1993, the amount of meat, milk, and eggs produced per unit of feed grain fed to animals increased approximately 15% in both developed and developing countries.

Policy makers need to reappraise the relative advantages and disadvantages of different types of food production on a regular basis. Production efficiency is only one of the relevant assessment criteria. Feed grains provide a buffer for food grain supplies; less is fed to ruminants when grain production is decreased due to climatic influences or conflicts that lead to a rise in prices. In the current global economic climate, policies to decrease the amount of grain offered to livestock are unlikely to decrease the number of hungry people. A goal of providing food from both plant and animal sources for those who wish them seems preferable.

Livestock and the Environment

Most human activities impact the environment; agriculture is no exception. Animal agriculture frequently is blamed for adverse environmental effects but, conversely, the positive role of animals in environmental conservation is rarely emphasized. For example, grazing modifies plant communities and can be managed to sustain or enhance desirable plants and be neutral or beneficial to watersheds and wildlife. However, it is the improperly managed grazing that adversely affects watershed function and wildlife habitat that attracts publicity. Recent evidence suggests that many claimed negative effects of overgrazing have, in fact, been overstated, relative to the impact of climatic factors, which have not been fully recognized. Transhumant systems, involving the seasonal movement of animals to take advantage of seasonal variation in forage production, have existed for millennia in parts of Europe, Africa, and Asia and have been successfully adapted in parts of the Americas. However, increasing human population pressure and associated development have caused grazing lands to be converted to crop production and have restricted animal movements. Management systems often have not been able to adapt to these constraints. Also, the land is often unsuited for cultivation, which removes more nutrients from the soil and can lead to erosion when the land is not covered by vegetation in fallow periods.

Increasing population pressure is forcing the conversion of rainforest to pasture, most notably in the Amazon basin, a process that has been strongly criticized for its impacts on carbon dioxide production and reduced biodiversity. A rapidly expanding human population in the region is creating need for additional economic development. Preventing further loss of rainforest will require provision of alternative economic opportunities for local people as well as changes in land use policies.

Mixed crop-livestock systems offer a number of opportunities for beneficial effects on the sustainability of food production in these regions and hence on the environment. Return of manure and urine to the soil increases both fertility and organic matter content and forage cultivation to provide livestock feed can decrease or ameliorate erosion. Using animals for draught power also decreases reliance on fossil fuel.

As animal production systems intensify, there is the potential for negative environmental impact from improper storage or application of manures polluting surface of ground waters. Again, the problem results from improper management rather than from the animals per se, because the same problem also can occur with improper use of chemical fertilizers.

Industrial livestock systems present the greatest challenge in terms of maintaining environmental quality. In these systems, large quantities of manure are concentrated in small areas, often not adjacent to the land producing the feed. Technologies such as lagoons, manure drying, solids separation, and biogas production have been developed but their implementation generally will require provision of appropriate incentives or development and effective enforcement of regulations to prevent pollution. There is now a much greater appreciation of the importance of considering environmental factors when deciding on the site and design of industrial livestock operations.

Water is important environmentally, not just in terms of pollution but also in terms of availability. It is often the first factor limiting food production. A large variation exists among the limited number of estimates of water used for animal production; much of it is due to differences in assumptions about use of irrigated crops for feed. A realistic estimate of water from wells or reservoirs used for beef production in the United States is around 4,000 liters (L)/kg.

Opportunities to Increase Production of Animal Food Products

Production efficiency of animal food products varies greatly around the world. However, increasing efficiency globally is not simply a matter of transferring the technologies developed in intensive systems to less intensive ones. Technologies must be adapted to the resources available to the producer and the local environment, both natural and economic. Recent advances in the biological sciences, e.g., the potential for speeding up genetic modification, provide tremendous opportunities for increasing animal production efficiency. New opportunities include

- more effective matching of genetic potential of animals to specific nutritional, environmental, and market conditions;
- breeding for disease resistance in animals, together with improved methods for disease diagnosis and use of more effective vaccines for disease prevention;
- genetically improving the nutritional value of animal feed;
- increasing understanding of nutrient utilization by animals, leading to more efficient production with less pollution; and
- precision farming involving improved systems for collating and analyzing information and using the results for more efficient allocation of resources.

The recent publicity and public interest in new biotechnologies have led to resistance to their adoption in some countries. Scientists need to be responsible for adequate safety testing and for keeping the public informed.

Policies

One current problem in food production is that while sufficient food to feed the world's population can be produced, it is not equitably distributed. There is little benefit in producing food if it cannot reach a market that can afford to purchase the products. Increased food production also will not be sustainable unless farmers can afford to purchase the necessary inputs and adopt practices that do not deplete the natural resource base. Appropriate government policies are therefore vital to ensuring access to resources, the financial viability of agricultural producers, infrastructure to deliver foods to markets, and the purchasing power of consumers. Although this report is not about policy per se, it highlights some issues that need to be addressed if animal agriculture is to deliver what is expected of it. These include

- food-pricing policies that give farmers a fair return for labor and investment;
- land reform policies that combine the provision of access to resources with incentives to conserve those resources;
- provision of banking and credit services to pastoralists and small-scale producers, to enable them to continue to make appropriate use of marginal environments; and
- policies to promote more equitable distribution of food in a global economy.

The Future

This report documents that animal agriculture makes both positive and negative contributions to total food supply. On balance, the integration and complementarity between crop and livestock production and the nutrient quality of foods from animals make animal agriculture a key component of most current food production systems. An important question is whether meeting the projected future increase in demand for animal products is feasible and sustainable. Economic projections indicate it will be feasible. Furthermore, substantial increases in efficiency of production are possible. Globally, levels of animal production are very much below biological potential. For example, global average milk production per cow is currently only 10% of that in the highest-producing herds. Doubling the volume of milk produced without increasing the number of cows should be possible by improving all aspects of management, including nutrition, breeding, and disease control. The amount of crop residues and by-product feeds will increase as crop production is increased to meet the demands of the increasing population; application of new technologies can improve the nutritional quality and utilization of these feeds.

Much of the increase in demand for animal products is for the outputs of pig and poultry production, which require high nutrient-density diets and thus increased consumption of feed grain. A primary requirement for feeding a growing world population is thus to increase crop yield per hectare, because there is limited opportunity to increase the area of land cultivated without adverse environmental impact. An increase in cereal yields of approximately 1.4% per year to 2020 would be required to meet the projected needs for direct cereal consumption and the projected increases in feed grain requirement at current conversion rates. Improvement in conversion efficiency has been occurring and, if continued, annual increases in cereal yields of as low as 1.1% would meet projected food demand. Such yield increases will be achieved only through continued investment in research, an appropriate economic climate, and policies that take account of food security requirements.

The events of the last decade have shown the risks in looking ahead on a 20-year planning horizon; thus, the assumptions made in this report are open to challenge. Nevertheless, the authors are of the view that animal agriculture will continue to make important contributions to meeting the diversity of human food needs without compromising the ability of the world to feed itself. For the world to be able to feed its growing population, scientists from many disciplines and politicians must work together toward a common goal, integrating the experience of our forefathers in producing food with the responsible application of new technologies.

1 Introduction

Projected human population trends and the existence of regional and world trade agreements mean that domestic agriculture, food production, and human food demand need to be considered in a global context.

The current global food supply, evenly distributed, is estimated to be sufficient for an adequate diet for the world's nearly six billion people, a fact that would surprise Malthus (1798) and others who, over the years, have predicted that human population would outstrip the world's food-producing capacity, with resulting famine. However, the unprecedented absolute increase in human numbers in recent decades, which is projected to continue for some time, and recent trends in crop yields and grain reserves remind us that the Earth's carrying capacity is finite. The possibility of food scarcity remains on the global agenda (American Association for the Advancement of Science, 1997; Brown, 1997; Tweeten, 1999).

Animal agriculture has long been and continues to be an integral part of food-producing systems throughout the world (Cheeke, 1985; Schwabe, 1984). Animal agriculture provides, in the form of meat, milk, and eggs, approximately one-sixth of all human food energy and more than one-third of human food protein as well as numerous other valuable goods and services. Interestingly, perceptions of the potential contributions of this segment of agriculture to future food supplies vary widely. On one hand, per capita demand for animal food products has expanded rapidly in a number of developing countries in the past 15 years, and large increases are projected to continue (Delgado et al., 1999). Because the regions where these increases are occurring contain the majority of the world's population, as well as the most rapid population growth rates, a very large increase in global demand for animal products is forecast. On the other hand, those such as Brown (1997), who foresee an impending shortage of cereal grains, advocate diverting grains now fed to animals to direct human use. However, de Haan et al. (1997) note that this shift in grain use is driven by economic forces and occurs today during times of grain shortage. Furthermore, as documented in this report, animal agriculture complements crop production in a number of ways. Given this and the complex interactions both within and between countries in a global economy, interventions such as proposed by Brown (1997) can have unintended consequences.

Feed grains, i.e., grains fed to animals, as opposed to grain directly consumed by humans, represent a buffer against temporary food grain shortages and will no doubt continue to fill that role if not purposely diverted to food use by structural changes in worldwide agriculture. When fed to animals, feed grains play important roles in the ability of animals to produce food from large quantities of plant materials that humans cannot eat. The contributions of animals to recycling plant nutrients and to using food-processing by-products that would otherwise represent a waste disposal problem indicate that a permanent reduction in feed grain use would have multiple ramifications for food-production systems.

The nutritional value of animal products is high at low intakes and an increase in intakes of meat, milk, or eggs, especially among children with currently low intakes, would improve nutritional status. It would be inappropriate for people from developed countries to impose their dietary beliefs on people at the opposite end of the dietary scale. In addition to the nutritional importance of foods of animal origin, many people desire the dietary variety and palatability obtained by including some animal products in their diets. As Cohen's (1995) analyses make clear, the world's human carrying capacity is not a fixed number but depends on the standard of living desired. For many people, some foods of animal origin are part of a desired standard of living and there seem to be no compelling reasons why, if feasible, this desire should not be met. Important questions, therefore, are whether the increased demand for foods from animals can be met and what impact meeting this demand is likely to have on other components of the food supply and on sustainability of food-production systems.

This report examines the multiple roles of animals in food-production systems and documents conversion rates of both human-inedible and human-edible plant materials into food by different types of animals in a variety of systems (Box 1). From these results, we estimate potential impacts of alternative production strategies on quantity, nutritional quality, and diversity of the global food supply. We examine prospects for and means of meeting the projected demand for animal products, considering also the goals of ensuring adequate supplies of other foods and maintaining rural livelihoods and the resource base on which future food production depends.

Box 1

Notes and Explanations

The report deals primarily with milk, eggs, and meat from cattle, sheep and goats, pigs, and poultry. Fish and other freshwater and marine food products are included in food supply summaries but the report does not deal with their production. It is recognized that fish and other seafoods are an important source of human food for which demand is increasing and that, because current harvest of many of the world's fisheries is at or beyond sustainable capacity, increases in production are expected to come from aquaculture (New, 1997). Aquaculture is, in fact, the fastest growing food-production system globally (Pinstrup-Andersen et al., 1997). Increased aquaculture production will compete with the production of other animals, particularly poultry and pigs, for feed resources. Aquatic species are quite efficient in the use of feed resources but an expansion of aquaculture will require increased supplies of feed grains and protein supplements.

The important topics of animal well-being and food safety have been comprehensively reviewed in recent CAST publications (Council for Agricultural Science and Technology, 1997b, 1998) and are therefore not included here.

The terms "animal" and "livestock" are used interchangeably to refer to the production or product from the food-producing species listed, including poultry. The international term "maize" is used for the crop usually called corn in the United States. The unit used for land area is hectares (ha) (1 hectare = 2.47 acres). The joule is used as the measure of energy.

Throughout the report, the term "food" refers to human food and "feed" to materials consumed by domestic animals.

The principal data source used is FAOSTAT (http://apps.fao.org), the database of the Food and Agriculture Organization of the United Nations. Although later summaries are available for a number of items, in the interests of consistency, the year 1993 (in most cases, the average of 1992 through 1994) was used in most summaries. It is noted that global production of all edible animal products was appreciably higher in 1995 than in 1993, i.e., beef + 4%; sheep and goat meat + 6%; pork + 11%; poultry meat + 15%; milk + 4%; eggs + 12%, consistent with the recent and projected increases presented in the report.

Population projections used were those from the United Nations (1996), i.e., 7.67 billion in the year 2020. We note that the 1998 projection has been revised downward to 7.50 billion.

The conversion rate of feed resources into usable product, i.e., the amount of meat, milk, or eggs per unit of input, is a key factor in determining the net contribution of animal agriculture to human food supply. As shown by the results of the case studies in this report, conversion rates vary among species, production systems, and products. As also shown by those analyses, there are large differences between conversion rates based on total inputs and inputs of human-edible materials; it is obviously the latter that determine effect on human food supply.

Conversion rates also depend on the endpoint chosen. Animal producers often use "feed consumed per pound of live weight gain," which is a useful measure for comparing efficiency of different feeds or groups of animals. However, the endpoint, live weight, is greater than the amount of human food available. Carcass weight is much closer to the actual amount of food from meat animals and is the endpoint generally used in this report. Obviously, it includes bone and some fat trim that is not consumed and a case could be made for use of trimmed cuts. However, trimming standards vary markedly between countries and for different kinds of meats and there is no single standard suitable for use on a global basis. Trimming losses from meat are analogous to milling losses from cereal grains and thus use of carcass weight represents a reasonable basis for comparing amounts of food from meat animals with that from plant sources.

2 Role of Animal Agriculture in the Human Food Supply

World population is projected to increase to 7.7 billion by the year 2020 (United Nations, 1996; medium variant), equivalent to an average annual compound growth rate of approximately 1.2% for the period 1995 to 2020. Thus, total food supply must increase at least this rapidly to maintain current per capita supplies. However, the majority (95%) of the population increase is forecast to occur in developing countries, where 77% of people live and where the recent trend of increased per capita consumption of meat, milk, and eggs is predicted to continue. Thus, demand for foods of animal origin is expected to increase more rapidly than total population.

Livestock have long played a key role in supplying calories and protein for human food in virtually all parts of the world, both directly (in the form of animal products) and indirectly (from the contribution of manure and draught power to crop production and the generation of income to enable purchase of food).

Current Consumption and Projected Demand for Foods of Animal Origin

In the first half of the 1990s, residents of developed countries consumed as food 78 kg of meat and 22 kg of fish per capita, with higher amounts of meat in the United States and higher amounts of fish in Japan. The corresponding figures for SubSaharan Africa were 12 kg of meat and 8 kg of fish. In developing Asian countries, people ate 18 kg of meat and 11 kg of fish, compared to 46 kg of meat and 9 kg of fish in Latin America (Food and Agricultural Organization of the United Nations, 1997; Westlund, 1995). Globally, average per capita intakes were approximately 35 and 14 kg for meat and fish, respectively.

Table 2.1 depicts the proportion of human dietary calories and protein from animal products in 1973 and 1993 in developed and developing countries (Figure 2.1). As this table emphasizes, animal products provide a significant proportion of human dietary protein. These data also illustrate that, while current consumption of animal products is much lower in devel-

Table 2.1. Percent of human food calories and protein from animal products, 1973–1993[a]

Region	Percent of calories from animal products[b]			Percent of protein from animal products		
	1973	1983	1993	1973	1983	1993
	(%)					
China	6	8	15	12	14	28
India	5	6	7	12	14	15
Other East Asia	7	11	15	21	29	38
Other South Asia	8	7	9	19	19	22
Southeast Asia	6	6	8	22	23	25
Latin America	16	17	18	39	42	46
WANA[c]	10	11	9	21	25	22
Sub-Saharan Africa	7	7	7	21	23	20
Developing world	8	9	11	19	21	26
Developed world	28	28	27	55	57	56
United States	31	29	28	68	66	64
World	15	15	16	34	34	36

[a]Source: Delgado et al., 1998. Raw data from FAOSTAT 9/17/97.

[b]Animal products, using the FAO definition, includes meat and meat products, dairy and egg products, and freshwater and marine animal products. Calculated from three-year moving averages.

[c]WANA = western Asia and North Africa.

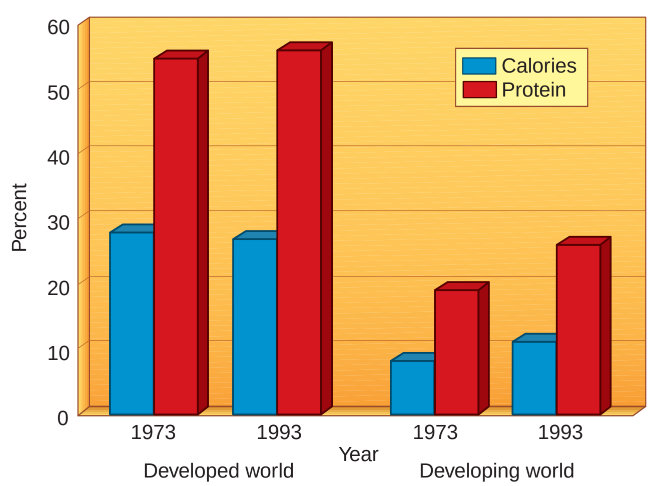

Figure 2.1. Annual percent calories per capita from animal products. Source: FAO data reported in Delgado et al., 1998.

oping countries, it is increasing much more rapidly than in developed countries. Table 2.2, showing per capita consumption of selected animal products for the two groups of countries, underscores this trend (Figure 2.2). Except for poultry meat, per capita consumption of meat, milk, and eggs has changed little over these two decades in developed countries; in fact, per capita beef consumption has declined. However, in developing countries, per capita consumption of all animal foods has gone up, with that for pork, poultry meat, and eggs approximately doubling and that for milk increasing nearly 50%.

Table 2.2. Annual per capita food consumption (kg) and percent of calories from selected livestock products, 1973 and 1993[a]

	Developed countries				Developing countries			
	1973		1993		1973		1993	
Commodity	kg	%	kg	%	kg	%	kg	%
Beef	26	3	25	3	4	1	5	1
Mutton and goat	3	1	3	1	1	0[b]	1	0[b]
Pork	26	4	29	5	4	2	9	3
Poultry	11	1	20	2	2	0[b]	5	1
Eggs	13	2	13	2	2	0[b]	5	1
Milk and products excluding butter	188	9	195	9	29	2	40	3
Meat subtotal	67	10	78	11	11	3	21	6
Totals	268	20	285	21	42	6	65	9

[a]Sources: Delgado et al., 1998. Raw data from FAOSTAT 12/10/97 and Rosegrant et al., 1997.
[b]Less than half a percent.

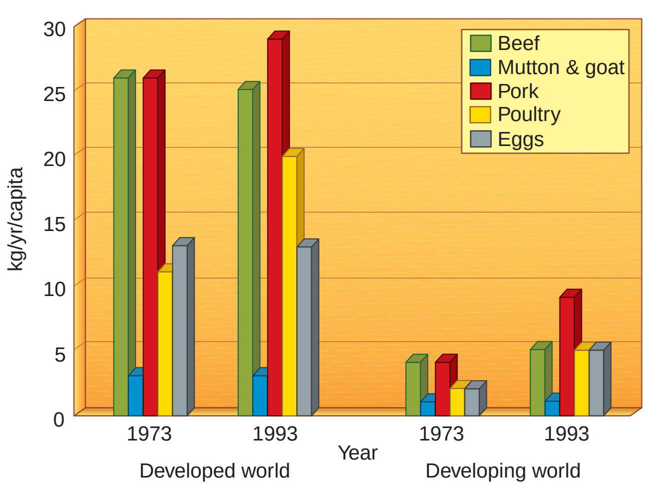

Figure 2.2. Per capita consumption (kg/yr) of selected animal products in developed and developing countries. Source: FAO data reported in Delgado et al., 1998.

Projections to 2020

Presently, there are no reliable projections of fish consumption on a global scale for more than a few years into the future. The best available projection for milk is an estimated growth rate for total dairy products production and consumption in developing countries of about 3.2% per annum through the year 2020 (Delgado et al., 1999). This estimate is consistent with an annual per capita growth rate of roughly 1.4%. A simple projection for fish through 2010 suggests that consumption in developing countries will grow from 9.3 kg/capita in 1988 to 1990 to 13.7 kg/capita in 2010, a 1.8% per capita growth rate per annum (Westlund, 1995).

For meat, the International Food Policy Research Institute (IFPRI) has developed IMPACT, an econometric simulation model of world crop and livestock markets that predicts demand to the year 2020 (Delgado et al., 1998; Rosegrant et al., 1995, 1997). Features of this model are (1) it incorporates detailed information from both developed and developing countries about present food consumption and supply relationships, (2) the livestock sector is relatively disaggregated by product, (3) the cereals feed markets and livestock markets are linked by specified relationships, and (4) both feed and meat prices are endogenously determined. These features allow the model to more closely simulate the real world livestock system, where livestock production is tied to the availability and cost of feed, yet consumption can be satisfied by trade, with repercussions for prices and quantities of cereals and livestock products worldwide.

Total and per capita consumption of meat for 1983 (average of 1982 through 1984) and 1993 (average of 1992 through 1994) and projected for 2020, based on the IMPACT model, are shown in Table 2.3 (Figures 2.3 and 2.4) for developed and developing countries and for the United States and China as the most populous countries in these two groups, respectively. Although as recently as the 1980s, people in the developing world consumed just over one-third of the global supply of meat, they are now consuming close to half. By 2020, this group is forecast to be consuming 63% of the total. Per capita consumption is forecast to change little in the developed world and actually to decrease slightly in the United States, while it is projected to increase more than 50% in the developing world, with a forecast 91% increase in China from

1993 to 2020.

Several factors are driving this increased demand in developing countries. One is their current relatively low meat, milk, and egg intake levels. Animal products are highly nutritious and palatable and add variety to diets. As documented in the next chapter, the nutritional benefits of an increase in animal food intake, where initial levels are low, are substantial, especially for young children. Throughout their evolutionary history, humans have consumed foods of animal origin, obtained originally by hunting and fishing, then for several millennia from domestic animals. Thus, a desire for such foods in the diet is, quite literally, natural.

The proportion of people living in cities, which is increasing in developing countries at an average rate of 3.5% per year (vs. 0.75% in developed countries), consistently is found to be positively associated with demand for animal products. For example, per capita consumption of milk and meat is much higher in Latin America, which has a proportion of urban dwellers similar to developed countries, than in other developing countries with similar income levels but lower urban population concentrations. European influence and a long tradition of stock raising are likely additional factors.

Per capita income is undoubtedly one of the most important factors affecting this demand. Throughout the world, as incomes rise, consumption of animal products increases, until some "satiety" point is reached, as perhaps is the case in developed countries (Figure 2.3). Industrialization and resulting rising incomes have been greatest in Asia in the past two decades, which is where the largest increases in animal product consumption, particularly meat, have occurred. From the early 1980s to the early 1990s, the annual rate of increase in demand for meat was 5.4% in all of Asia, except India and China, and 8.3% in China, compared to 1.8% in the United States and even less in Europe. With its huge population and projected per capita meat consumption of 63 kg in

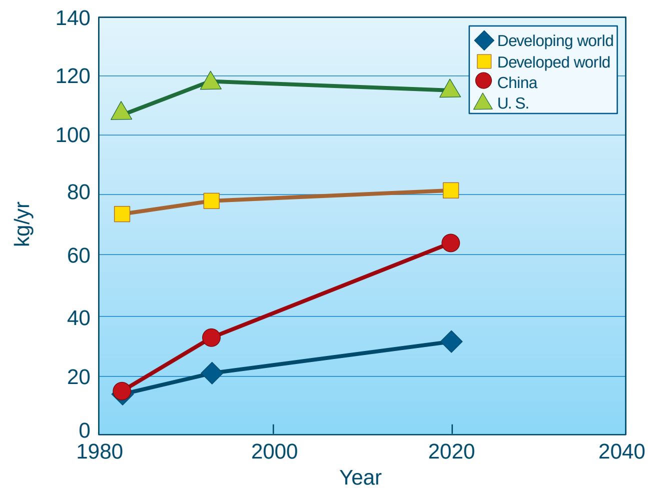

Figure 2.3. Per capita meat consumption (kg/yr). Source: FAO data reported in Delgado et al., 1998.

Table 2.3. Past and projected consumption trends of meat, to the year 2020[a]

Region	Annual growth of meat consumption 1982–1993 (%/yr)	Projected annual growth of meat consumption 1993–2020 (%/yr)	Total meat consumption (Mt) 1983	Total meat consumption (Mt) 1993	Total meat consumption (Mt) 2020	Per capita meat consumption (kg) 1983	Per capita meat consumption (kg) 1993	Per capita meat consumption (kg) 2020
China	8.3	3.2	17	39	89	16	33	63
India	3.1	3.0	3	4	8	4	4	7
Other East Asia	5.4	2.6	2	4	8	22	44	70
Other South Asia	5.4	3.3	1	2	5	6	7	10
Southeast Asia	5.4	3.6	4	7	18	11	15	28
Latin America	3.2	2.2	15	21	38	40	46	57
WANA[b]	2.6	2.7	5	7	15	20	20	23
Sub-Saharan Africa	2.1	3.4	4	5	11	10	9	11
Developing world	5.3	2.9	50	89	194	15	21	31
Developed world	1.2	0.5	88	99	113	74	78	81
United States	1.8	0.6	25	31	37	107	118	114
World	2.8	1.8	139	188	306	30	34	40

[a]Sources: Delgado et al., 1998. Raw data prior to 1995 from FAOSTAT (9/17/97) and projections to 2020 from the IFPRI IMPACT model (Rosegrant et al., 1997).

[b]WANA = western Asia and North Africa.

2020, China clearly will be a dominant factor in determining global demand for livestock products.

IFPRI projections to 2020 are based on the assumption that India, for religious and cultural reasons, will retain its preference for vegetarian diets. If this should change to any significant extent, India, with a population rapidly approaching one billion, would have a major effect on world livestock markets.

Recent growth in consumption of different meats and consumption in 2020 projected from the IMPACT model are presented by region in Table 2.4 and Figures 2.5 and 2.6. In both developed and developing countries, the largest recent increase and the largest projected increase are in poultry meat. Total production of each of the three major meats (beef, pork, poultry) is forecast to increase in both regions. Table 2.5 presents rates of growth in production and total production (Figure 2.7). The very high annual rates of increase from 1983 to 1993 in production of pork, poultry, and total meat in developing countries, i.e., 6.1, 7.4, and 5.2%, respectively, are not expected to be sustained, although rates above 2% per year are pro-

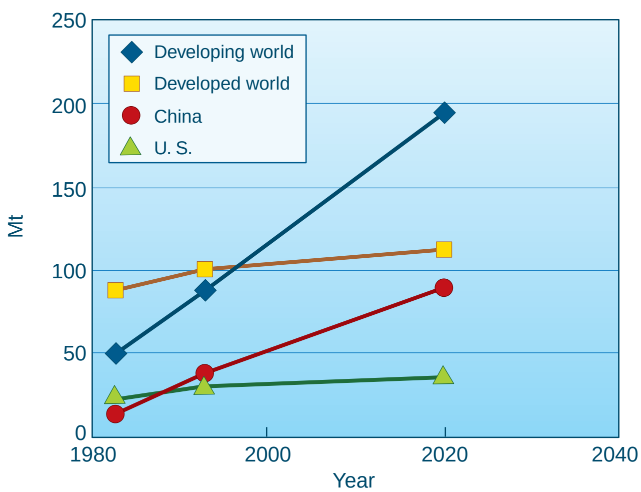

Figure 2.4. Total meat consumption (Mt) in the developing and developed world, China, and the United States. Source: FAO data reported in Delgado et al., 1998.

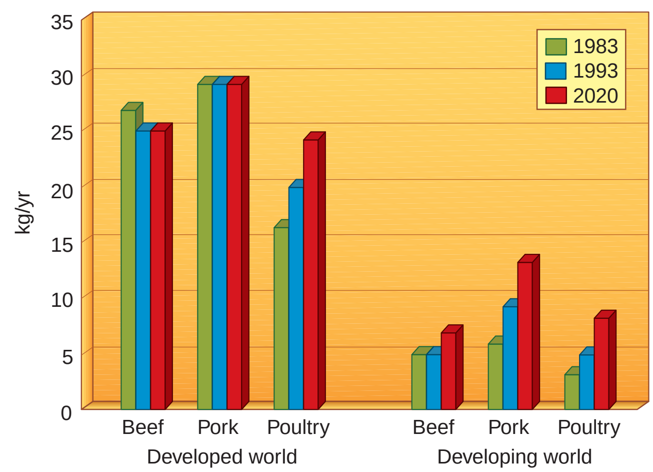

Figure 2.5. Per capita consumption (kg/yr) of beef, pork, and poultry in the developed and developing world. Source: FAO data reported in Delgado et al., 1998.

Table 2.4. Past and projected consumption trends of various meats, to the year 2020[a]

Region	Annual growth of meat consumption 1982–1993	Projected annual growth of meat consumption 1993–2020	Total consumption 1983	1993	2020	Per capita consumption 1983	1993	2020
	(%/yr)		(Mt)			(kg)		
Developed world								
Beef	0.1	0.3	32	32	35	27	25	25
Pork	0.9	0.2	34	38	40	29	29	29
Poultry	3.3	0.9	19	26	33	16	20	24
Meat	1.2	0.5	88	99	113	74	78	81
Developing world								
Beef	3.1	2.8	16	22	47	5	5	7
Pork	6.1	3.0	20	39	85	6	9	13
Poultry	7.4	3.1	10	22	50	3	5	8
Meat	5.3	2.9	50	89	194	15	21	31

[a]Sources: Delgado et al., 1998. Raw data prior to 1995 from FAOSTAT (12/10/97) and projections to 2020 from the IFPRI IMPACT model (Rosegrant et al., 1997).

jected for each in these countries through 2020. As a result, developing countries are projected to be producing by the year 2020 slightly more beef, double the pork, and a fourth more poultry meat than developed countries (Figure 2.8).

Higher demand in developing countries is expected to increase imports from developed countries. Net imports from developed to developing countries projected by the IMPACT model represent about 13% of beef, 2% of pork, and 8% of poultry production in developing countries by 2020.

Whether or not these projections for regional and global demand are met will depend on many factors. The recent economic downturn in several Asian economies may well slow the rate of growth in demand, at least temporarily. The feasibility of meeting the projected increases and the implications for other components of the food supply are discussed later in this report. What seems clear from these and other projections (U.S Department of Agriculture, Economic Research Service, 1996; Food and Agriculture Organization of the United Nations, 1997) is that (1) a very

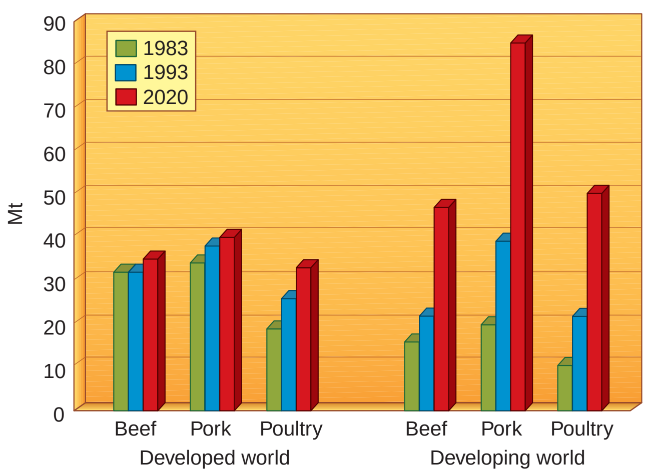

Figure 2.6. Total consumption (Mt) of beef, pork, and poultry in the developed and developing world. Source: FAO data reported in Delgado et al., 1998.

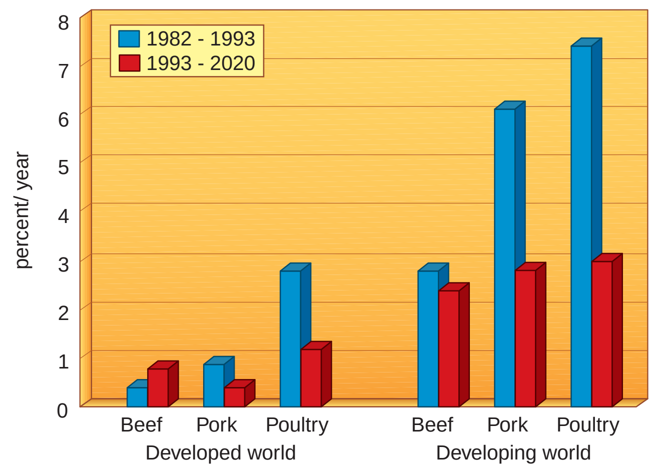

Figure 2.7. Growth of production (%/yr) of beef, pork, and poultry in the developed and developing world from 1982–1993 and estimated from 1993–2020. Source: FAO data reported in Delgado et al., 1998.

Table 2.5. Past and projected production trends of various meats, to the year 2020[a,b]

Region	Annual growth of production 1982–1993	Projected annual growth of production 1993–2020	Total production 1983	Total production 1993	Total production 2020	Per capita production 1983	Per capita production 1993	Per capita production 2020
	(%/yr)	(%/yr)	(Mt)	(Mt)	(Mt)	(kg)	(kg)	(kg)
Developed								
Beef	0.4	0.8	32	33	40	27	25	29
Pork	0.9	0.4	35	37	41	29	29	30
Poultry	2.8	1.2	17	26	37	14	20	27
Meat	1.2	0.8	92	100	124	77	78	89
Developing								
Beef	2.8	2.4	17	22	42	4	5	7
Pork	6.1	2.8	21	39	84	6	9	13
Poultry	7.4	3.0	9	21	46	3	5	7
Meat	5.2	2.7	51	88	182	15	21	29

[a]Sources: Delgado et al., 1998. Raw data prior to 1995 from FAOSTAT (9/17/97) and projections to 2020 from the IFPRI IMPACT model (Rosegrant et al., 1997).

[b]Meat includes beef, pork, mutton and goat, and poultry. Annual growth of meat production 1982–1993 is the compound growth rate from regressions fitted to FAO annual data. Metric tons and kilograms are three-year moving averages centered on the year shown.

large increase in demand for foods of animal origin over the next two decades is highly probable; (2) demand is expected to increase for all of the major meats, milk, and eggs; (3) nearly all (95%) of the increase in demand is expected to occur in developing countries; and (4) although most of the production to meet this demand is expected to occur within the countries generating the demand, significant increases in international trade in animal food products and in feed grains also are forecast.

Indirect Contributions of Animals to Food Supply

Contributions to Crop Production

Draught Power

Horses were used as the main source of power for cultivating land in developed countries, e.g., the United States and western Europe, until the twentieth century, when they were replaced by motorized power. In contrast, draught animals (usually cattle, buffalo, donkeys, horses, mules, or camels) and even humans still provide the major source of power for cultivation in many developing countries—enough to cultivate at least 320 million ha (Food and Agricultural Organization of the United Nations, 1997) (Figures 2.9–2.14). In some countries, donkeys are important for transport (Zenebe and Fekade, 1997). Although use of animals for transportation is important, provision of draught power remains much more so; it is estimated that for every 10 African farmers

Figure 2.8. Pigs produce more meat than any other animal species in both developed and developing countries.

Figure 2.9. Buffalo used in preparation of a paddy for planting rice, Indonesia. Photograph courtesy of Eric Bradford, University of California, Davis.

Figure 2.10. Buffalo used for transportation in China. Photograph courtesy of Eric Bradford, University of California, Davis.

Figure 2.11. Cowpea fodder transported by donkey in Niger. Photograph courtesy of David Elsworth, International Livestock Research Institute, Nairobi, Kenya.

using animal power in crop production, only one uses a cart for transportation (Dawson and Barwell, 1993).

Farmers owning draught animals tend to have larger farms than those not owning animals, suggesting that access to draught animals increases the area that can be cultivated (Francis, 1988; Sumberg and Gilbert, 1992). This may be due to labor savings associated with the use of draught animals. In central Nigeria, for example, draught animals decrease the time for land preparation for rice production from 315 hours/ha to 94 hours/ha (Lawrence et al., 1997). However, draught animals also can impose additional labor costs. Delgado and McIntire (1982) concluded that the main barrier to draught animal adoption is the cost of the extra labor associated with maintaining the ox team. Panin (1987), on the other hand, compared manual hoeing to bullock traction and concluded that the latter was technically and economically superior. Bullock traction reduced labor bottlenecks and shortened fieldwork time. One constant between these studies is that sufficient land must be available to permit expansion of cropping activities, notably cash crops such as groundnuts or cotton. In Ethiopia, Gryseels et al. (1984) observed a positive relationship between the number of oxen owned by a farmer and both the area cultivated and the percentage of land sown to marketable cereals. However, extending cultivation into less suitable, marginal land may lead to environmental degradation and poor crop yields (Kruit, 1994).

Continuing to use animal power instead of progressing to fossil-fueled mechanized power has saved millions of dollars in foreign exchange. Ramaswamy (1985) estimated that 30 million tractors would be required to replace the 300 million draught animals used on small farms in Asia. In some systems, e.g., Southeast Asia, draught animal power has been partly or largely replaced by mechanical equipment. This is particularly true wherever irrigation becomes available and the intensity of production, in combination with favorable crop prices, ensures the viability of mechanization (Bunyavejchewin et al., 1993). A number of other factors seem to be associated with the adoption of machinery, such as improvements in rural infrastructure, especially road construction, and raising educational standards. For example, in Nigeria, the promotion of primary school education has decreased the time children can spend caring for animals and thus has increased the cost of keeping cattle in tethered or cut-and-carry systems (Resource Inventory and Management, Ltd., 1992).

Figure 2.12. **Camels used for transportation in Senegal. Photograph courtesy of Eric Bradford, University of California, Davis.**

Figure 2.13. **Millet transported by oxen near Niamey in Niger. Photograph courtesy of David Elsworth, International Livestock Research Institute, Nairobi, Kenya.**

Figure 2.14. **Akamba people in the Machakos District of Kenya using oxen for plowing. Photograph courtesy of David Elsworth, International Livestock Research Institute, Nairobi, Kenya.**

It should be noted that, in many countries, draught animals are not kept solely for traction. There is increasing interest in using milking cows for draught purposes (Zerbini et al., 1996). Draught animals also are crucial to manure production, which becomes increasingly important as fallow periods decrease and access to commercial fertilizers is limited. Crop residues and agricultural by-products are a major source of feed for draught animals; in some regions, removal of these waste products may be an added advantage.

Nutrient Recycling

Most soils lack sufficient native fertility to sustain efficient crop production. While global fertilizer use increased from 81 to 96 kg/ha of cropland, fertilizer use in subSaharan Africa in 1988 to 1990 was estimated to be only 11 kg/ha of harvested land, a rate projected to increase to only 21 kg/ha harvested land by 2020 (Food and Agricultural Organization of the United Nations, 1993). Crop response to manure varies according to plant and soil types, agro-ecological zones, and manure quality (Figure 2.15). McIntire et al. (1992) estimated increases in grain yield ranging from 15 to 86 kg grain per ton of manure applied to cropland. Powell (1986) reported a response of 180 kg maize grain per ton of manure applied in the subhumid zone of Nigeria. An added benefit is the residual positive effect of manure, which may persist for up to three cropping seasons after application (Ikombo, 1989; Powell et al., 1998).

Smaling et al. (1992) compared the effects on maize yield of manure and chemical fertilizers, separately and in combination. Manure increased yields similarly to the best chemical fertilizer treatment on two of three soil types. On all three soil types, highest yields, but not consistently the highest economic returns, resulted from the chemical/manure combination.

The economic value of manure is recognized not only in developing countries but in developed countries as well (Mullinax et al., 1998).

More information on the contributions of animal agriculture to recycling plant nutrients and maintaining soil fertility is provided by Romney et al. (1994), de Haan et al. (1997), and Powell et al. (1995, 1998).

Contributions of Livestock to Food Accessibility

Livestock as a Cash Source

In many countries, access to food is limited not by availability but by purchasing power. For example, grain production in Ethiopia has increased and the country has become a net exporter. Yet, some of their export has been purchased by the European Community (EC) for distributing to poor Ethiopians!

Livestock frequently are sold by poor people to generate cash to purchase food in times of stress, such as during a drought. In Kenya, farmers use cash generated from dairy cattle production to purchase inputs, e.g., fertilizer, for crop production. The purchased fertilizer and manure from the animals can contribute to improved soil fertility and higher crop yields.

Livestock as a Balance for Crop Production

Grain prices and levels of production fluctuate from year to year. Livestock serve to balance fluctuations

Figure 2.15. Confinement sheep and goat housing, cut-and-carry system in Indonesia. An important product of this system is manure (fertilizer) for food crop production. Photograph courtesy of Eric Bradford, University of California, Davis.

Figure 2.16. Dung collection to use for fuel and land application in Nigeria. Photograph courtesy of David Elsworth, International Livestock Research Institute, Nairobi, Kenya.

by providing a means of using excess grains in times of surplus. Therefore, livestock help to support a base price for grains and a reserve that can be shifted to human use if there are shortages. Livestock represent a principal means of using and “storing” residues, by-products, and grains when there are surplus supplies and prices are low. The potential human food represented by animals “on the hoof” is an important aspect of food security where other food reserves may not be available.

Manure as Fuel

In some countries, notably in South Asia, animal dung has an important use as cooking fuel. The desired consistency of the dung influences the diet selected by farmers for their cattle (Figure 2.16) (Thorne and Herrero, 1998).

Nonfood Livestock Products as a Cash Source

In addition to food products, livestock produce fiber, skins, draught power, and manure, which can be sold if not used by the owner.

3 Role of Animal Products in Human Nutrition and Health

The relationship between consumption of animal products and human nutrition and health in highly developed western countries, particularly the United States, has been widely debated for a number of years. A recent publication from the Council on Agricultural Science and Technology (CAST) discussed these issues in depth (Council for Agricultural Science and Technology, 1997a). Favorable contributions to health for which there seems to be general agreement include the fact that animal products are quantitatively important sources of energy and protein in both developed and developing country diets—27 and 63%, respectively, in the United States and 16% and 36%, respectively, on a global basis (Table 2.1, Figure 2.1, Figures 3.1–3.2). Animal proteins have higher digestibilities (96 to 98%) than most plant proteins (65 to 70%). Furthermore, the amino acid composition of animal proteins is superior to that of plants. The biological values of animal proteins range from 90 to 100, relative to egg protein—the reference protein set to 100 by convention—while values for plant proteins range from 50 to 70%. The bioavailabilities of important minerals (including calcium, phosphorus, iron, zinc, magnesium, and manganese) and vitamins (thiamin [B_1], riboflavin [B_2], niacin, pyridoxine [B_6], and B_{12}) are much higher in animal as opposed to most plant products.

Negative concerns regarding foods of animal origin center on cholesterol and saturated fatty acid content. Implications of these issues regarding human health have been publicized and remain highly controversial (Council for Agricultural Science and Technology, 1997a). It should be noted that the favorable characteristics of animal products are based on strong, rigorous experimental data, while the negative effects attributed to animal products are and have long been based on statistical inference. As is appropriate in science, statistical inference must be questioned until experimental data establishing direct cause and effect relationships are available. This point was made strongly in the 1980 publication of the Food and Nutrition Board of the National Research Council (NRC) entitled *Toward Healthful Diets* and renewed by Harper in his 1993 publication, "Challenge of Dietary Recommendations to Curtail Consumption of Animal Products." The point was that "Association among diet, serum cholesterol, and HD [heart disease] mortality have proven weak. Interventions to lower serum cholesterol have reduced HD mortality only marginally and have not reduced total mortality" (Harper, 1993). The continuously changing recommendations arising from statistical inference reinforce the weak-

Figure 3.1. Milk sales in Kenya. Photograph courtesy of David Elsworth, International Livestock Research Institute, Nairobi, Kenya.

Figure 3.2. Beef carcass with ribeye exposed. Photograph courtesy of Martin Vavra, Oregon State University, Burns, Oregon.

ness of inferring cause and effect relationships from statistical data. The Council for Agricultural Science and Technology (1997a) has presented an analysis of this controversy as it has evolved in the United States. For the more global analysis of the role of animal products in human nutrition and health, we have adopted the view that low to moderate consumption of animal products is beneficial to the nutritional status and health of humans, even though excess consumption may, in some cases, be detrimental. This generalization applies to all foods, as evidenced by current NRC and U.S. Department of Agriculture (USDA) nutritional guidelines, which emphasize variety and warn against under- or overconsumption of individual food groups.

In support of and in concert with subsequent chapters of this report covering types of animal production systems (Chapter 4), resource use (Chapter 4), and opportunities for meeting future demands for livestock products (Chapter 5), two decisions were made. The first was that our approach to these analyses should be quantitative. The second was that the best way to approach the desired quantitative result would be to couple global and regional analyses with more detailed and focused analyses of a selected group of countries with diverse diets and animal agriculture production systems. The countries selected were Argentina, Egypt, Kenya, Mexico, South Korea, and the United States. Argentina was selected to represent a productive pastoral system. Also, the national diet of Argentina is based on significant quantities of animal products (30% and 62% of energy and protein, respectively) (Table 3.1). Egypt was chosen because of a less-than-median intake of animal products (6 and 16% of energy and protein, respectively) (Table 3.2) and a diverse set of animal production systems. Kenya was chosen because primary animal production systems are pastoral and occur in arid and semi-arid environments. Also, the Kenyan national diet (Table 3.3) is similar to that of Egypt in terms of per capita intakes of energy and protein from animal products, i.e., 0.97 megajoules (MJ)/d and 15.5 g/d for Kenya, as compared to 0.88 MJ/d and 13.2 g/d for Egypt. Total intakes of energy per capita in Kenya are significantly lower than in Egypt (7.6 vs. 13.5 MJ/d). Mexico was selected to represent a maize-based national diet intermediate in animal product content (16% and 40% of energy and protein, respectively) (Table 3.4). Also, as is true for Argentina, the potential for increasing animal production is great and rapid improvements already are evident. South Korea was selected to represent a country with a rice-based national diet with intermediate portions of animal products (14% and 35% of energy and protein intakes, respectively) (Table 3.5) and an animal agriculture heavily based on

Table 3.1. Per capita consumption of major food groups in Argentina (1993)[a]

Item	Energy MJ/d	Protein g/d	Fat g/d
Animal products			
Meat and products	2.30	41.3	39.4
Animal fats and products	0.34	0.1	9.0
Eggs and products	0.08	1.6	1.4
Milk and products	1.10	15.4	16.1
Fish and products	0.05	2.0	0.0
Total	3.87	60.4	65.9
Plant products			
Cereals and products	3.85	24.2	2.5
Fruit and products	0.33	1.1	0.4
Vegetables and products	0.21	2.0	0.0
Vegetable oils and products	1.53	0.0	41.4
Beans, pulses, and products	0.03	0.5	0.0
Root crops and tubers	0.51	3.8	0.4
Sugar and sweeteners	1.76	0.0	0.0
Alcohol products	0.54	0.2	0.0
Miscellaneous	0.16	2.5	1.0
Total	8.93	34.3	45.7
Total demand	13.0	98.0	115.0

[a]Based on data from FAOSTAT.

Table 3.2. Per capita consumption of major food groups in Egypt (1993)[a]

Item	Energy MJ/d	Protein g/d	Fat g/d
Animal products			
Meat and products	0.34	7.1	5.5
Animal fats and products	0.23	0.1	6.2
Eggs and products	0.03	0.6	0.6
Milk and products	0.23	3.4	3.5
Fish and products	0.05	2.0	0.0
Total	0.88	13.2	15.8
Plant products			
Cereals and products	8.94	58.3	15.3
Fruit and products	0.52	2.0	1.0
Vegetables and products	0.33	4.0	1.0
Vegetable oils and products	0.83	0.0	22.0
Beans, pulses, and products	0.36	6.4	0.0
Root crops and tubers	0.21	1.0	0.0
Sugar and sweeteners	1.18	0.0	0.0
Alcohol products	0.00	0.0	0.0
Total	12.57	73.0	42.3
Total demand	13.5	85.0	58.4

[a]Based on data from FAOSTAT.

by-products and imports. The United States was included as a representative developed country, with relatively high intakes of animal products (27% and 63% of energy and protein, respectively). In addition to the current U.S. food intake patterns (Table 3.6), data on dietary trends in the United States during the twentieth century are presented in Table 3.7.

The countries selected cover a range of diets that

Table 3.3. Per capita consumption of major food groups in Kenya (1993)[a]

Item	Energy MJ/d	Protein g/d	Fat g/d
Animal products			
Meat and products	0.31	6.4	5.1
Animal fats and products	0.04	0.0	1.2
Eggs and products	0.01	0.3	0.2
Milk and products	0.58	6.8	7.6
Fish and products	0.04	2.0	0.0
Total	0.97	15.5	14.1
Plant products			
Cereals and products	3.78	24.0	9.0
Fruit and products	0.22	1.0	0.0
Vegetables and products	0.06	1.0	0.0
Vegetable oils and products	0.66	0.0	18.0
Beans, pulses, and products	0.18	3.0	0.0
Root crops and tubers	0.66	2.0	0.0
Sugars and sweeteners	0.75	0.0	0.0
Alcohol products	0.11	0.0	0.0
Total	6.61	31.0	29.0
Total demand	7.58	47.0	43.1

[a]Based on data from FAOSTAT.

Table 3.4. Per capita consumption of major food groups in Mexico (1993)[a]

Item	Energy MJ/d	Protein g/d	Fat g/d
Animal products			
Meat and products	0.93	14.0	16.4
Animal fats and products	0.30	0.0	8.1
Eggs and products	0.18	3.3	2.8
Milk and products	0.66	9.9	7.9
Fish and products	0.09	3.0	1.0
Total	2.16	30.0	36.2
Plant products			
Cereals and products	6.10	38.0	13.0
Fruit and products	0.44	2.0	1.0
Vegetables and products	0.10	1.0	0.0
Vegetable oils and products	1.22	0.0	33.0
Beans, pulses, and products	0.48	6.0	0.0
Root crops and tubers	0.10	0.0	1.0
Sugar and sweeteners	2.11	0.0	0.0
Alcohol products	0.26	0.0	0.0
Total	10.99	49.0	50.0
Total demand	13.2	83.0	87.0

[a]Based on data from FAOSTAT.

Table 3.5. Per capita consumption of major food groups in South Korea (1993)[a]

Item	Energy MJ/d	Protein g/d	Fat g/d
Animal products			
Meat and products	0.99	11.1	21.0
Animal fats and products	0.19	0.1	5.1
Eggs and products	0.15	2.9	2.6
Milk and products	0.12	2.0	1.0
Fish and products	0.39	14.0	3.0
Total	1.84	30.1	32.7
Plant products			
Cereals and products	6.61	31.0	4.0
Fruit and products	0.28	1.0	0.0
Vegetables and products	0.62	9.0	2.0
Vegetable oils and products	1.00	0.0	27.0
Beans, pulses, and products	0.15	3.0	1.0
Root crops and tubers	0.14	1.0	0.0
Sugar and sweeteners	1.21	0.0	0.0
Alcohol products	1.05	1.0	0.0
Total	11.39	53.0	39.0
Total demand	13.5	86.0	74.0

[a]Based on data from FAOSTAT.

Table 3.6. Per capita consumption of major food groups in the United States (1993)[a]

Item	Energy MJ/d	Protein g/d	Fat g/d
Animal products			
Meat and products	1.77	38	28
Fats and products	0.50	0	14
Eggs and products	0.21	4	4
Milk and products	1.52	22	21
Fish and products	0.09	5	1
Total	4.09	69	68
Plant products			
Cereals and products	3.53	25	3
Fruit and products	0.52	1	1
Vegetables and products	0.26	3	1
Vegetable oils and products	2.39	0	65
Beans, pulses, and products	0.45	2	0
Root crops and tubers	0.42	3	0
Sugar and sweeteners	2.58	0	0
Alcohol products	0.66	1	0
Total	10.91	40	76
Total demand	15.1	109	145

[a]Based on data from FAOSTAT.

reflect a diversity of agricultural, particularly animal, production systems (see Chapter 4). Another reason for including Egypt, Kenya, and Mexico is that an excellent, complete, cooperative study of diets of children in Egypt, Kenya, and Mexico has been carried out. This study, the Human Nutrition Collaborative Research Support Program (NCRSP) sponsored by the Office of Nutrition, Bureau for Science and Technology, U.S. Agency for International Development (Calloway et al., 1992), was selected to help focus our discussion of several critical issues relevant to nutritional benefits potentially arising from consumption of animal products by children. Several data from this study are summarized in Table 3.8.

Taken in aggregate, the countries selected (Tables 3.1–3.6) present a wide range of national diets. Average daily per capita intakes of total energy, protein, and fat were highest in the United States at 15 MJ, 109 g, and 145 g, respectively. The other countries ranged from 7.6 (Kenya) to 13.5 MJ/d (Egypt and Korea) for total energy, from 47 (Kenya) to 98 g/d (Argentina) for protein, and from 43 (Kenya) to 115 g/d (Argentina) for fat. Percentages of energy from fat ranged from 16 (Egypt) to 36 (United States), while percentages of total energy from animal fats ranged from 4 (Egypt) to 19 (Argentina). Percentages of total protein from animal sources ranged from 16 (Egypt) to 63 (United States); the contribution of meat ranged from 8 (Egypt) to 42 (Argentina), milk from 2 (Korea) to 20 (United States), eggs from 1 (Egypt, Kenya) to 4 (Mexico, United States), and fish from 2 (Argentina) to 16 (Korea). Thus, the data presented in Tables 3.1–3.6 illustrate that a range of national diets exists and that these can, for the most part, satisfy the nutritional needs of a population. Basically, the national diets reflect the agricultural opportunities for food production in each region and the balancing of food production opportunities with human nutritional needs.

Table 3.7. Food consumption per capita per year by major food groups in the United States through time[a]

Food Group	1909–1913	1957–1959	1977	1986	1993
Meat[b]	64	65	73	55	51
Poultry	8.2	15.4	24.5	21.4	27.7
Fish	5.9	5.9	7.7	7	6.8
Eggs	16.8	21.3	15.4	14.8	13.7
Total dairy[c]	161	217	204	269	260
Butter	8.2	3.6	1.8	2.1	2
Fats and oils	18.6	22.2	26.8	29.2	29.5
Total cereals	132	67.2	64.9	73.5	85.8
Sugars and sweeteners	40.4	48.1	59.4	58.8	66.7

[a]Sources: USDA Statistics. All values in kg/year.

[b]Largely ruminant and pig meats.

[c]Includes all dairy products (fluid milk, cheese, butter, etc.).

Table 3.8. Per capita consumption of major food groups by toddlers and school children in Egypt, Kenya, and Mexico[a]

	Toddlers (18–30 months)			School children (7–9 years)		
Item	Egypt	Kenya	Mexico	Egypt	Kenya	Mexico
Animal products (% energy)						
Meat and products	5.8	0.5	2.8	5.5	0.7	2.3
Animal fats and products	6.2	0.1	1.5	5.6	0.1	1.3
Eggs and products	1.1	0.2	2.5	0.7	0.0	1.9
Milk and products	4.8	6.8	6.3	4.1	2.4	2.1
Plant products (% energy)						
Cereals and products	48.2	52.5	58.0	57.4	65.8	70.6
Fruit and vegetable	4.3	3.1	1.3	4.5	3.3	1.4
Legumes and nuts	4.2	9.9	7.4	4.0	13.8	6.5
Vegetable fats	7.4	3.2	7.3	7.3	2.7	5.7
Root crops and tubers	3.2	17.9	2.0	3.0	7.8	1.2
Sugar, etc.	14.8	5.8	10.3	7.9	3.6	6.2
Totals						
Energy (MJ/d)	5.0	3.5	4.6	7.4	6.0	7.8
Proteins (g/d)	35.8	23.1	33.1	54.3	42.5	53.2
Animal protein (g/d)	13.5	3.8	9.6	17.5	2.9	10.1

[a]Data from Beaton et al., 1992 and Murphy et al., 1995.

These adaptations of human populations to local food production and distribution opportunities will continue, economic necessities, drought, global warming, and other factors notwithstanding. However, modern agricultural and human nutritional research can and should provide the bases for more appropriate adaptations to optimize nutrition and health. Energy intakes in the several countries are all between 12 and 15 MJ/d, with the exception of Kenya, where energy intakes calculated from available data are only 7.6 MJ/d, a surprisingly low value. Protein intakes in most countries are in the 80 to 100 g/d range, with 30% or more derived from animal products, indicating protein and amino acid adequacy. Of concern is Egypt, where only 16% of protein is derived from animal products; however, the Egyptian intake of 85 g total protein/d should be adequate, even given the low lysine content of cereal grain-derived products that contribute 69% of the total diet protein. A more prominent concern is the low protein intake of 47 g/d in Kenya, despite an appropriate balance between animal and plant proteins. The marginal total protein intake in Kenya, coupled with the low energy intake, suggests that protein would be used as a source of energy, which could result in deficiencies in specific or limiting amino acids. This danger would be greatest in growing children and is a common situation in a number of low-income African and Asian countries.

The data presented in Table 3.8 from the Human Nutritional Collaborative Research Support Program (NCRSP) study (1992) illustrate the diets available to toddlers and schoolchildren in three example countries where growth and development of children are below reference values. In addition to reduced growth, Kenyan children exhibited diet-associated depressions in the development of cognitive abilities (Sigma et al., 1989). Energy intake by Kenyan toddlers was 68% of average intakes by Egyptian and Mexican toddlers that are, on average, normal and considered adequate. Similarly, energy intake by Kenyan schoolchildren was below those in Egypt and Mexico, considered adequate to support normal growth. Both total protein and animal protein intakes in Kenyan children were marginal, especially when most of the animal protein was from milk and milk products (Table 3.8), foods particularly low in methionine, zinc, and iron. Total protein and amino acid intakes of Egyptian and Mexican children were deemed adequate to support normal growth, according to the NCRSP summary report. This observation led to a very detailed, multivariate analysis of nutrients potentially limiting to growth in the three countries. In Kenya, it was determined that increasing energy intake was most important. Additional nutrient inadequacies identified in the Kenyan diet were iron, zinc, calcium, and vitamins B_{12}, D, and E. Nutrient inadequacies identified in the Mexican diet were iron, zinc, vitamins A, B_{12}, C, D, E, and riboflavin. Deficiencies in Egypt were iron, calcium, and vitamins A and D. The high availabilities of iron, zinc, vitamin B_{12}, and riboflavin in meat and calcium in milk led to a general recommendation in the NCRSP report that animal products—meat in particular—be increased in the diets of children in these countries. These data and observations clearly illustrate the value of animal products in the diet for human growth, health, and well-being.

Authors of a recent CAST report (Council for Agricultural Science and Technology, 1997a) emphasized that, although overconsumption of saturated fats in ruminant meat generally is recognized as being undesirable, total fat consumption is the primary health concern with regard to heart disease, atherosclerosis, and other vascular diseases. Although statistical inference, e.g., on saturated fatty acid intake vs. premature death, polyunsaturated fatty acid intake vs. breast cancer, is suspect, let us accept the assumption that excessive saturated fat and high total fat intake can negatively impact human health. Fat intakes in Egypt, Kenya, Mexico, and South Korea range between 16 and 25% of total energy intake (Tables 3.3–3.5), well within the range of current NRC and USDA recommendations, as are intakes of animal fats of not more than 10% of total energy. Residents of these countries do not seem to be at risk because of their fat intakes. In Argentina, fats provide 33% of total energy intake, of which 57% is of animal origin (corresponding U.S. values are 36 and 47%). These values are on the high side but fit well with current food production practices in these countries.

Considerable attention has been focused on consumption of ruminant and pig meats in the United States over the past 30 years. This has led to a decrease in per capita consumption of these meats from 65 to 75 kg/yr from 1909 to 1977 to 51 kg/yr in 1993 (Table 3.7). In contrast, consumption of poultry meats has increased from 8.2 kg/yr in 1909 to 27.7 kg/yr in 1993, while consumption of fish remained approximately constant. Egg consumption decreased from a high of 21.3 kg/yr to a current low of 13.7 kg/yr. The most dramatic change in animal products in the U.S. diet has been the drop in per capita butter consumption, from 8.2 kg/yr in 1909 to 3.6 in 1957—coincident with the availability of margarine—and to 2.0 kg/yr in 1997. The decreases in ruminant meat and butter consumption are considered beneficial by many nutritionists. However, what frequently is not noted is that total consumption of fats and oils increased from 18.6 to 29.5 kg/yr between 1909 and 1993, cereal consumption has decreased from 132 to 85.8 kg/yr, and consumption of sugars has increased from 40.4 to 66.7 kg/yr (Table 3.7). Based on current NRC and USDA recommendations, all these changes are undesirable.

It should become clear when comparing the trends in food intakes presented in Table 3.7 that current dietary recommendations of national agencies and views promulgated by advocate organizations have not defined an optimum nutritional strategy for humankind. In context with the brief discussion presented here with regard to diets of children and the large variance in national diets, any number of diets are available that can satisfy human requirements as long as they supply adequate amounts of energy, amino acids, and micronutrients.

4 Animal Production Systems and Resource Use

Domestic animals evolved initially as scavengers, obtaining their food from materials not otherwise usable by humans and converting these into food, fiber, work, and other products useful to humans. This basic role of domestic animals (i.e., extracting and concentrating value from low-cost inputs) remains important today. As animal agriculture has evolved in response to market requirements, the nutritional density and quality of diets has been improved. Nevertheless, even in market-oriented production systems, the value of the product far exceeds the value of the inputs.

Production Systems

Animal production systems have been classified (Seré and Steinfeld, 1996) into three broad categories: grazing, mixed crop-livestock, and industrial (landless). Stratified systems combine elements of two or all three. These systems often involve different species of animals, use different resources, and differ greatly in animal productivity. All contribute useful products or services. Table 4.1 presents the quantity of livestock products produced by grazing, mixed crop-livestock, and industrial systems. Globally, mixed crop-livestock systems produce the largest quantities of animal products. Only in poultry meat and egg production does the industrial system surpass the mixed system.

De Haan et al. (1997) have estimated the growth rates for these systems from 1982–1983 to 1992–1993 and found that mixed systems are growing most rapidly. However, it is uncertain if the predominance of the mixed system will prevail over the long term. For example, with rapid economic growth in the developing world and increased demand for pork and poultry products, there may be a greater shift toward industrial systems. In the Organization for Economic Cooperation and Development (OECD), i.e., the most industrialized countries, the amount of pig meat and eggs produced in the industrial system has increased to 54.2 and 87.9% vs. the 39.3 and 67.9%, respectively, in the global total (Table 4.1). This indicates that, as urbanization occurs and the demand for meat products increases, industrial systems are capable of filling newly generated demand.

Grazing Systems

By definition, grazing systems involve herbivores grazing native rangelands, tame grasslands, and other lands that usually are not suited for food crop pro-

Table 4.1. Quantity (1,000 t) and percent of global livestock products produced by the three major production systems[a]

	Grazing		Mixed crop-livestock		Industrial	
Product	1,000 t	%	1,000 t	%	1,000 t	%
Beef and veal	12,289	23.4	34,249	65.1	6,055	11.5
Buffalo	0	0.0	2,652	100.0	0	0.0
Sheep and goat	2,981	30.0	6,860	69.0	100	1.0
Pig meat	685	1.0	42,821	59.8	28,163	39.3
Poultry meat	796	1.8	10,469	24.2	31,967	73.9
Eggs	524	1.3	12,289	30.8	27,071	67.9
Dairy milk	38,775	8.2	434,332	91.8[b]	0	0.0

[a]Source: Seré and Steinfeld, 1996.

[b]The authors list intensive dairy systems as part of mixed crop-livestock systems, which in general they are. However, some modern dairy production could also be classified as industrial.

duction. Domesticated herbivores (ruminants—cattle, sheep, goats, buffalo; camelids—camels, llamas, alpacas; equines—horses, mules, donkeys) and, to a lesser extent, harvested game constitute the animal component in grazing systems (Figures 4.1–4.6). Grazing systems occur in a wide range of ecozones: arid, semiarid, tropical/subtropical, and temperate. Livestock production in these ecozones is conducted under a wide array of production practices stemming from natural resource differences and methods of resource use. From these various resources, significant portions of ruminant products are produced (Table 4.1).

Globally, increasing pressures are being placed on grazing resources as a result of increased human population. For example, traditional grazing lands are being brought into cultivation to produce food crops, and as a result, livestock use grazing areas for longer periods each year. This and other factors are leading

Figure 4.1. Extensive sheep and goats grazing in Senegal. Photograph courtesy of Eric Bradford, University of California, Davis.

Figure 4.2. Camels grazing desert rangeland in Kuwait. Photograph courtesy of Martin Vavra, Oregon State University, Burns, Oregon.

Figure 4.3. Intensive sheep production on seeded pastures in New Zealand. Photograph courtesy of Howard Meyer, Oregon State University, Corvallis.

Figure 4.4. Milk sheep grazing in the Roquefort region of France. Photograph courtesy of Eric Bradford, University of California, Davis.

Figure 4.5. Hereford calf. Most beef cattle everywhere, whether grazed throughout life or finished in feedlots, are born and spend most of their life on range or pasture. Photograph courtesy of John Dunbar, University of California, Davis.

to concern about environmental impacts of grazing on biodiversity, water resources, and other resources. These issues are discussed further in Chapter 5.

Mixed Farming Systems

Mixed crop-livestock systems are the largest animal production systems in terms of animal numbers, total production, and number of people served (Figures 4.7–4.18). The complementarities between crops and livestock are critical to ecological and economic stability of farming systems in many regions where human population and demand for food are increasing but technology and inputs are not readily available. Key elements in the contribution of livestock are traction (power), manure (fertilizer), and enhanced income (cash) (Winrock International, 1992). Moving across agro-ecosystems and phases of socioeconomic development, the intensity of technology and the interaction with the environment dramatically change the manner in which mixed systems are constructed. Mixed systems have the capacity to change rapidly as

Figure 4.6. Supplementing beef cattle with a molasses/urea mix when grass is scarce. Photograph courtesy of John Dunbar, University of California, Davis.

Figure 4.7. Tethered goats during the night provide manure fertilizer to land in Kenya. Photograph courtesy of David Elsworth, International Livestock Research Institute, Nairobi, Kenya.

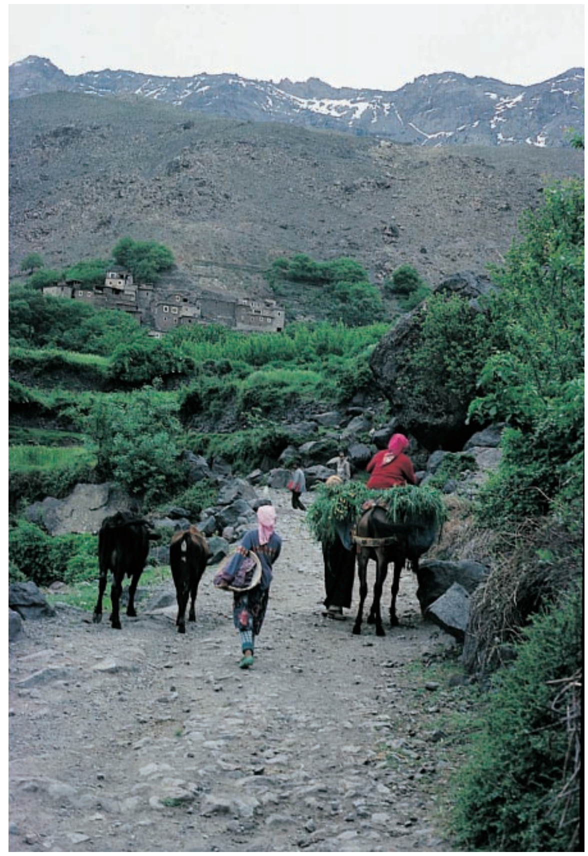

Figure 4.8. Donkey transporting forage in Morocco. Photograph courtesy of Eric Bradford, University of California, Davis.

Figure 4.9. Fodder being transported by camels in Niger. Photograph courtesy of David Elsworth, International Livestock Research Institute, Nairobi, Kenya.

markets, infrastructure, and income grow. In many instances, mixed systems serve as a bridge between grazing and industrial systems. Furthermore, they also can serve as an element of the stratified system. Generally, as rural population pressure increases and less land becomes available, both crop and livestock producers need to intensify. McIntire et al. (1992) showed that, as population pressure increases, crop and livestock activities often integrate.

Mixed crop-livestock systems encompass approximately 2.5 billion ha of land, of which 1.1 billion ha is arable rainfed, 0.2 billion ha is irrigated land, and 1.2 billion ha is grassland. These systems use both ruminants and nonruminants (poultry, pigs). On a global basis, mixed farming systems are the principal source of meat (54%) and milk (90%). Mixed farming systems are most successful where rainfall, soil fertility, and other environmental factors enable successful crop production, with livestock as an important but generally secondary element of the system. Animals add value to low-opportunity cost inputs, including feed (roadside forages, crop residues, by-products) and labor. Animals also provide important nutrient cycling functions, for example, by collecting and transporting nutrients from rangelands to croplands and by their digestive processes, especially rumination, a particularly effective composting mechanism.

Some 80% of farmers in Africa and Asia (including not only crop producers but even the landless) keep small flocks of poultry that survive largely through scavenging. From a biological viewpoint, this type of production is sustainable, because all of the inputs come from renewable resources, although off-take rates are low.

Figure 4.10. Fodder being transported by donkey in Kenya. Photograph courtesy of David Elsworth, International Livestock Research Institute, Nairobi, Kenya.

Figure 4.11. Human transport of forage in Indonesia. Photograph courtesy of Luis Iniguez, ICARDA, Aleppo, Syria.

Figure 4.12. Human transport of forage in Indonesia. Photograph courtesy of Luis Iniguez, ICARDA, Aleppo, Syria.

Figure 4.13. Stall feeding maize residue in a smallholder dairy in Kenya. Photograph courtesy of David Elsworth, International Livestock Research Institute, Nairobi, Kenya.

As described in Chapter 2, in developing countries, animals are a primary source of power for cultivation, a means of "storing" residues and by-products, and a source of savings that can be cashed in when needed (e.g., for purchase of seed, fertilizer, and other crop inputs, or for food). In developing countries, population pressure, poverty, and underdeveloped infrastructure are the fundamental factors affecting the success of mixed farming systems. Soil nutrient depletion can occur and lead to involution of the mixed system, which manifests itself as a downward spiral resulting in monoculture cropping systems, lower-quality food crops being produced, and increased undernutrition and famine (Cleaver and Schneiber, 1994).

Environmentally, at its best, the mixed farming system can maintain soil fertility by recycling soil nutrients and allowing the introduction and use of rotations between various crops, forage legumes, and fallow periods. Incorporation of livestock into the farming system also can maintain soil biodiversity,

Figure 4.14. Market sales of livestock in Niger. Photograph courtesy of David Elsworth, International Livestock Research Institute, Nairobi, Kenya.

Figure 4.15. Manuring in Kenya. Photograph courtesy of David Elsworth, International Livestock Research Institute, Nairobi, Kenya.

Figure 4.16. Night tethering of cows for land fertilization in Kenya. Photograph courtesy of David Elsworth, International Livestock Research Institute, Nairobi, Kenya.

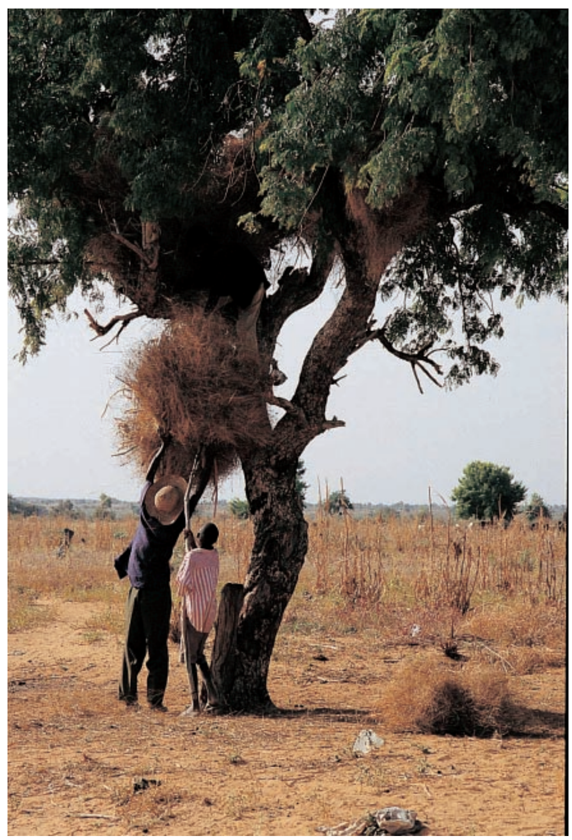

Figure 4.17. Fodder storage in Niger. Photograph courtesy of David Elsworth, International Livestock Research Institute, Nairobi, Kenya.

minimize soil erosion, increase water conservation, and provide suitable habitat for birds.

Mixed systems can challenge environmental stability by causing soil nutrient depletion when population pressure becomes too high, thus placing excess demands on the resource base. In developed countries, on the other hand, heavy commercial fertilizer application and increased numbers of animals can result in nutrient surpluses on the land.

Industrial Systems

Industrial production of pork, poultry, and feedlot beef and lamb is the fastest growing form of livestock production (Figures 4.20–4.22). In 1996, it provided 79% of the poultry meat and 39% of the pork produced globally (de Haan et al., 1997). This type of production system has to date been adopted to a greater extent in developed countries.

The growth of these systems has been stimulated by the market opportunity from urbanized populations and income growth. Industrial systems generally concentrate large numbers of livestock in a small area, intensify feed input over a short period of time, and exercise tight management control over the production and processing activities to increase productivity and reduce wastage. Industrial systems specifically take advantage of scale economies to reduce costs of production, processing, and marketing. They also depend on access to capital and development and implementation of new technologies that can reduce costs or add value to the product.

Principal types are meat production from pigs and poultry, large-scale dairy operations, and beef feedlots. For beef production, the industrial system is often the final component of stratified systems in which livestock are finished to market requirements before slaughter.

The added value to the final product, plus the fi-

Figure 4.18. Feeding crop residues in Kenya. Photograph courtesy of David Elsworth, International Livestock Research Institute, Nairobi, Kenya.

Figure 4.19. Jersey dairy cows on high quality pasture. Photograph courtesy of Thomas Shultz, University of California, Cooperative Extension, Tulare.

Figure 4.20. A modern California dairy in the United States. Photograph courtesy of Thomas Shultz, University of California, Cooperative Extension, Tulare.

nancial savings from shortening time to slaughter, make it profitable to utilize concentrate feeds, including feed grains, oilseed meals, and other food-processing by-products, some of which could be consumed by humans. Industrial systems drive trade in feed grains and other feed sources, providing an opportunity to crop farmers for diversification and additional income. However, as for expansion of any crops, care is needed to avoid cultivation of erosion-prone soils. The greatest environmental concern about industrial systems is the concentration of large amounts of manure and urine in small areas and the resulting potential for pollution of soil, water, and air, unless wastes are carefully managed and monitored. On the other hand, industrial systems, due to intense use of capital and economies of scale, have the greatest capacity to process wastes to minimize negative impacts.

Figure 4.21. Feedlot finishing of beef cattle in the United States. Rations typically contain up to one-third of by-product feeds as well as grain and forage. Photograph courtesy of John Dunbar, University of California, Davis.

Figure 4.22. Industrial broiler production involves large numbers of birds. Photograph courtesy of Ralph Ernst, University of California, Davis.

Stratified Systems

These stratified systems are characterized by moving livestock from site to site, often with change of ownership, typically linking and taking advantage of the lower-cost opportunities in grazing, mixed farming, and industrial systems. In the United States, the typical example is beef production, in which calf production is from cows kept on low-cost grazing lands (including relatively dry rangelands in the west and pasturelands in other regions). After weaning, calves may be moved to better-quality grazing, such as cultivated forages or winter wheat grazing, before finishing on predominantly concentrate diets (e.g., feed grains, milling by-products) in commercial feedlots.

The development of stratified systems is driven by opportunities for cost reduction. Typically, the livestock elements of the system move to where inputs are less expensive. For example, some vertically integrated poultry and pig operations contract with growers to utilize low-cost family labor. Another example of a stratified system involves production of replacement dairy heifers on family farms in the central and northern United States for large-scale industrialized dairy operations in California and Florida. Stratified systems also may improve product quality, by controlling the finishing stage to ensure a more uniform product that meets market requirements for quality and hygiene. Stratified systems generally locate the finishing operation close to the point of slaughter, to minimize stress and transportation costs before slaughter.

The animals involved in "finishing" systems are often by-products of another major animal system. Examples include feeding of male calves from dairy systems and terminal cross-bred lambs from meat breed sires from wool production systems. These by-products of the primary system generally are purchased by operators who specialize in the feeding and finishing of these types of animals for meat production. (Systems 2 and 3, described in Box 2, represent examples of stratified systems.)

Resources Involved in Animal Production

The feeds used for animal production in these different systems are numerous and varied. Although much of the feed used consists of materials that humans cannot consume directly, some is human-edible. Meat, milk, or eggs produced entirely from human-inedible feedstuffs clearly add to human food supply. Feeding human-edible materials to animals can either decrease or increase the total human food supply. Reductions result from feed-to-food conversion rates less than 100%; increases result from the increased efficiency of utilization of the human-inedible portion of the diet as a consequence of providing the animals with nutritionally better balanced diets. The net effect is influenced by the proportions of human-edible and -inedible materials fed, species of animal, production system, and product, all of which vary widely when all of animal production is considered. In all cases, the nutrient density and variety of the human food supply are increased.

Human-Inedible Materials

Forage from Rangelands

Globally, 3.35 billion ha of land are grazed by livestock (Seré and Steinfeld, 1996) (Figures 4.23–4.24). Most of this land is too arid, steep, rocky, or infertile to permit crop production and would produce no human food if not grazed by animals. These lands are of low productivity, compared to arable land, but, collectively, they support about 360 million cattle and more than 600 million sheep and goats (de Haan et al., 1997), plus lesser numbers of other species. Grazing lands supply only about 23% of the world's beef production and 30% (Table 4.1) of the world's sheep and goat meat but, because they complement and make possible other livestock production systems, their importance is not fully indicated by the amount of meat produced directly from them. For example, the U.S. stratified beef production system (Box 2) would not be feasible if there were not a supply of calves for further feeding coming from cow herds maintained on grazing lands.

Production of meat and milk from this source obviously adds to the food supply. However, as the population increases, there is greater pressure for other potential functions of the world's grazing lands, such as crop production or recreational use. Some alternatives are compatible with well-managed grazing; others are not. There is concern about deleterious effects of heavy livestock grazing pressure on biodiversity and sustainability of ecosystem function (see Chapter 5). It is generally accepted that, on significant portions of the world's grazing lands, improved management practices need to be implemented to ensure the long-term sustainability of this feed resource and to preserve other environmental services provided by these lands. Some strategies for such improved management are described briefly in Chapter 5 and are covered in more detail by Humphreys (1994) and de Haan et al. (1997).

Cultivated Forages

Cultivated forages include grazed forages (rainfed or irrigated pastures) and harvested forages (hays and silages). In some cases, these crops are grown on land suitable for food crop production. More often, they are grown on steeper or otherwise more erodible arable lands where they reduce erosion (see Box 3), on less productive soils, or in rotation with food crops to improve the soil's organic content and condition. Forage legumes grown in rotation with other crops not only do not require nitrogen fertilizer but also some of the atmospheric nitrogen they fix in the soil is available to subsequently planted food crops. Growing forage crops in rotation with other crops can help break pest or disease cycles and provide other agronomic benefits. Thus, cultivated forages represent an important

Figure 4.23. Cattle grazing shortgrass prairie in eastern Colorado. Photograph courtesy of Martin Vavra, Oregon State University, Burns, Oregon.

Figure 4.24. Cattle grazing sagebrush-steppe rangeland in Oregon. Photograph courtesy of Martin Vavra, Oregon State University, Burns, Oregon.

Box 2

Impact of Production System on Amount and Type of Feed Required per kg Beef

Three strategies for beef production used in different countries or at different times or places within countries, depending on availability of feeds and their prices, were compared.

1. Range forage only; no supplemental feeds. For six months of each year, forage is sufficient to support modest levels of reproduction and growth; for the remaining six months, animals, on average, simply maintain weight. Calves wean at 150 kg at six months of age, gain 0.5 kg/d for each six-month forage growth season, reaching 420 kg at 42 months or 510 kg at 54 months. Annual calf crop is 65 calves weaned per 100 cows.
2. Cows are supplemented sufficiently to wean a 90% calf crop (90 calves/100 cows) of 240 kg calves at seven months. Calves are carried as stockers, i.e., for an additional growing period, on grass, gaining 0.5 kg/d to 370 kg, then finished in a feedlot on a high-concentrate diet (e.g., Nebraska diet, Table 4.16) to 510 kg.
3. The cow herd is managed as in Number 2 but calves go directly to the feedlot at weaning and are fed to 510 kg.

The growth patterns for the three systems are illustrated in the figure.

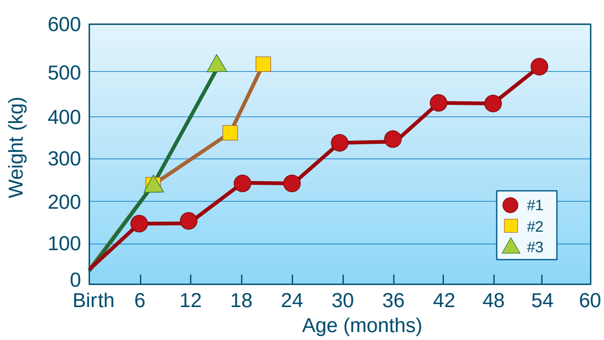

Figure B2.1. Growth patterns (ages in months and weight in kg) of beef production in three production systems (1 = grazing; 2 and 3 = stratified).

Total energy required for cows and bulls, replacement animals (20%/year), and for market animals to slaughter weight was calculated using the program described by Oltjen et al. (1992). Estimated proportions of human-edible feedstuffs fed were based on the values in Table 4.18. Results were as follows, with inputs and outputs calculated per cow in the herd per year:

	System			
	1		2	3
Slaughter wt. (kg)	420	510	510	510
Carcass wt. (kg) obtained from				
Young animals	113	142	221	221
Cull cows	45	45	52	52
Total	158	187	273	273
Feed energy (MJ x 10^3)				
Total	59.3	71.4	65.8	62.8
Human-edible	0	0	10.8	12.5
MJ in feed/kg carcass				
Total	377	381	241	230
Human-edible	0	0	39.5	46.0

The results are consistent with the efficiencies reported in Table 4.17, which were calculated from national data on inputs and outputs. They illustrate clearly the increase in efficiency of total feed use by raising the nutrient density of the diet. With 16 to 20% of the total feed energy coming from human-edible sources, the total energy required per kg of meat produced is reduced by 37 to 40%. Choice of system is determined primarily by economic factors but there are, potentially, substantial environmental implications of the tradeoffs among the systems.

part of the complementarity of livestock and crops described for mixed farming systems.

Forage crops fed to livestock can, in some cases, yield more human food per hectare than food crops for direct human consumption (see Box 4).

Crop Residues

Large amounts of plant materials associated with the production of food crops are not edible by humans but can be used as animal feed (Figures 4.25–4.26). These include crop residues (e.g., straws, stovers, etc. associated with the production of cereal grains and other feed and food crops) and food and fiber processing by-products such as oilseed meals (cakes), brewers grains, sugar beet pulp, and numerous other residuals from food and fiber production, which are not suitable as human food. Some of the more important crop residues and by-products available for animal feed are listed in Table 4.2, along with average dry matter, energy, and protein contents.

As shown in the table, nutritive value, as indicated by metabolizable energy and crude protein content, varies widely among these products. Brans, brewers grains, and oil seed meals (cakes) are good sources of protein and these, along with molasses and beet pulp, are also good sources of livestock feed energy; whole cottonseed is quite high in both energy and protein.

Crop residues, on the other hand, are generally quite low in both digestible energy and protein, although, in some cases, they can be improved in feeding value by chemical treatment. Treated or not, crop residues constitute the basic feed supply in many live-

Box 3

Cultivated Forages and Soil Erosion

Cultivated forages grown to provide feed for livestock include grasses, legumes, and mixtures of these two. Most forage crops are perennials, forming a sod that reduces water and wind erosion. An example of the impact on soil loss is shown in the table below. Also of interest from these data is the relatively low soil loss, compared to that with cultivated crops, on rangeland (natural plant community), and the decrease in recent years in soil loss on cropland, most probably associated with adoption of conservation tillage practices such as no-till and reduced tillage cropping practices, which protect the soil from erosion by leaving more crop residue on the soil surface.

Estimated sheet, rill, and wind erosion by land use in Nebraska [a]

Year	Cultivated crop land	Fallow crop land	Pasture	Rangeland
	Soil loss in tons/hectare/year			
1982	7.2	1.5	1.2	1.3
1987	6.7	1.3	1.0	1.2
1992	5.8	1.1	1.0	1.2

[a]Source: USDA Soil Conservation Service. 1992 national resources inventory. USDA-SCS, Washington D.C.

Figure 4.25. Beef cattle utilizing sorghum stubble following harvest of the grain crop. Photograph courtesy of John Dunbar, University of California, Davis.

Figure 4.26. Sheep grazing cereal stubble in Morocco. Photograph courtesy of Eric Bradford, University of California, Davis.

Box 4

Human Food from Feed and Food Crops

Some crops grown to feed livestock are raised on arable land that could be used to grow food crops for direct human consumption. A common assumption is that growing food crops will result in more human food, because it avoids the losses resulting from the fact that animals convert feed to meat, milk, or eggs with less than 100% efficiency. In some cases, that assumption is valid, but because of the high nutritional quality and palatability of the foods produced by animals, the tradeoff is generally considered worthwhile. However, the amount of meat, milk, or eggs produced from a unit of land is a function of crop yield as well as conversion rate by the animal. A crop such as alfalfa, for example, yields much more tonnage than any food crop that might replace it, while dairy cattle convert their feed to milk with relatively high efficiency. As shown by the example in the table below, in California, more human food energy and protein (of higher quality) is obtained per hectare from growing alfalfa and feeding it to dairy cows than by growing wheat. The alfalfa requires more water but less nitrogen fertilizer. Tomatoes and grapes, two high-value crops more likely than wheat to be grown on land suitable for alfalfa, produce only a fraction of the food energy or protein of either wheat or milk from alfalfa.

A second example of a difference in yield between crops that relates to human food supply also is shown in the table. Maize (Nebraska data) produces more than twice as much grain per hectare as wheat. Most maize is used as livestock feed, while most wheat is used for human food, with the result that, on average, wheat will produce more human food per acre than maize. However, the variety added to diets by the animal products from maize makes this tradeoff generally acceptable. An additional important point relates to calculations of the number of people that could be fed with the grain used to feed livestock (Pimentel et al., 1997). Implicit—if not explicit—in such calculations is the assumption that one ton of human food would be available for each ton of grain not fed to animals. Given people's preference for wheat vs. maize, expansion of wheat area at the expense of area cropped to maize would not give an equivalent increase in human food because of the lower yields of wheat.

Inputs and human food outputs for various crops (human food energy and protein from maize and wheat calculated assuming 20% milling losses) [a]

		Inputs[b]				Outputs[c]		
						Yield DM	Human	
		N	P	K	Water		DE	CP
Location	Crop	kg/ha			cm	t/ha	MJ x 10^3/ha	t/ha
Calif., Central Valley								
(irrigated)	Alfalfa	0	67	90	146	16.25	—	—
	Milk (from alfalfa)	0	67	90	146	2.89	62	0.80
	Wheat	134	34	0	61	4.05	51	0.46
	Tomato	224	34	56	122	0.54	8	0.09
	Grape	34	0	34	91	1.25	19	0.04
Nebraska	Maize	157	15	5	34	7.41	100	0.58
(irrigated)	Wheat	90	12	4	8	3.49	44	0.40
Nebraska	Maize	125	13	5	0	5.25	71	0.41
(dryland)	Wheat	40	6	0	0	1.92	24	0.22

[a]Data compiled by J. W. Oltjen and K. G. Cassman.

[b]Inputs: N = nitrogen; P = phosphorous; K = potassium.

[c]Outputs: DM = dry matter; DE = digestible energy; CP = crude protein.

stock production systems (e.g., rice straw as the principal forage for dairy rations in many Asian countries; wheat and barley straws as the principal forages for summer, autumn, and winter feeding, particularly for sheep, throughout the Mediterranean region). In the latter region, many farmers consider the stubble grazing and conserved straw from cereal crops to be at least as important as grain production; even in years when they fail to get a grain crop due to lack of rain, the crop usually produces some forage to help maintain their livestock.

Food and Fiber Processing By-Products

Data on total amounts of the two major classes of by-products listed in Table 4.2 and on crop residues from four major cereal crops are presented in Table 4.3 for selected countries and the entire world. The crop residues were calculated from the production of wheat, rice, maize, and barley, assuming 55% of each crop is residue and 45% is grain and that 50% of the residue is left in the field for soil cover and to provide soil organic matter (Loomis and Connor, 1996). Additional production details for specific by-products and crop residues in the listed countries are reported by Fadel (1999).

The data in Table 4.3 indicate marked variation among countries in total and in per capita supplies of these major classes of feedstuffs. For example, Kenya has below-average per capita supplies of each of the groups of feedstuffs, reflecting and contributing to the lower-than-average per capita food supply described earlier (Chapter 3).

The United States produces less total quantity of each of these classes of feedstuffs than China except

Table 4.2. Nutrient composition for ruminants of by-product feedstuffs, dry matter basis (from National Research Council, 1989)

By-product feedstuffs	Dry matter (g/100 g)	Metabolizable (MJ/kg)	Crude protein (g/100 g)
Miscellaneous			
Almond hulls	90	7.7	2.1
Bagasse	90	6.3	1.5
Beet pulp	91	12.6	9.7
Brans	90	12.8	17.2
Brewers grains	21	10.4	25.4
Citrus pulp	21	12.6	7.3
Whole cottonseed	92	16.0	23.0
Molasses[a]	76	11.8	7.2
Cakes			
Soybean	89	13.8	49.9
Ground nut	92	12.5	52.3
Sunflower seed	93	10.3	49.8
Rape and mustard seed	91	11.0	40.6
Cottonseed	91	12.3	45.6
Palm kernel[b]	91	11.0	40.6
Copra	91	12.1	23.4
Sesame seed	93	12.5	49.1
Miscellaneous cakes[b]	91	11.0	40.6
Corn germ meal	91	11.9	22.3
Corn gluten feed and meal[c]	90	13.8	33.9
Soap stock oils	100	30.6	0.0
Crop Residues			
Wheat	89	6.3	3.6
Rice[d]	91	6.2	4.3
Barley	91	7.2	4.3
Maize	85	7.4	5.9

[a]Average of low quality sugar cane molasses and molasses from sugar beets.

[b]Same as rape and mustard seed composition.

[c]Assume 20% corn gluten meal and 80% corn gluten feed.

[d]National Research Council (1984) used for rice crop residue.

for oilseeds, the latter due to the very large U.S. soybean production. Soybean meal represents a special case as a by-product feed; for most crops, the food crop represents the larger and the by-product the lesser proportion of the crop. However, for soybeans, the oilmeal used for livestock feeding represents the greater portion, with the primary food product, currently soybean oil, the lesser portion. This situation could change in the future, as more of the soybean protein could be used for direct human consumption. However, processing soybeans into products such as tofu also results in by-products useful for livestock feeding. Whole cottonseed and cottonseed oil meal contain a compound, gossypol, which is toxic to humans, pigs, poultry, and horses, but which is detoxified in the rumen of cattle, sheep, and other ruminants. As a result of this detoxification and its high protein and energy content, cottonseed, where available, is an important ruminant feed.

Grasser et al. (1995) reported on the feeding and dollar values of by-products sold to the California dairy industry. Total annual dollar value of just nine by-products in 1992 was $232 million, representing more that one-fourth of the total concentrate feed used annually in the state's dairy industry. Cottonseed alone was worth $125 million. Applying Grasser's methods of estimation to the global supply of by-products (excluding crop residues) in Table 4.3 indicates these would energetically support over 500 million tons of milk production, nearly equal to current total world milk production. Conversion rates would, of course, vary depending on the feeding, management, and genetics of the animals involved, with high conversion rates facilitated by the availability of high-quality forage, as in the system evaluated. Also, by-product use may be spread across several animal species, not just dairy.

The totals in Table 4.3 represent an underestimate of the total by-products available, because numerous additional crops such as cassava, sweet potato, and many fruit and vegetable crops yield by-products that can be excellent feed (cull broccoli and carrots are examples). Bakery waste, where available, is a valuable source of high-energy feed. These by-products are generally less important in terms of tonnage than the ones listed, less accurately reported, and their nutritive values are often less well defined, but where available, they can be a key source of feed for animals. Total crop residues also would be much higher than those shown in Table 4.3, because the latter are based only

Table 4.3. Crop residue and by-product feedstuff production, metabolizable energy (ME) and protein (CP) content for selected countries, 1993[a]

	Argentina	China	Egypt	Kenya	Korea Republic	Mexico	United States	World
Miscellaneous[b]								
Prod^n, 10^3 t	2,557	40,389	2,890	596	893	6,183	15,030	221,084
kg/capita	75	34	48	23	20	70	57	40
ME, 10^9 MJ	24.5	497.3	31.2	5.3	11.4	56.0	177.3	2,301
CP, 10^3 t	219	6,387	337	44	152	473	2,041	23,767
Cakes[b]								
Prod^n, 10^3 t	322	12,019	602	34	2,658	2,891	23,374	124,105
kg/capita	10	10	10	1	60	33	89	22
ME, 10^9 MJ	3.9	154.9	8.0	0.4	34.4	38.4	317.3	1,612
CP, 10^3 t	148	5,661	290	14	1,174	1,324	11,377	56,522
Crop Residues[b]								
Prod^n, 10^3 t	6,530	163,444	5,286	434	3,643	4,720	60,377	651,498
kg/capita	193	137	88	17	83	54	230	118
ME, 10^9 MJ	43.2	1,039.4	34.0	3.1	22.7	33.1	410.9	4,194
CP, 10^3 t	277	6,945	224	23	157	237	2,789	27,393

[a]Data summarized from Fadel (1999).

[b]See Table 4.2 for feedstuffs within each group.

on wheat, rice, maize, and barley.

For the by-products (excluding crop residues, soap stocks, and molasses) in Table 4.2, Fadel (1999) has calculated that, as a weighted world average, every 100 kg of food produced yields 37 kg of animal feed by-product. This re-emphasizes the importance of integration of crop and animal production in food production systems.

Animal by-products also are recycled through animals (Figures 4.27–4.33). For every 100 kg of edible meat, about 100 kg of animal by-products are generated, with about half typically fed to animals (Romans et al., 1994), with leathers, glues, pharmaceuticals, and many other useful products coming from the remainder. With regard to feeding animal by-products, the outbreak of bovine spongiform encephalopathy (BSE) in cattle in Britain emphasizes the need for special care in the feeding of animal by-products, particularly to the same species or class of animal.

Figure 4.27. Almond hulls are a high energy content feed for ruminants. Photograph courtesy of John Dunbar, University of California, Davis.

As an example of the value of feeding animal by-products, a rice straw-based livestock diet, even supplemented with adequate protein, is too low in energy to support efficient milk production. Supplementing such feeds with animal fat helps convert them to a productive diet, facilitating the use of an abundant but low-quality residue with the addition of another human-inedible material.

The waste disposal function of animals in utilizing these many by-products also represents a valuable service. There is some residual waste in terms of manure (which itself is valuable if properly used) but the volume is greatly reduced. If by-products such as citrus pulp, nonfood-grade molasses, and wet brewers grains were not used for feeding livestock, the cost of the food products with which they are associated would be higher, both because of lost income from the sale of by-products and much higher waste disposal costs. In countries with strict environmental regulations, there is a strong effort on the part of industries producing by-products with potential animal feed value to have these products tested and, if acceptable, registered as feedstuffs, as this can greatly reduce the cost of disposing of a product otherwise considered waste.

Human-Edible Materials Used as Animal Feeds

Domestic animals convert a wide variety of human-inedible materials into high-quality human food but they also consume approximately one-third of the global cereal grain supply. Although the proportion of the

Figure 4.28. Dried beet pulp is a good feed for cattle. Photograph courtesy of John Dunbar, University of California, Davis.

Figure 4.29. Citrus pulp used in dairy cattle rations. Photograph courtesy of Eric Bradford, University of California, Davis.

world's population that is undernourished is decreasing (American Association for the Advancement of Science, 1997), more than 800 million people do not yet have an adequate diet. It has been suggested (e.g., Brown, 1997) that grain now used to feed animals should be used for direct human consumption. This shift can and does occur in times of local or temporary food grain shortages but the use of high-energy feeds, in combination with forages and by-products, has important implications for overall efficiency of animal production and thus for quantity and quality of the human food supply.

The first demand on nutrients from the feed consumed by animals is for maintenance, i.e., for vital functions such as respiration, and digestion and absorption of nutrients. Nutrients in excess of maintenance requirements are available for productive functions: growth, reproduction, lactation, fiber production, and work. If animals consume a low nutrient-density diet, for example, a low quality forage, they may have only enough digestive capacity to meet

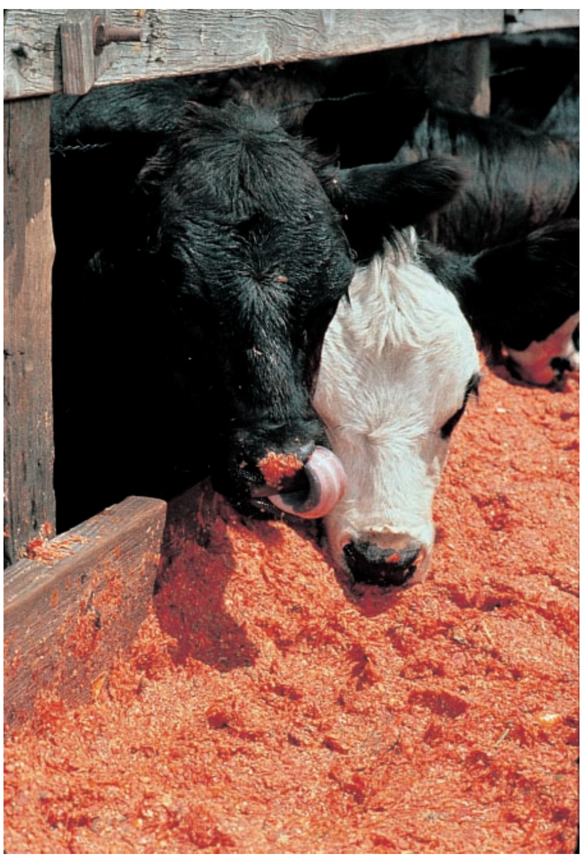

Figure 4.30. Tomato pomace. Originally a waste product, now used in ruminant rations with feed value similar to alfalfa. Photograph courtesy of John Dunbar, University of California, Davis.

Figure 4.31. Commodity barn, California dairy. Whole cottonseed in center bay. Photograph courtesy of Thomas Shultz, University of California, Cooperative Extension, Tulare, California.

Figure 4.32. Carrot waste by-product from carrot processing being stockpiled for livestock feed. Photograph courtesy of Martin Vavra, Oregon State University, Burns, Oregon.

Figure 4.33. Chaff dumps are created during wheat combining as a way to accumulate waste material to be consumed by cattle. Photograph courtesy of Martin Vavra, Oregon State University, Burns, Oregon.

their maintenance needs (or even less, in which case they can survive only by drawing on body reserves in fat or muscle). In this situation, productive functions cannot occur until the nutrient content of the feed is increased. Thus, a key principle in improving the productivity of animals is to increase the proportion of nutrients going to productive functions and thereby reduce the proportion used for maintenance. Providing adequate nutrients is, of course, also a key tenet of good animal husbandry.

Providing adequate nutrients may require increasing the quantity of feed or the nutrient density, or both, depending on what is limiting. This may be achieved by moving animals to a new location at the end of the growing season in one area, as is routinely done in transhumant systems; controlling stocking rate so that each animal has adequate forage (although this may not solve forage quality problems during dry seasons); providing cultivated forages; or by feeding higher nutrient-density diets containing cereal grains or by-product feeds. The choice among these options depends on the species of animals involved, which have different digestive systems, and on the availability and costs of alternative feed sources in relation to potential returns.

Nonruminant animals, such as pigs and poultry, do not digest fibrous feeds well, so they must have balanced, high-energy diets at all times if they are to achieve their productive potential. For example, scavenging chickens might produce 50 or fewer eggs per hen per year; modern strains of laying chickens fed to meet their nutrient requirements average in excess of 250 eggs per hen per year. This level cannot be achieved on a scale approaching that required to meet global demand without use of cereal grains and protein supplements.

Ruminant animals can digest high-fiber feeds such as grasses and crop residues but their productivity is greatly enhanced by including higher-energy (and protein, if needed) feeds in their diets. For example, cattle in pastoral systems in many developing countries depending only on natural forage, may gain weight just during the forage growing season, often only three to six months of the year, and maintain or even lose weight the remainder of the year. Thus, they typically do not reach slaughter weight until three to five years of age. In contrast, calves put into a feedlot at weaning and fed a high-energy diet may reach slaughter weight at 14 to 16 months of age, reducing the maintenance period for the animal by two-thirds or more. Also, in a pastoral system with no supplements provided, many cows produce a calf only every other year; where better forage and/or supplemental feed (usually hay or by-products) are supplied to the breeding herd during periods of natural forage deficiency, more than 90% of the cows produce a calf each year. The difference between the two systems in proportion of total feed going to maintenance (i.e., in gross feed conversion efficiency) is substantial (see Box 2). However, as described in Box 2 and in subsequent sections, the system with the more favorable total feed conversion efficiency generally involves use of human-edible materials as a part of the animals' diets.

The feeding of substantial quantities of grain to beef cattle in large feedlots is a relatively recent practice, confined largely to developed countries and stimulated by the fact that grain yields per hectare increased much more rapidly than demand for grain for human food from the 1950s through the 1980s, resulting in surpluses. Prices of grains in constant 1990 dollars declined 78% from 1950 to 1992 (Mitchell and Ingco, 1993). Feedlot feeding has, in fact, been an important buffer for grain prices and, if real prices of grains rise in the future, alternative systems using less grain will be adopted.

One such system, outlined in Box 2, involves calves grazing on improved range or pasture for a period after weaning, with only a short period in the feedlot prior to slaughter. This practice will increase slaughter age but uses less grain than when animals are fed from weaning in the feedlot. This system is followed when grain prices rise; during the 1970s, when world grain prices increased sharply, feeding of grain to cattle in feedlots in the United States decreased 50% in one year.

The relationship between nutrient density of the diet and overall efficiency of production leads to a number of tradeoffs. Higher nutrient-density diets are obtained by using some human-edible feed inputs but result in more production of food from fewer animals, occupying less land, producing less waste, and in the case of ruminants, producing less methane. Intensification of animal as well as crop production is potentially an important means of reducing human pressure on land (Waggoner et al., 1996).

Estimates of the amounts and types of concentrate feeds (which include human-inedible as well as human-edible feedstuffs) used for different types of animal production in developed and developing countries were compiled from FAO data sources by Hendy et al. (1995). These data are summarized in Tables 4.4 and 4.5, along with FAO data on amounts of the different products.

Approximate conversion rates for grain to meat, milk, or eggs for developing and developed countries were calculated from the totals in Table 4.5 and included in the table. The assumption made that cereal grain content of the concentrate ration for all of the species is the same is probably not correct; it is likely to be higher for poultry and pigs and lower for ruminants, due to the inclusion of more by-products for the latter. Even without adjustment for this possible bias, the grain/product ratios for ruminants compare favorably with those for poultry and pigs. The data in Table 4.5 document the lower use of feed grains in developing vs. developed countries.

For additional information on conversion rates by food animals and on reasons for variation in reported estimates of conversion rates, see Box 5.

A fact often overlooked in the feed grain/food grain debate is that the most important feed grain, maize, yields substantially more per hectare than the most important food grains, wheat and rice. Maize is consumed directly by humans but wheat and rice are strongly preferred in much of the world. Most land used to grow maize is not suited for rice, so a shift in use from feed grain to food grain would undoubtedly result in a shift from maize to wheat. Such a shift in the United States would lower total yield by about 4 tons/ha (see Box 4). Shifting half the 27 million ha of maize to wheat, in the United States alone, would reduce total grain production by an estimated 50 million metric tons (Mt) annually, which may be compared with total U.S. wheat production of about 65 Mt per year. Thus, the net increase in human food calories from this shift would be only a fraction of that projected from the assumption of a 1:1 replacement of feed grain by food grain.

The primary reason for the apparent failure of grain to be used to satisfy all human needs before any is used for animals is an income problem; people in countries where food shortages occur lack the means

Table 4.4. Cereal grains and other concentrate feeds used in developed/developing countries (1990–1992)[a]

	World total	Developing countries		Developed countries	
Feeds	Mt	Mt	% of world total	Mt	% of world total
Cereals	600.5	186.8	31.1	413.7	68.9
Brans	118.9	88.7	74.6	29.2	24.6
Oilseeds and cakes	132.7	49.5	37.3	81.5	61.4
Roots and tubers	129.9	76.1	58.6	54.6	42.0
Total	982.0	401.1	41	579.0	59

[a] Source: Hendy, 1995: 1. Table 3. 2. Table 6.

Table 4.5. Concentrate feed use and food production (Mt) from animals in developing and developed countries (1992–1993)

	Developing countries				Developed countries			
Product	Production[a]	Concentrate feed[b]	Grain[c]	Grain/ product	Production[a]	Concentrate feed[b]	Grain[c]	Grain product/
Beef, veal, and buffalo meat	22.2	14.5	6.8	0.31	32.1	118.1	83.9	2.61
Sheep and goat meat	6.1	4.2	2.0	0.33	3.9	4.3	3.1	0.78
Pig meat	38.5	144.2	67.8	1.76	36.8	190.3	135.1	3.67
Poultry meat	18.8	62.9	29.6	1.57	26.0	78.8	55.9	2.15
Four meats	85.6	225.8	106.2	1.24	98.8	391.5	278.0	2.81
Milk	177.1	81.7	38.4	0.22	352.8	162.9	115.7	0.33
Eggs	23.6	78.1	36.7	1.56	18.1	55.7	39.5	2.18

[a]FAOSTAT, 1997.

[b]Hendy et al., 1995, Table 11.

[c]Assuming proportion of concentrate feed made up of cereal grains is 47% and 71% for developing and developed countries, respectively (see Table 4.4), and is the same for all classes of animals (see text).

Box 5

How Much Grain Does It Take to Produce a Pound of Meat? Conversion Rates of Human-Edible Inputs by Different Species of Food-Producing Animals

Widely varying estimates of the amount of grain required to produce a pound of meat from different species have been reported in recent years in both the popular press and in some scientific journals. Unfortunately, some of the estimates are incorrect, in some cases by a two- to four-fold margin.

Estimates (from Table 4.5) of the grain fed per unit of carcass weight of four meats produced, in developed and developing countries, are as follows:

	Grain Per Unit of Product	
Product	Developed countries	Developing countries
Beef	2.6	0.3
Sheep and goat meat	0.8	0.3
Pork	3.7	1.8
Poultry Meat	2.2	1.6

These results from global summaries of grain fed and meat produced are consistent with the results of detailed analyses of inputs and outputs for different countries and production systems reported in Chapter 4 of this report.

A global estimate of conversion rate of human-edible feed to human food was presented by Steinfeld et al. (1997), who calculated that, worldwide, animals consumed 74 million tons of human-edible protein and produced 54 million tons of human food protein. This gives an input:output ratio of 1.4:1. As it happens, the ratio of biological value of animal protein to that of plant protein is, on average, also 1.4:1. On this basis, from the perspective of human protein nutrition, the use of animals does not decrease the amount of protein available for humans, which has been an issue of concern.

The grain:product ratios above may be contrasted with the values of 12:1 for beef and 2:1 for poultry used by Waggoner (1998), or the values of 8:1 for beef, 3:1 for pork and 2:1 for poultry presented in a recent issue of National Geographic (October 1998). Clearly, the largest differences are in conversion rates reported for beef cattle.

There are several reasons for the discrepancies. The most common is the assumption that the feed fed to animals is 100% grain. As documented in the case studies in this report, diets of all species of food-producing animals include some materials not edible by humans; for ruminants, the human-inedible portion is often 100% and always more than 50%, on a life-cycle basis. The amount of grain required to produce meat from ruminants such as beef cattle is therefore seriously overestimated by neglecting the forage and by-products that make up the largest part of their diet.

A second source of discrepancy is consideration of only a portion of the life cycle. Beef cattle in U.S. feedlots typically require five to seven pounds of feed to produce one pound of gain; 50 to 70% of the feed may be human-edible, giving a human-edible input:product ratio of 2.5 to 5:1 for this part of the production cycle. However, the animals have reached 50 to 70% of final live weight (45 to 65% of carcass weight) when they enter the feedlot, with the gain up to that time coming entirely or almost entirely from forage (see Box 2 and Table 4.16). In other words, only 35 to 55% of the meat produced by the animals is produced during the period when human-edible inputs are fed. Thus, the grain:beef ratio is between 0.9 and 2.8:1, based on final live weight of the animal, or between 1.4 and 4.4:1, based on carcass weight, consistent with the average developed country value of 2.6:1 in the table.

A third factor contributing to discrepancies in reported conversion rates is variation in choice of end point, e.g., live weight, carcass weight, boneless cuts (see Box 1).

The fact that several of the input:output ratios are greater than 1:1 does mean that feeding less grain to animals would translate to somewhat more total food for humans. It would also mean a food supply with less variety and lower nutrient density. As noted elsewhere in this report, grains fed to animals represent a buffer for human food grain supplies; whenever grain becomes scarcer and more expensive, less is fed to animals. Grains and protein supplements fed to animals also improve the conversion rates of forages and by-products to human food.

The efficiency with which animals convert human-edible inputs to human food is a factor to be considered in determining policy related to human food supply. Better policy decisions will result if the discussions on the subject are based on actual conversion rates and not on estimates from assumptions that ignore what animals actually eat.

to purchase food on the world market. In general, hunger occurs where people cannot produce enough food or lack the means to purchase the food they need. Better income distribution and food distribution, to facilitate the transfer of food from surplus to deficit areas, is an important global goal. However, it is unlikely to be achieved efficiently or effectively by imposing mandated constraints on livestock production. The first consequence of feeding less grain to animals in developed countries is likely to be a drop in grain prices, prompting growers to shift to other crops. A tax on animal foods in more affluent countries, as has been suggested (Brown, 1997), could increase global prices for these foods and might have limited effect on consumption by those who now consume adequate or more than adequate amounts, but it would reduce consumption of animal products among those who would benefit most from these foods in their diets.

Water

In some parts of the world, water is the first limiting factor in food production (Figure 4.34). The use of water in animal production is, therefore, of interest. Some very high estimates of water requirements for this segment of agriculture have been reported. For example, Pimentel et al. (1997) reported an estimate of 100,000 liters (L) of water per kg of beef. This estimate is apparently based on the assumption that all feed used for beef production comes from irrigated land, which is clearly not the case. Beckett and Oltjen (1993) estimated the total use of developed water for U.S. beef production, including water for irrigation, drinking water, and water used for animal processing at marketing. They calculated that total water requirement was 3,682 L/kg of beef, less than 4% the amount estimated by Pimentel's group. Beckett and Oltjen's analysis showed that water use is sensitive to the extent of use of irrigated pasture, which is a major reason that most beef cattle, in the United States and elsewhere, obtain much, if not all, of their feed from nonirrigated land.

Figure 4.34. **Cattle drinking at a waterhole in Niger. Photograph courtesy of David Elsworth, International Livestock Research Institute, Nairobi, Kenya.**

Alfalfa, the most important feed in many intensive dairy-production regions, uses large quantities of water. However, alfalfa is a high-yielding crop and, as shown by Loomis and Wallinga (1991), its efficiency of water use compares favorably with that of other crops. Also, as documented in Box 4, alfalfa fed to dairy cattle can result in a higher return of human food per hectare than do other crops likely to be grown on the same land.

Energy

Widely varying estimates of the relative energy requirement for production of animal and plant foods have been reported. Coley et al. (1998) reported the results of an analysis of the fossil fuel energy used in the production, processing, and distribution of 85 foods in typical diets in the United Kingdom. The "embodied energy" varied widely among the foods, with meat, milk, and eggs below the average of all foods. Pimentel (1997), on the other hand, state that animal protein production requires more than eight times the energy required for plant protein.

The large discrepancy between these estimates is due mainly to the assumptions used, with differences in the production systems considered a possible factor. Pimentel has overestimated the proportion of animal feed coming from grains and other cultivated crops involving use of fossil fuel.

In all areas of resource use, it is important that policies affecting allocations be based on properly quantified estimates of the resources actually used. For human-edible feed inputs to livestock production, good estimates are becoming available, but, as outlined in Box 5, the human-edible portion of the feed fed to animals has often been substantially overestimated. For water and energy, only a very few well quantified estimates have been made, and more, relating to a wider range of food production systems, are needed. For water, the estimates should be based on developed water, i.e., water available for allocation to other human uses. Whether crop production, for food or for feed, is rainfed or requires irrigation is also a critical consideration in determining the water cost of food.

Case Studies

Generalities regarding alternative strategies for optimizing the clear complementarities between crop and animal agriculture in terms of human food production, sustainability of food-production systems, and the environment in a global context were discussed in previous chapters. These were, indeed, generalizations based on highly aggregated data. In this section, quantitative estimates of the contributions of animals to human food production systems in specific countries and states—Argentina, Egypt, Kenya, Mexico, South Korea, the United States, Nebraska, and California—will be presented. These examples were selected to illustrate the range of current animal production systems and, hopefully, to correct widespread misinformation regarding the true contributions of animals to food production. The global data presented in Tables 4.4 and 4.5 and in Box 5 and accompanying text addressed the misinformation issue briefly; however, it is important to address further the range of animal production systems in the world and current and potential contributions of animals to human food production through presentation of specific, quantitative case studies.

The case studies undertaken were comprehensive and detailed. Due to space limitations, it is not feasible to present the complete analyses. Therefore, each step will be presented with one or two example calculations from the several case studies to illustrate the approach used.

The first step in our analyses was to inventory the world's land resources plus those of each country and state selected for the case studies (Table 4.6). The data were summarized and are presented here because they define and must underlie any analysis of resources available for feed and food production in a given state, country, or region. The world's land resources are 13.4 ∞ 10^9 hectares. Only 11% is considered arable by the UN-FAO (FAOSTAT). Twenty-one percent of U.S. land is considered arable, while 26% is grasslands and range, and an additional 32% is considered forest and woodland, some of which yields forages that can be grazed by ruminant livestock and thereby contribute to the food supply. The remaining 21% is desert and urban land. Nebraska, selected to represent the American Midwest, has a high percentage of arable land (41%) and extensive grassland and range (53%) resources. The well-known arable valleys of California are highly productive but comprise only 10% of the state's land area. The remainder is mountainous, forested pasture, rangelands, urban areas, and other like areas. In the other case study countries, 3% (Egypt) to 17% (South Korea) of land resources are arable; zero (South Korea) to 52% (Argentina) of land resources are grass- and rangelands. An example of differences among countries in proportions of types of land is illustrated in Figure 4.35. As indicated earlier, the range of land resources represented in the case study selections essentially dictated a wide array of solutions to the goal of optimizing food production.

The second step in the analyses was to collect quantitative data on feed resources and utilization relevant to each case study. General summaries regarding cereal grain and by-products available for and utilized in animal production are presented in Tables 4.2–4.4. USDA and FAO data available on the Internet were used to assess feed and food grain utilization in animal production and tabulated for each case study. An example summary for the United States is presented in Table 4.7. These data tabulations defined the amounts of feed and food grains, by-products, and crop residues (Tables 4.2 and 4.3) that could be used in the case study calculations for the several animal species

Table 4.6. Land utilization (hectares x 10^6) (1993)[a]

	Arable	Permanent pasture	Forest and woodland	Total	Human population (x 10^6) 1997
World	1,503.3	3,435.1	4,180.0	13,387	5,848
Argentina	27.2	142.0	50.9	278	36
Egypt	3.2	0	0	100	64
Kenya	4.5	21.3	16.8	58	28
Mexico	24.7	79.0	48.7	196	94
South Korea	2.1	0.1	6.5	10	46
United States	184.0	239.2	296.0	936	272
California	10.1	18.3	14.8	41	32
Nebraska	7.8	10.0	0	20	2

[a]FAOSTAT, 1997.

and production strategies.

Available data on harvested forages—silages, hay, straws, or crop residues—also were tabulated, as these are important to ruminant production. FAO and USDA data available for some countries seemed fairly complete, based on cropping strategies used, e.g., ha in various crops and yields, as revealed by the national diets summarized in Tables 3.1–3.6. For several case studies, the data were not reported or were clearly incomplete. When complete, these data were used in formulating national livestock diets. In the other cases, it was necessary to consider harvested forages as dietary components comparable in quality to grassland and range forages. Errors associated with this assumption are small, because countries in which maize silage, which is higher in quality than average forages, is utilized, quantities produced were reported.

The major sources of nutrients in most ruminant animal production systems are pasture, range, and woodland or forest forages. Forage yields and animal intakes of forage from these sources often are not available or reported and are generally suspect because of the difficulty of obtaining accurate data. Because of this uncertainty, the usual approach is to calculate intakes of grazing animals based on their estimated maintenance energy requirements, pregnancy and lactation requirements, rates of gain, and ranging activity needs. This approach was used in the calculations presented here.

Based on land resources (Table 4.6) and production systems characteristic of each country or state selected for the case studies, feed resources utilized in animal production were computed from data on cereal grain, by-product, conserved forage, and crop residue supplies (Tables 4.2–4.4), when the latter were available. Calculations of pasture, rangeland, and woodland forage yields and animal feed intakes were based

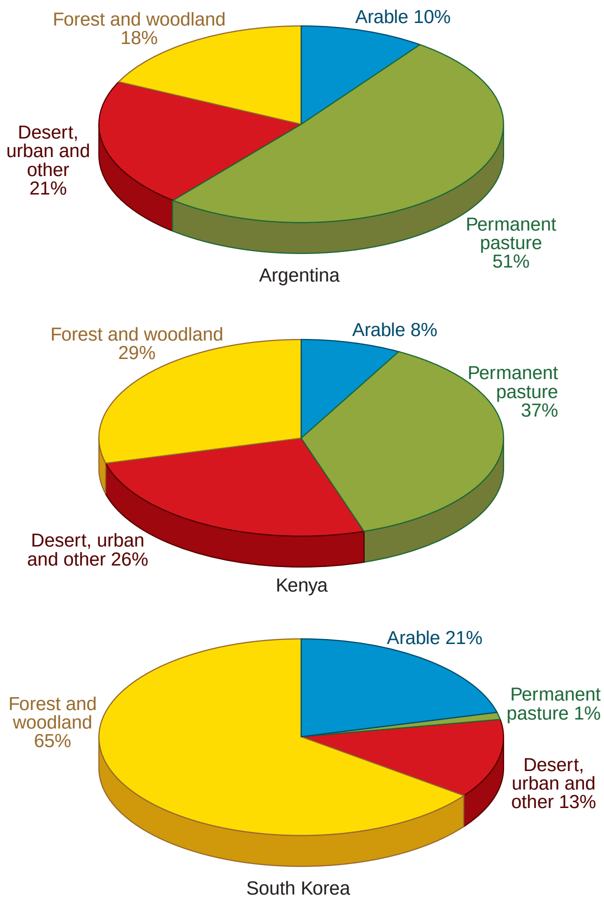

Figure 4.35. Land utilization (%) in Argentina, Kenya, and South Korea in 1993 (FAOSTAT, 1997).

Table 4.7. United States grain production, export and use for feed and food (1992–1994 average)[a]

			Domestic use	
	Total production	Net export (import)	Feed	Food, seed, alcohol
Crop	Mt	%	%	%
Wheat	65.1	49	22	78
Rice	8.1	44	0	100
Corn	219.4	20	76	24
Sorghum	17.5	34	98	2
Barley	8.9	5	56	44
Oats	3.5	(34)	37	63
Rye	.3	(36)	43	57
Total	322.8	27	67	33

[a]Source: U.S. Department of Agriculture, 1997. http://www.usda.gov/NASS/pubs/agstats.htm.

on estimated animal requirements for reported stocking and production rates.

The next step was to tabulate the number of animals of each livestock species in each country, rates of turnover as indicated by numbers of animals slaughtered each year and total production in terms of meat (carcass weights), eggs, and milk (Tables 4.8–4.13). The data presented in these tables are largely self explanatory but a few summary comments are appropriate. Comparisons of the total stocks of each species, numbers slaughtered each year, and total production (carcass yields) allow calculations of percentages of each group slaughtered each year, or the inverse, average ages of animals at slaughter. For example, respective average ages at slaughter for cattle for Argentina, Egypt, Kenya, Mexico, South Korea, and the United States are 4.4, 2.3, 7.1, 5.3, 3.6, and 3.0 yr. Respective numbers of swine slaughtered

Table 4.8. Cattle numbers, productivity, and contribution to individual country/state diets[a]

Country	Stocks[b]	Slaughtered[b]	Total production[c]	Percentage of total production[d]	Energy[e]	Protein[e]
Argentina	52.7	11.9	2,508	74	23.3	348.6
Egypt	3.0	1.3	175	20	1.4	26.7
Kenya	13.0	1.8	230	63	1.9	35.0
Mexico	30.7	5.8	1,256	38	11.7	174.6
South Korea	2.8	0.8	204	15	1.9	28.4
United States	99.2	33.3	10,584	34	103.7	1,471.2
California	4.6	0.9	280	—	2.7	38.9
Nebraska	5.9	6.6	2,090	—	20.5	290.5

[a]Based on FAO and USDA (1993) data from the World Wide Web.

[b]Values expressed in millions (10^6) of animals.

[c]Total production reflects total carcass weights in thousands (10^3) of metric tons.

[d]Percentage of total animal carcass production of all species including beef and dairy cattle, swine, buffalo, poultry meat, small ruminants, equids, rabbits, and game.

[e]Human-edible energy outputs in billions (10^9) of MJ and protein outputs in millions (10^6) of kg. Based on data presented in Table 4.14.

Table 4.9. Swine numbers, productivity, and contribution to individual country/state diets[a]

Country	Stocks[b]	Slaughtered[b]	Total production[c]	Percentage of total production[d]	Energy[e]	Protein[e]
Argentina	2.85	2.08	177.3	5.2	2.29	20.21
Egypt	0.03	0.07	2.9	0.3	0.04	0.33
Kenya	0.10	0.08	5.0	1.4	0.06	0.57
Mexico	16.83	12.46	821.6	24.9	10.60	93.66
South Korea	5.93	9.68	786.0	57.9	10.14	89.60
United States	57.90	93.07	8,041.0	25.8	103.73	916.67
California[f]	0.26	—	18.4	—	0.24	2.10
Nebraska	4.30	5.62	476.8	—	6.15	54.36

[a]Based on FAO and USDA (1993) data from the World Wide Web.

[b]Values expressed in millions (10^6) of animals based upon a census taken annually.

[c]Total production reflects total carcass weights in thousands (10^3) of metric tons.

[d]Percentage of total animal carcass production of all species including beef and dairy cattle, swine, buffalo, poultry meat, small ruminants, equids, rabbits, and game.

[e]Human-edible energy outputs in billions (10^9) of MJ and protein outputs in millions (10^6) of kg. Values were calculated from carcass weights and yields of energy and protein in ready to eat, trimmed cuts tabulated in USDA Handbook 8. Based on data presented in Table 4.14.

[f] Many of the swine slaughtered in California are imported. Therefore outputs were calculated on the basis of locally produced animals.

each year per 100 census animals are 73, 248, 77, 74, 163, and 161 in the six countries. The data in Tables 4.6–4.13 allow calculation of average carcass weights of animals slaughtered and, from these values, estimates of live weights of the several species at slaughter can be derived. Calculated live weights (in kg) at slaughter for cattle were 384 for Argentina, 237 for Egypt, 230 for Kenya, 394 for Mexico, 467 for South Korea, and 527 for the United States; swine weights were 114, 58, 87, 88, 108, and 115 kg, respectively. The estimates of time to slaughter and live weights at slaughter were essential to calculations of rates of gain, maintenance requirements, and, finally, to estimates of total feed inputs required for the production of meat, milk, and eggs. Also presented in Tables 4.8–4.10 and 4.12 are percentage contributions of each species to total carcass weights of animals slaughtered in each country for meat. Although carcass yields from species such as rabbits, horses, mules, and game were included in the calculations, their relative (%) contributions are not presented because they are minor. The estimates of human-edible outputs of energy and protein from the several animal industries presented in Tables 4.8–4.13 were calculated from data in Table 4.14 derived from Agriculture Handbook 8 (U.S. Department of Agriculture, 1975, 1979, 1990, 1992). These data complement the data on meat consumption in the several country tabulations presented in Tables 3.1–3.6 in that they further break down the types of animal products available in each country. For example, in Argentina and Kenya, beef is the major meat produced, at 74 and 63%, respectively,

Table 4.10. Poultry meat production and contribution to individual country diets[a]

Country	Stocks[a]	Total carcass yield[b]	Percentage of total production[c]	Energy[d]	Protein[d]
Argentina	51.3	550	16.1	3.68	80.8
Egypt	51.8	339	38.8	2.27	49.8
Kenya	24.0	47	12.9	.31	6.9
Mexico	296.3	1,071	32.5	7.18	157.4
South Korea	73.9	366	27.0	2.45	53.8
United States	1,790.3	12,400	39.8	83.08	1,822.8

[a]Poultry meat production is sum of broilers, turkeys, ducks, and geese. Stocks expressed in millions. Based on FAO and USDA (1993) data from the World Wide Web.

[b]Total carcass yield in thousands (10^3) of metric tons.

[c]Percentage of total animal carcass production of all species including beef and dairy cattle, buffalo, poultry meat, small ruminants, swine, equids, and game.

[d]Human-edible energy outputs in billions (10^9) of MJ and protein outputs in millions (10^6) of kg. Based on data presented in Table 4.14.

Table 4.11. Numbers of laying hens, productivity, and contribution of eggs to individual country/state diets[a]

Country	Laying stock[b]	Eggs/bird/year (at 50 g/egg)	Total production[c]	Energy[d]	Protein[d]
Argentina	19.0	240	228.9	1.56	26.3
Egypt	19.0	147	140.0	1.02	16.1
Kenya	16.8	48	40.3	0.40	4.6
Mexico	126.0	196	1,233.6	8.63	141.6
South Korea	46.7	192	448.0	3.14	51.4
United States	284.7	253	3,601.7	24.44	413.5
California	28.0	251	350.9	2.38	40.3
Nebraska	7.9	257	101.5	0.69	11.6

[a]Based on FAO and USDA (1993) data from the World Wide Web.

[b]Values expressed in millions (10^6) of animals.

[c]Values expressed in thousands (10^3) of metric tons.

[d]Human-edible energy outputs in billions (10^9) of MJ and protein outputs in millions (10^6) of kg. Based on data presented in Table 4.14.

while Egypt, Mexico, and the United States are intermediate at 20 to 38%, and South Korea is low in beef production at 15%. Swine production and consumption are very low in Argentina, Egypt, and Kenya (0.3 to 5.2%); very high in South Korea (57.9%); and about 25% in Mexico and the United States. Poultry meat production is higher in the United States, Korea, and Mexico, than in the other countries. Small ruminant contributions are largest in Egypt and Kenya. These statistics, along with other data presented in Tables 4.8–4.13, reflect a wide range in national preferences, resources available, and allocations to the several national livestock production enterprises. Differences among three of the countries in proportion of animal proteins provided by different foods from animals are illustrated in Figure 4.36.

Several simplifications are implicit in the summaries presented in these tables. Data on broilers, turkeys, ducks, and geese were combined in Table 4.10. Sheep and goat production data were combined as small ruminants in Table 4.12. Slaughter data reported by FAO do not distinguish sources or previous uses of the animals slaughtered within a species. For example, dairy cattle and hens slaughtered at the end of their milk and egg production careers are incor-

Table 4.12. Small ruminant numbers, productivity, and contribution to individual country/state diets[a]

Country	Stocks[b]	Slaughtered[b]	Total production[c]	Percentage of total production[d]	Energy[e]	Protein[e]
Argentina	28.2	5.50	72.2	2.1	621.1	10.1
Egypt	6.7	4.56	94.0	10.8	808.6	13.2
Kenya	12.8	4.44	50.7	14.0	435.7	7.1
Mexico	16.3	4.95	70.2	2.2	603.5	9.8
South Korea	0.6	0.17	2.6	0.2	22.0	0.4
United States	12.0	5.46	162.4	0.5	1,397.4	22.7
California	1.1	0.96	18.1	NA[f]	156.0	2.5
Nebraska	0.2	0.16	2.4	NA	20.9	0.3

[a]Small ruminants refer to sheep and goats. Based on FAO and USDA (1993) data from the World Wide Web.

[b]Values expressed in millions (10^6) of animals.

[c]Total production reflects total carcass weights in thousands (10^3) of metric tons.

[d]Percentage of total animal carcass production of all species including beef and dairy cattle, swine, buffalo, poultry meat and eggs, small ruminants, equids, rabbits, and game.

[e]Human-edible energy and protein outputs are in millions (10^6) of MJ and kg, respectively. Based on data presented in Table 4.14.

[f] NA = not available.

Table 4.13. Number of milk cows, milk production, and contribution to individual country/state diets[a]

Country	Milk cow stock[b]	Milk yield (kg/cow/year)	Total production[c]	Energy[d]	Protein[d]
Argentina	2.20	3,282	7,220	18.4	237.5
Egypt	1.47	679	1,000	2.8	34.9
Kenya	4.25	489	2,080	5.7	72.8
Mexico	6.48	1,178	7,630	20.8	267.2
South Korea	0.32	5,806	1,806	5.1	65.0
United States	9.66	7,123	68,800	175.6	2,263.3
California	1.20	8,595	10,310	26.3	339.3
Nebraska	0.09	6,223	530	1.3	17.4

[a]Based on FAO and USDA (1993) data from the World Wide Web.

[b]Values expressed in millions (10^6) of animals.

[c]Values expressed in thousands (10^3) of metric tons.

[d]Human-edible energy outputs in billions (10^9) of MJ and protein outputs in millions (10^6) of kg. Milk fat percentages used were 3.3% for Argentina and United States, 3.5% for South Korea and Mexico, and 3.7% for Egypt and Kenya. Based on data presented in Table 4.14.

porated into cattle and poultry slaughter statistics. Sheep kept for wool production are incorporated into sheep slaughter data, while beef cow and bull slaughter data are not separated from total beef slaughter data. These limitations in available data dictated how costs of animal production were assigned in calculations to be presented. In a previous analysis, Bywater and Baldwin (1980) incorporated feed costs associated with pregnancy and raising of replacement heifers and energy and protein yields from the slaughter of calves and cull cows arising from the dairy enterprise in their calculations of input:output relationships for this industry. This was possible because specific statistics were available for California but was not feasible in the case study calculations presented here. Therefore, nutrient costs associated with pregnancy in dairy cattle were accounted as costs of meat production and only direct costs associated with the growth of replacement heifers and milk production were assigned in calculations of the efficiency of milk production. Similarly, costs of growing replacement hens, sows, wool-bearing sheep, and other like animals were assigned to the meat-production enterprises.

The next steps in the case study analyses required that animal populations be subdivided in terms of age, gender, size, and rates of production, to enable the energy and protein inputs required to produce the outputs of the several animal industries presented in Tables 4.8–4.13 to be estimated. Energy and protein requirements of animals were calculated using appropriate data from NRC publications on the nutrient requirements of domestic animals. These data, along with information on feed resources available for each country, prevailing animal production practices based on available literature, and, often, personal communications were used to formulate appropriate diets. Also, because human-edible inputs to animal agriculture are essential to calculations of the net contributions of animals to the food supply, estimates of the proportions of human-edible energy and protein in feedstuffs used to formulate diets used in animal production were calculated. Data on the total and human-edible energy and protein contents of feeds often used in livestock diets and incorporated into our calculations are presented in Table 4.15.

An example of how animal populations were sub-

Table 4.14. Edible nutrients in one kg of carcass[a]

	MJ	g Protein	g Fat
Beef			
Choice	9.8	139	193
Select	9.3	139	180
Utility	8.3	152	148
Pork	12.9	114	287
Poultry meat	6.7	147	107
Lambs			
Choice	9.3	139	179
Good	8.6	140	162
Eggs[b]			
Whole	6.1	115	102
Milk			
Whole (3.5%)	2.72	35	35

[a]Values from USDA Handbook 8 on nutrient composition of foods.

[b]Egg values corrected for weight of shell.

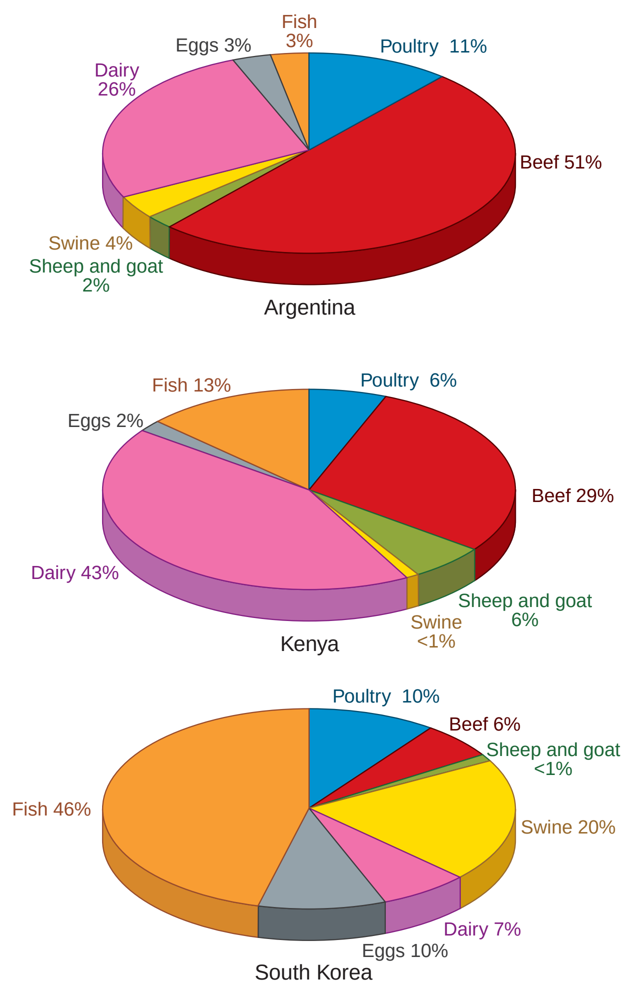

Figure 4.36. Relative contributions (%) of various animal food products to total animal food in Argentina, Kenya, and South Korea. Based on FAO and USDA (1993) data from the World Wide Web.

divided and their energy and protein intakes were accounted is presented in Table 4.16 for beef cattle in Nebraska. This state posed a problem in that many of the animals finished and slaughtered there are born elsewhere and shipped in as either weaned calves or yearlings (see footnote to the table). This fact forced

Table 4.15. Dry matter (as fed) metabolizable energy, protein values, and human-edible fractions used in calculations of returns on total and human-edible inputs in livestock production[a]

				Human-edible fraction	
Feedstuff	% DM[b]	MJ/kg[c]	% Crude protein[c]	Energy	Protein
Barley	89	11.0	10.0	0.7	0.6
Brans[d]	89	10.5	17.1	nil	nil
Corn	89	14.0	8.5	0.8	0.6
Cottonseed oil meal[d]	91	12.1	45.0	nil	nil
Forages[d]	30–90	6.7–10.0	5–23	nil	nil
Meatmeal[d]	93	59.0	50.0	nil	nil
Oats	89	10.7	10.0	0.7	0.7
Poultry by-products	93	12.3	60.0	nil	nil
Sorghum	87	13.8	8.8	0.6	0.6
Soybean oil meal[d]	90	10.2	48.5	0.7	0.7
Whole cottonseed	92	14.6	23.9	nil	nil

[a]Values derived from various National Research Council publications.

[b]Used for calculation of dry matter (DM) in diets formulated by linear programs on an as fed basis.

[c]Expressed on dry matter basis.

[d]Brans includes cereal brans, distiller grains and other high quality plant by-products. Forage values used vary dependent on region and time of year and crop, e.g., grass hay, corn silage, etc. Meat meal value is for meat and bone meal.

Table 4.16. Basis for estimates of total and human-edible energy inputs to beef production in Nebraska

Animal	Number[a]	Energy requirement (MJ/animal)	Total energy input (MJ)	Fraction energy human-edible	Human-edible energy input (MJ)	kg human-edible protein/ MJ human-edible input	Human-edible protein input (kg)[b]
Cows (calving)	5.58	34.1	190	0.1	19	0.003	57
(dry)	0.15	21.5	3.22	nil	—	—	—
Calf feed intakes to weaning at 240 kg	5.58	4.7	26.06	nil	—	—	—
Weaned calves to feedlot (240 to 535 kg)	2.79	23.7	66.18	0.4	26.5	0.014	371
Stockers to 370 kg	2.79	12.7	35.54	nil	—	—	—
Stockers to feedlot (370 to 535 kg)	2.79	15.6	43.52	0.58	25.24	0.014	353
Replacements	0.382	26	9.9	0.1	0.99	0.001	1
Total			374.4		71.73		782

[a]Numbers of animals in millions (10^6). Total number of cows calving includes 1.76 x 10^6 cows in Nebraska and 3.82 x 10^6 cows that produced calves elsewhere. The calves produced elsewhere were then imported to Nebraska as weaned calves @ 240 kg (2.64 million) or as yearlings @ 370 kg (1.146 million). Dry cows represent only those in Nebraska. Estimates (Cassman, 1998) indicate that the sum of local and imported weaned calves entering feedlots directly was 2.79 million while 1.644 million of Nebraska's weaned calves were grown on range to 370 kg before entering the feedlot. Feed costs for replacements are only those of Nebraska as only cows and bulls from Nebraska are represented in slaughter statistics.

[b]Energy requirements in thousands (10^3) calculated according to National Research Council (1984). Requirements for cows calving include costs of maintenance, activity, pregnancy, and lactation. Requirements for dry cows are costs of maintenance and activity. Energy requirements for replacements represent costs for maintenance and growth to maturity (545 kg). Total and human-edible energy inputs in billions (10^9). Human-edible protein input in millions (10^6).

a decision to aggregate to a "greater Nebraska." Thus, nutrient requirements for all cows producing calves later slaughtered in Nebraska were considered in the calculations ([$1.76 \infty 10^6 + 3.82 \infty 10^6$] ∞ [costs of cow maintenance + pregnancy + lactation] $34.06 \infty 10^3$ MJ/cow year = $190 \infty 10^9$ MJ). The fraction of human-edible energy intake for beef cows was calculated at 0.1 of total intake. This is probably an overestimate, as supplements for late pregnant and lactating cows under pasture and range conditions are most often crop residues and by-products. This value reflects the decision to present conservative estimates of returns on human-edible inputs. Forages were considered the sole inputs to dry cows and nursing and weaned calves to the average weight of 240 kg. According to Nebraska estimates, half of these calves go directly into feedlots and are fed to a finished weight of 535 kg. About 40% of the several diets fed to these calves from weaning to finishing are human-edible. The other weaned calves are raised as stockers on rangeland and pasture to 370 kg and then moved to feedlots for finishing. Fifty-eight % of the diets fed to these cattle during the feedlot phase are human-edible. Total energy inputs to beef production in "greater Nebraska" were $374.4 \infty 10^9$ MJ in 1993. Of this, 19.2% ($71.73 \infty 10^9$ MJ) was human-edible. Human-edible outputs as beef (Table 4.8) were $20.5 \infty 10^9$ MJ giving an estimate of gross efficiency of 6% (20.5/374.4) and an estimated return on human-edible energy input of 29% (20.5/71.7). Comparable calculations of efficiencies of conversion of total and human-edible protein inputs yield estimates of 8.0% and 37% (Table 4.17).

Sample calculations of the human-edible fractions of feedlot diets used in finishing cattle in Nebraska, California, and South Korea are presented in Table 4.18. As noted earlier, Nebraska has a high percentage (41%) of arable land and extensive pasture and rangeland. Thus, it follows that a large proportion of beef production is based on grazing animals and that feedlot rations are based heavily on maize and soybean oil meal. Efficiencies of forage conversion to meat are low, so the gross efficiency of energy use for production (6%) is lower than that for the United States taken in aggregate (Table 4.17). Similarly, the heavy use of human-edible feeds in finishing rations lowered the estimates of human-edible returns for energy and protein reported in the same table. Feedlot rations used in California (Table 4.18) are characteristically higher in by-products and forage, lower in cereal grains relative to Nebraska, and also incorporate cottonseed oil meal instead of soybean oil meal as the primary protein supplement. As a result, the human-edible portion of the rations is less, at 46%. South

Table 4.17. Beef: gross efficiencies of conversion of diet energy and protein to product and returns on human-edible inputs in products[a]

Country	Energy		Protein	
	Gross efficiency	Human edible return	Gross efficiency	Human edible return
Argentina	0.02	3.19	0.02	6.12
Egypt	0.03	NC[b]	0.02	NC
Kenya	0.01	NC	0.01	NC
Mexico	0.06	16.36	0.02	4.39
South Korea	0.06	3.34	0.06	6.57
United States	0.07	0.65	0.08	1.19
California	NC	NC	NC	NC
Nebraska	0.06	0.29	0.08	0.37

[a]Gross efficiencies calculated as outputs of human-edible energy and protein (Table 4.8) divided by total energy and protein inputs (Table 4.16). Human-edible returns calculated as human-edible outputs divided by human-edible inputs (Tables 4.8 and 4.18).

[b]NC = not calculated. California was not calculated because many beef calves produced in Northern California are shipped from the state for finishing. As a result, a large portion of the cattle fed in California arise from the dairy industry. Human-edible returns for Egypt and Kenya were not calculated because human-edible inputs are very low or nil, which would have resulted in values approaching infinity.

Table 4.18. Example ingredient compositions of beef cattle finishing rations and fractions of human-edible inputs

Ingredient	State/Country		
	Nebraska	California	S. Korea
Barley	—	5.0	—
By-products[a]	10.0	14.0	51.1
Corn/wheat	70.0	48.0	14.3
Corn silage	7.0	—	—
Cottonseed oil meal	—	7.0	14.7
Forage	5.0	20.0	13.4
Soybean oil meal	5.0	—	—
Tallow	—	3.0	4.3
Minerals, etc.	3.0	3.0	2.2
Total MJ/kg	11.8	12.0	10.5
Fraction human-edible energy[b]	0.69	0.46	0.12

[a]Include cereal brans, molasses and, in the case of South Korea, corn gluten feed, copra, and palm meals.

[b]Calculated as the sum of human edible constituents of diets times metabolizable energy value of each ingredient times the human-edible fraction of each (Table 4.17) divided by the metabolizable energy value of the diet. For example, barley and corn are the only human-edible in the California diet. Thus, the fraction of human-edible energy in the diet is calculated as (11.0 x 0.7 x 0.05 [barley] + 14.0 x 0.8 x 0.48 [corn])/12.0 = 0.48. Without rounding used in tabular values, actual answer is 0.46.

Korean rations for beef production are very high in by-product feeds and low in cereal grains, resulting in a slightly lower metabolizable energy density (10.5 MJ/kg) than for Nebraska and California, very low human-edible inputs (12%) and very high returns for human-edible inputs of 460 and 600% for energy and protein, respectively. Beef production systems in Argentina, Mexico, Egypt, and Kenya are largely pastoral in nature, so gross efficiencies are low and returns on human-edible inputs are high (Table 4.17). Human-edible inputs in Egypt and Kenya are very low, so ratios of output/input approach infinity and, thus, were not calculated. Similarly, small ruminants are either minor contributors of meat (Table 4.12) or are produced on forage diets in the case study countries, so a table showing returns from human-edible inputs is not presented.

Swine and poultry convert feeds to products more efficiently than do ruminants (excluding dairy cattle) but require higher quality diets and, therefore higher human-edible inputs to perform adequately. Rations formulated for swine, broilers, and layers are presented in Table 4.19. All diets are high in metabolizable energy/kg (11.0 to 13.4), as are fractions of human-edible energy content (0.58 to 0.73). The lower value for the fraction of human-edible energy in South Korean swine diets reflects a greater use of by-products.

Swine-production systems in the United States and South Korea are clearly intensive in nature. Rates of turnover of the swine populations are high, at about 160%/year, indicating two farrowings per sow year and high rates of gain due to high-quality management and the use of high-energy diets (Table 4.19). Gross efficiencies for energy and protein inputs ranged from 16 to 21%; returns on inputs of human-edible energy and protein ranged from 26 to 51%, respectively (Table 4.20). Swine in Argentina and Mexico are managed less intensively. Stock numbers and productivity (Table 4.9) indicate a rate of turnover in the swine population of 75%, consistent with one farrowing per sow per year or an older age at slaughter. This results in lower efficiencies of utilization of total and human-edible inputs (Table 4.20). Swine production in Egypt and Kenya makes small contributions to total meat production in these countries (Table 4.9). Diets are low in nutrient density, leading to low rates of production and, in turn, low gross efficiencies and

Table 4.20. Swine: gross efficiencies of conversion of diet energy and protein to product and returns on human-edible inputs in products[a]

	Energy		Protein	
Country	Gross efficiency	Human-edible return	Gross efficiency	Human-edible return
Argentina	0.15	0.24	0.07	0.11
Egypt	0.16	0.64	0.09	0.43
Kenya	0.16	0.54	0.10	0.39
Mexico	0.13	0.25	0.08	0.21
South Korea	0.20	0.35	0.16	0.51
United States	0.21	0.31	0.19	0.29
California	0.18	0.26	0.19	0.30
Nebraska	0.21	0.28	0.17	0.29

[a] Gross efficiencies calculated as outputs of human-edible energy and protein (Table 4.8) divided by total energy and protein inputs (Table 4.16). Human-edible returns calculated as human-edible outputs divided by human-edible inputs (Tables 4.9 and 4.19).

Table 4.19. Example rations for intensive swine and poultry production systems[a]

	Swine		Broilers		Layers
Ingredient	United States	S. Korea	California	S. Korea	United States
Barley/oats	33.0	—	—	—	2.0
By-products	1.8	20.2	10.7	7.9	13.6
Corn/wheat	49.2	59.1	68.3	71.2	65.6
Soybean oil meal	12.0	14.2	15.9	16.7	14.8
Tallow/fat	1.0	3.5	2.1	1.0	1.0
Minerals, etc.	3.0	3.0	3.0	3.2	3.0
Total MJ/kg	11.7	11.0	13.4	13.2	12.0
Fraction human-edible energy	0.73	0.58	0.62	0.65	0.62

[a]Rations for gestation, lactation, growing and lactation in intensive production facilities for swine are very similar within most countries in composition and fractions of human-edible energy and protein. Therefore, a single ration was used for all swine in each country. Rations for the United States and California were formulated using linear programs and ingredient prices as of November 1997. Rations for South Korea were provided by W. J. Maeng, 1998.

relatively high returns on human-edible inputs (Table 4.20).

Poultry meat and egg production systems follow a very similar pattern to that observed with swine. Countries with abundant cereal grains and those that choose to divert their more limited cereal grain resources to poultry meat production utilize diets ranging from 11.5 to 13.4 MJ/kg (Table 4.19). Gross efficiencies of energy and protein conversion for these diets range from 15 to 23% and 24 to 38%, respectively, while returns on human-edible energy and protein inputs range from 28 to 89% and 69 to 224%, respectively (Table 4.21). Relatively high quality poultry rations are used in Argentina but gross efficiencies and human-edible returns are somewhat lower than in, for example, South Korea and the United States. This seems to be attributable to significantly higher average live weights at slaughter. Poultry rations in Egypt and Kenya are significantly lower in quality but are still of good quality, resulting in similar gross efficiencies of energy and protein conversion of 15 and 24% and 23 and 38%, respectively. Returns on human-edible inputs in these two countries were quite high, at 68 and 163% and 89 and 224%, respectively, reflecting low human-edible inputs (Table 4.21).

Laying hens in Argentina, Mexico, South Korea, and the United States are of high genetic merit and are fed high-quality diets. This is reflected in egg yields per bird year of 190 to 250. Eggs per bird year in Egypt are lower at 147, probably reflecting diets somewhat lower in quality, given established relationships between energy density of diets and productivity. Egg yields by hens in Kenya are very low (48 per bird year), probably reflecting an extensive management system wherein low-quality diets are fed to birds of lower-than-average genetic merit (Table 4.11). A similar pattern is evident in the efficiency data presented in Table 4.22. Gross efficiencies of energy and protein conversion in countries with intensive production systems were 14 to 17% and 19 to 24%, respectively. Returns on human-edible energy and protein inputs in these countries were 20 to 26% and 31 to 45%, respectively. Returns on human-edible energy and protein inputs in Egypt were high at 57 and 88%, reflecting low human-edible feed inputs, as indicated previously.

Dairy cows are characteristically fed diets containing high percentages of forage, as indicated in Table 4.23. As a result, fractions of human-edible energy in diets are low, even for high-producing animals. U.S. diets have the highest fraction of human-edible input (30%) among the case study countries, due to cereal grain content and widespread use of soybean oil meal as a protein supplement. The value for California is somewhat lower at 23% due, in part, to the use of whole cottonseed in the rations. Values for Argentina (19%) were lower yet, because of lower cereal grain use and higher forage utilization. The human-edible fraction of 9% for South Korea reflects high use of forage and by-products. Rations used in Mexico were also low in human-edible inputs, while those in Egypt and Kenya included none.

Milk yields per cow varied greatly in the several case studies, from a low of 489 kg/yr in Kenya to a high of 8,595 kg/yr in California. These differences can be attributed to differences in genetic potential and diets, and to alternative uses of the cattle, particularly in Egypt and Kenya, where very little genetic im-

Table 4.21. Poultry meat: gross efficiencies of conversion of diet energy and protein to product and returns on human-edible inputs in products[a]

	Energy		Protein	
Country	Gross efficiency	Human-edible return	Gross efficiency	Human-edible return
Argentina	0.18	0.28	0.30	0.69
Egypt	0.15	0.68	0.24	1.63
Kenya	0.23	0.89	0.38	2.24
Mexico	0.20	0.34	0.33	0.83
South Korea	0.21	0.30	0.34	1.04
United States	0.19	0.28	0.31	0.62

[a]Gross efficiencies calculated as outputs of human-edible energy and protein (Table 4.8) divided by total energy and protein inputs (Table 4.16). Human-edible returns calculated as human-edible outputs divided by human-edible inputs (Tables 4.10 and 4.19).

Table 4.22. Eggs: gross efficiencies of conversion of diet energy and protein to product and returns on human-edible inputs in products[a]

	Energy		Protein	
Country	Gross efficiency	Human-edible return	Gross efficiency	Human-edible return
Argentina	0.17	0.26	0.23	0.45
Egypt	0.12	0.57	0.15	0.88
Kenya	0.06	0.23	0.04	0.22
Mexico	0.14	0.25	0.19	0.38
South Korea	0.14	0.20	0.19	0.31
United States	0.17	0.24	0.24	0.36
California	0.17	0.27	0.23	0.47
Nebraska	0.18	0.23	0.24	0.33

[a]Gross efficiencies calculated as outputs of human-edible energy and protein (Table 4.8) divided by total energy and protein inputs (Table 4.16). Human-edible returns calculated as human-edible outputs divided by human-edible inputs (Tables 4.11 and 4.19).

provement has occurred in the national herds and cattle are used for multiple purposes (see Chapter 2 on indirect contributions of animals to food production). Major differences are attributable to differences in rations offered to lactating cows. California has the highest milk production of any state, due mostly to the availability of very high-quality alfalfa and whole cottonseed. The genetic potential of dairy cows in South Korea is comparable to that of dairy cattle in the United States. Thus, the difference in milk production is almost totally due to the lower metabolizable energy of diets fed, 8 MJ/kg compared to 10.9 MJ/kg. Rations fed in Argentina are relatively high in metabolizable energy at 10 MJ/kg but metabolizable energy derived from forages and by-products (89% of ration) is not utilized as efficiently for lactation as is energy derived from cereal grains. Indeed, all new systems for formulating diets for dairy cattle, e.g., U.S. National Research Council, U.K. Agricultural Research Council (ARC), correct for this difference. Dairy cows in Argentina may be somewhat lower in genetic potential than those in the United States but supporting data are lacking. Milk production in Egypt and Kenya reflects, in part, the low quality of forages available. Respective gross efficiencies of conversion of diet energy and protein to milk energy and protein were 25 and 26% in the United States, 19 and 21% in South Korea, and very low in Egypt and Kenya (Table 4.24). Human-edible returns in the United States were all higher than 1.0, indicating that dairy cows add to the supply of energy and protein for human consumption. Values for South Korea and Argentina were 3.74 and 4.61, indicating that dairy cattle make a major addition to the human energy supply. Because human-edible inputs in Egypt and Kenya are very small, human-edible returns would be extremely high and are not presented because the numbers are meaningless. In the United States, returns on protein inputs were essentially 200% and, in Argentina, 164%. Human-edible protein inputs in South Korea are low. As a result, the return on inputs was 14-fold, indicating a major contribution of the dairy industry to the supply of high-quality protein for the country's population.

Table 4.23. Example rations for dairy production systems[a]

Ingredient	Argentina[b]	United States	California	S. Korea[b]
By-products	19.0	10.0	11.0	—
Cereal grains	6.0	20.0	25.0	10.0
Forage[c]	70.0	60.0	54.0	85.0
Oil meals[d]	2.0	8.0	8.0	3.0
Other	3.0	2.0	2.0	2.0
Total MJ/kg	10.0	10.9	10.9	8.0
Fraction human-edible energy	0.19	0.3	0.23	0.09

[a]Rations described are weighted averages of several used at different stages of a one-year lactation cycle.

[b]Based on information provided by Daniel Rearte of INTA for Argentina and by W. J. Maeng for South Korea.

[c]Forages include alfalfa, corn silage, grass hay, and pasture.

[d]Oil meals include sunflower, soybean and cottonseed oil meals, and whole cottonseed.

Table 4.24. Milk: gross efficiencies of conversion of diet energy and protein to product and returns on human-edible inputs in products[a]

	Energy		Protein	
Country	Gross efficiency	Human-edible return	Gross efficiency	Human-edible return
Argentina	0.19	4.61	0.16	1.64
Egypt	0.09	NC[b]	0.10	NC
Kenya	0.07	NC	0.09	NC
Mexico	0.12	0.79	0.11	1.06
South Korea	0.26	3.74	0.19	14.30
United States	0.25	1.07	0.21	2.08
California	0.27	1.16	0.23	2.26
Nebraska	0.23	1.07	0.20	2.04

[a]Gross efficiencies calculated as outputs of human-edible energy and protein (Table 4.8) divided by total energy and protein inputs (Table 4.16). Human-edible returns calculated as human-edible outputs divided by human-edible inputs (Tables 4.13 and 4.23).

[b]NC = not calculated.

5 Meeting Future Demand for Livestock Products

Meeting the projected global demand for foods of animal origin in the year 2020 will require a production increase of more than 50% for meat, milk, and eggs. This calls for an increase in the feed supply or in the efficiency with which animals convert feed to food or, most probably, both.

Feed Supplies

As detailed in the preceding section, many types of feedstuffs are used for animal production. Potential increases in the amounts of different groups of feedstuffs vary and, particularly for ruminants, ample opportunity exists to substitute one type of feed for another. We consider here the prospects for increasing the feed supply in different categories, noting that an increase in feed quality, e.g., higher energy and protein contents, would increase nutrients available to the animal and therefore be equivalent to an increase in feed supply.

Range Forage

Nearly all grazable areas, particularly in developing countries, are now grazed (Figures 5.1–5.5). An interesting exception is the rubber and oil palm plantations of Southeast Asia and elsewhere (see Box 6) but, in general, prospects for expansion of grazing land in these countries are limited. Interest is growing in alternative and additional uses of rangeland, such as recreation, biological preserves, crop production, industrial development, and housing. Some of these uses are compatible with continued grazing and some are not. While some areas now grazed are good potential cropland (for example, in parts of Latin America, notably Argentina), conversion of rangeland to crop production in low-rainfall areas is particularly disadvantageous. As stated in a report of a study of grasslands in Northern China (National Research

Figure 5.1. Goats grazing semi-arid brushland in Kenya. Photograph courtesy of Eric Bradford, University of California, Davis.

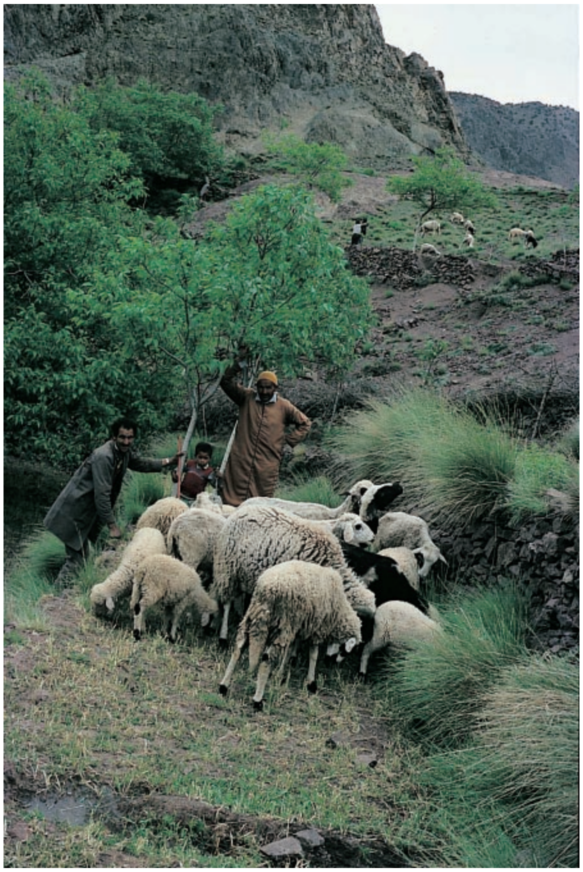

Figure 5.2. Smallholder sheep flock in the High Atlas Range in Morocco. Photograph courtesy of Eric Bradford, University of California, Davis.

Council, 1992), "The cultivation of land previously devoted to livestock grazing reduced the area available to feed livestock. Later, when crops grown in marginal areas failed, land erosion followed and viable rangeland was lost—now and for many years to come."

Substantial improvements are possible in forage production from rangelands by better grazing management and more effective use of tools such as fire and modifying species composition. Improvements in genetic potential of animals for specific production environments, as well as in the management of the animals, also will increase productivity. As discussed in Chapter 5, environmental and alternative use issues related to rangelands will have important impacts on what can be done (Figures 5.8–5.11). Diversion of rangeland to alternative uses will counter at least a portion of the gains from using more efficient and sustainable technologies.

Figure 5.3. Rotational grazing of seeded pastures in New Zealand. Photograph courtesy of Howard Meyer, Oregon State University, Corvallis.

Figure 5.4. Different environments and forage quality involve different breeds for most efficient production. Dual purpose (dairy/beef) cattle in a good rainfall area in Germany. Photograph courtesy of Eric Bradford, University of California, Davis.

Cultivated Forages

Cultivated forages have received much less attention from plant scientists than have cereal, fruit, and vegetable crops. As a result, great potential exists to improve yield and quality of forage crops through development of new varieties and cultural practices. An important question is how much land will be available for these crops. On one hand, as demand for food crops increases, pressure will grow to devote land currently used for forage crops to food crop production (with potential impacts on soil erosion) (see Box 3). On the other hand, substantial areas of land formerly used to grow forage crops, e.g., in the northern tier of states in the eastern and central United States, are now idle. The primary reason is that livestock production from these lands is not currently profitable. Some of the lands are reverting to forest; once that has happened, that may be their preferred use. However, much of this land represents a potential reserve for future livestock production that could be tapped if an increase in prices for ruminant products made it profitable. An increase in real prices of cereal grains would likely result in increased demand for forages, particularly good quality ones.

Crop Residues and By-Products

In general, crop residues and by-products are expected to increase in proportion to increases in food

Figure 5.5. Crossbred beef cattle in a dry summer climate in California. Photograph courtesy of Eric Bradford, University of California, Davis.

crop production. The ratio is not always one to one; for example, the short-straw cereals of the green revolution had a higher ratio of grain to total plant (harvest index) than the taller cereals they replaced. As a result, crop residue yield increased less than grain yield. However, the harvest index may be nearing a physiological maximum in these cereals; thus, the current proportionality between food crops and the residues and by-products for animal feed may change little in the future. If the harvest index remains relatively unchanged and food crop production parallels human population, the per capita supply of animal products from this source should at least be maintained and could be increased with more research on improved utilization. However, meeting increased per capita demand for meat, milk, and eggs will likely require increases in other feed sources.

Box 6

Utilization of Forage Growing under Estate Tree Crops for Livestock Production

Most areas of the world that produce potentially grazable forage are usually fully utilized for livestock grazing. An interesting exception is the forage that grows naturally under estate tree crops, such as rubber and oil palm, of which there are several million ha in Southeast Asia alone, as well as substantial areas in Africa and Latin America (Figures 5.6 and 5.7).

The total amount of forage potentially available from these tree crop production systems is substantial. The environments are characterized by relatively high and dependable rainfall year round and, therefore, year-round green forage, an obvious advantage for livestock production. Use of this forage by livestock can reduce the need for herbicide use by 18 to 38%, an important environmental advantage. Livestock production has the potential additional advantages to the landowners, whether of large or small holdings, of income diversification and greater use of available labor, including family labor.

Livestock production from this resource presents special challenges, in two respects in particular. One is temporal variation in forage supply. While the environment supports year-round forage growth, there is a five- or six-fold or greater variation in amount of forage over the life cycle of the tree crop, e.g., about 25 years for rubber plantations. Forage production is abundant in the first few years after the trees are planted, decreases to a very low level as the canopy closes, and increases again in later years as individual trees are lost. Thus, availability of stands of trees planted at regular intervals in adjacent areas is essential to maintaining a relatively uniform number of animals. Second, the warm, humid climate year round, ideal for forage production, is also ideal for the maintenance of high internal parasite challenges to the animals.

Challenges, opportunities, and approaches to utilizing this important resource are discussed in the volume edited by Iniguez and Sanchez (1991).

Figure 5.6. Sheep grazing under young rubber trees in North Sumatra. Photograph courtesy of Eric Bradford, University of California, Davis.

Figure 5.7. Goats grazing on a small landowner's holdings that include banana plants. Photograph courtesy of Martin Vavra, Oregon State University, Burns, Oregon.

Feed Grains

Projected Demand

Meeting projected demand for animal products is expected to require an increase in the global supply of feed grains. In addition to the prospect that other sources of animal feedstuffs are projected to keep pace with but not exceed human population growth, the greatest increases are projected in pig, poultry, and aquaculture production, which require high-energy diets. The fact that animals of all species fed higher nutrient-density diets produce more product per animal in less time is also a factor favoring increased use of feed grains.

Information on total feed grain use for selected countries and regions in 1983 and 1993 and projections for 2020 from the IFPRI IMPACT model (Rosegrant et al., 1997) are presented in Table 5.1. These represent past and projected use for all animals, i.e., meat, milk, and egg production. The approach and assumptions used for projecting feed grain use are detailed by Rosegrant et al. (1997).

The projection of world feed grain requirements of 927 Mt for 2020 represents a 46% increase from the 1993 total, which would require a 1.4% annual compound growth rate in supply, i.e., slightly more than the human population growth rate projected for that period.

Projections from the IMPACT model baseline scenario (Table 5.1) assume little change in conversion rates of animal feed to human food. Two factors, acting in opposite directions, can be envisioned that would affect global conversion rates. One is an improvement in conversion rate due to better animal production technology. Significant improvement in average feed conversion rates globally has occurred in recent years and several potential means of further increases are outlined later in this report. Continuing improvement at the rate that seems to have occurred from 1983 to 1993 (see Table 5.2) would mean that the increased global demand for meat could be met with a smaller increase in global feed grain supply.

Other factors could increase the amount of grain required per unit of product, particularly meat. As noted in Table 4.5, the apparent grain requirement for meat production in developing countries is low compared to that in developed countries. In China, the world's largest meat-consuming country, total feed grain use (for all animal production) as reported by FAO was 73 Mt in 1993 (Table 5.1); total meat production was 39 Mt. Data are not available for China on feed grain used for milk and egg production but using the averages for Asia of 16% for milk and 20% for eggs (Hendy et al., 1995) would indicate 47 Mt (64% of 73) of grain used for meat production, for a grain:meat ratio of 1.20. This is a remarkably low grain requirement, particularly for a country where pigs are the dominant species, and indicates use of large quantities of feedstuffs not recorded in national feed supply statistics, such as kitchen wastes and locally produced feeds. Inaccuracies in either the meat production or feed use statistics might also be factors in the surprisingly low ratio.

With rapid urbanization and industrialization in countries such as China, including an increase in in-

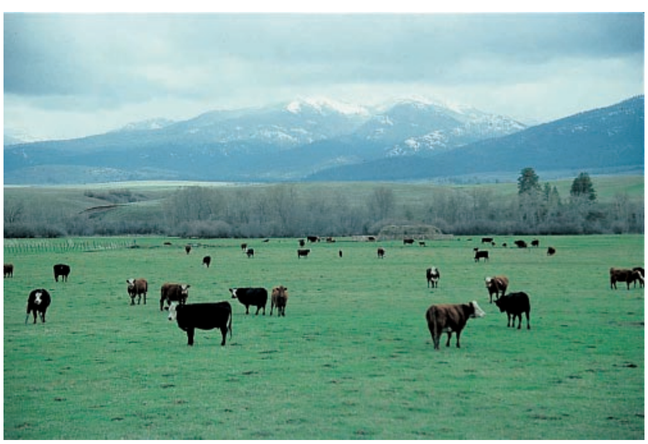

Figure 5.8. Typical intermountain United States cattle operation with cows grazing private meadowland and public rangeland in the mountains in the background. Photograph courtesy of Martin Vavra, Oregon State University, Burns, Oregon.

Figure 5.9. Livestock grazing systems can be developed that are compatible with or in some cases may actually benefit wildlife. Burrowing owl in western rangeland. Photograph courtesy of Martin Vavra, Oregon State University, Burns, Oregon.

dustrial pig and poultry production, it seems unlikely that the amounts of kitchen wastes and other currently nonrecorded feeds used for animal production will rise as rapidly as total production, which in China is forecast to more than double by 2020. The grain:meat ratio may, therefore, rise, due to an increase in proportion of grain in average livestock diets, even with a concurrent increase in biological efficiency.

To examine the possible impacts of each of these kinds of changes, the IMPACT model was re-run with two alternative sets of assumptions (Delgado et al., 1999):

Scenario A. Increasing feed conversion efficiency relative to baseline, based on improved animal-production technologies.

- Developed countries: 0.5% per year improvement in average conversion rate of feed grain to food product from now to 2020.
- Developing countries: 1.0% per year improvement

Table 5.1. Past and projected trends in use of cereal as feed, to the year 2020[a]

	Annual growth rates			Total cereal use as feed			Per capita cereal use as feed	
	Cereal production 1982–1993	Cereal use as feed 1982–1993	Projected cereal use as feed 1993–2020	1983	1993	2020	1993	2020
Region	%/yr			Mt			kg	
China	2.0	5.8	3.2	40	73	171	62	120
India	3.2	3.5	3.0	2	4	8	4	6
Other East Asia	–2.0	6.7	2.5	4	11	22	115	183
Other South Asia	2.1	1.5	2.9	1	2	4	7	8
Southeast Asia	2.4	8.6	2.9	6	15	32	32	49
Latin America	0.7	2.5	1.9	38	54	90	118	137
WANA[b]	3.9	1.8	2.1	23	34	60	92	94
Sub-Saharan Africa	4.1	5.3	2.3	2	2	4	4	4
Developing world	2.3	4.3	2.6	126	194	390	45	62
Developed world	0.2	0.1	0.7	453	443	536	346	386
United States	0.0	1.0	0.9	132	159	199	603	622
World	1.3	0.9	1.4	579	637	927	115	120

[a]Sources: Delgado, et al., 1998. Raw data prior to 1995 from FAOSTAT (9/17/97) and projections to 2020 from the IFPRI IMPACT model (Rosegrant et al., 1997).

[b]WANA = western Asia and North Africa.

Table 5.2. Estimated increase in feed grain conversion efficiency, 1983 to 1993

	Developed countries			Developing countries		
	1983	1993	Change	1983	1993	Change
Total meat (Mt)[a]	88	99	+12%	50	89	+78%
Total feed grain (Mt)[b]	453	443		126	194	
Feed grain for meat (Mt)[c]	290	284	–2%	74	114	+54%
Grain/meat	3.30	2.87		1.48	1.28	
Conversion rate (meat/grain)	0.30	0.35	+15%	0.68	0.78	+15%

[a]From Table 2.3.

[b]From Table 5.1.

[c]Assuming percentage of total feed grain fed to meat animals was the same for both periods (64% and 59% for developed and developing countries, respectively; Table 4.5).

in average conversion. (A higher value than for developed countries was assumed because of the greater gap currently between actual and potential production levels.)

Scenario B. Decreasing apparent feed conversion efficiency of the human-edible portion of livestock diets, relative to baseline, due to an increase in grain as a percentage of the total feed.

- Developed countries: 0.5% per year decrease in average conversion rate. (A lower value than for developing countries was assumed because a higher proportion of production is already from industrial systems.)
- Developing countries: 1.0% per year decrease in average conversion rate.

The effects of these changes in conversion rates on demand for feed cereals are shown in Table 5.3. The assumed improvement in conversion rate (Scenario A) would reduce demand, compared to the baseline projection, by an average of 13% in developing countries and 7% worldwide, while the decrease in effective conversion rate (Scenario B) would result in respective increases of 16 and 8%. Changes in developed countries would be very small due to the relatively small population growth and the assumption of less change in efficiency.

The results in Table 5.3 indicate changes under the alternative assumptions of less than 1% in consumption of animal products in every region. While prices of feed grains as represented by maize would change by –17% and +21% for Scenarios A and B, respectively (Table 5.4), meat and milk prices are projected to change by no more than 2%. As a result, there is little change in projected consumption, i.e., conversion rates potentially have a large impact on cereal and livestock producers but small impacts on consumers. Trade in feed grains would be significantly affected; the model projects, for example, that imports of feed grain by China would decrease by 46% for Scenario A and increase 53% under B.

Global cereal grain use for feed in 1993 (1992–1994 average) was 637 Mt (Table 5.1), 33% of the corresponding total cereal production of 1994 Mt. The IMPACT model baseline scenario projects an increase in total cereal demand from 1993 to 2020 of 41% (Rosegrant and Ringler, 1997; weighted average from Table 2.2). Replacing the baseline feed grain estimate with those from Scenarios A and B, with no change in other demand for cereals, changes these figures to 34% and 44%, respectively. These would require annual compound rates of increase in total cereal production to the year 2020 of 1.11 and 1.37%, respectively.

Which, if either, of the two scenarios is probable? Opinions vary on this issue (within this panel as well as in published reports). We have little doubt that increases in biological conversion efficiency are feasible and probable. However, food product/grain in-

Table 5.3. Total percentage changes in projections of aggregate consumption in 2020 due to changes in assumptions relative to baseline[a]

	Alternative Scenario A: Increasing feed conversion efficiency[b]				Alternative Scenario B: Decreasing feed conversion efficiency[c]			
	Beef, sheep, and goat meat	Pork and poultry	Dairy products	Cereals used as feed	Beef, sheep, and goat meat	Pork and poultry	Dairy products	Cereals used as feed
Region	(percent difference between new scenario and baseline)							
China	0	0	0	–15	0	0	0	17
India	0	1	0	–9	0	0	–1	11
Other Asia (including WANA[d])	0	1	1	–10	–1	0	–1	12
Latin America	1	1	0	–15	0	–1	–1	19
Sub-Saharan Africa	0	0	0	–12	0	0	0	14
Developing countries	0	1	0	–13	0	0	–1	16
Developed countries	0	0	0	–2	0	0	0	2
World	0	0	0	–7	0	0	0	8

[a]Source: Delgado et al., 1999.

[b]Ratio of output: cereal grain input assumed to increase due to technological inprovements in animal production.

[c]Ratio of output: cereal grain input assumed to decrease due to shift to industrial production with more grain fed.

[d]WANA = western Asia and North Africa.

put will decrease if grain as a proportion of the total ration increases more rapidly than the increase in biological efficiency (Scenario B). The debate centers on the probability of increased industrial production, with higher grain content rations, relative to traditional production, with much of the feed coming from kitchen wastes, crop residues, and by-products.

As noted earlier in the report, real grain prices have declined markedly in recent decades. The IMPACT baseline scenario (Table 5.4) and other economic assessments project that this decline will continue. As long as grain prices keep decreasing, an increase in grain use for livestock feed is likely to occur, which results in more meat, milk, etc., from fewer animals at lower cost. Avery (1996) and others have pointed out that intensification of livestock production as well as crops uses less land and fewer total resources and therefore has important environmental benefits.

An alternative view is that by Preston (1998), who argues that an integrated crop-livestock-energy system, using local feedstuffs and indigenous breeds and technologies, would be more productive, more energy efficient, and better for the environment than industrial production, especially in the tropics.

Each of these approaches might be “best” in some sense according to the situation. Availability/price of fossil fuel will be an important determinant. At this point, we tend toward the view that an increase in industrial-type production is probable, at least in the short term. The relative influences of the two factors affecting efficiency of grain use are difficult to predict. At present, we estimate only that the annual rate of increase in demand for cereal grains will be between 1.1 and 1.4% from now until 2020.

Projected Supplies

Cereal harvest area has increased little in recent years and is expected to contribute little to increased future production (Dyson, 1996; Rosegrant and Ringler, 1997), although technological advances, e.g., development of salt-tolerant and short season varieties could lead to some expansion. Counter balancing such increase will be losses to desertification, urbanization, and decreased supplies of irrigation water. Thus, it is generally perceived that increases in supply will need to come from increased yields. The projections in the previous section, and a number of analyses from primarily economic perspectives, assume that, given the necessary price incentives, grain production will rise sufficiently to meet demand. Yield increases on the order postulated as necessary to meet demand in 2020 are less than those in recent years (Dyson, 1996). Tweeten (1999) has summarized evidence that the rate of increase in cereal yields has declined fairly steadily since the 1960s, and projects a continued decline. Dyson (1996) suggests that the factors involved are more economic than biological, and that the trend can be arrested or reversed.

Because economic models such as IMPACT only assume changes in yields but do not shed light on the technological advances needed to effect the needed yield increases, we will consider the prospects for achieving these increases from an agronomic perspective.

Despite tremendous increases in yields over the past four decades, present cereal yields are well below the achievable potential of existing crop varieties when water, nutrients, and pest pressure are nonlimiting. For example, the highest reported maize

Table 5.4. Real prices of selected crop and livestock products as projected by the IMPACT model[a]

Year	Wheat	Rice	Maize	Soybeans	Beef	Pork	Poultry	Lamb	Milk
	(constant 1990 US$/t)								
IMPACT base prices									
1992–1994	148	275	126	263	2,023	1,366	1,300	2,032	234
IMPACT baseline projections									
2010	146	293	127	244	1,835	1,260	1,175	1,915	217
2020	133	252	123	234	1,768	1,209	1,157	1,842	199
Increasing feed conversion efficiency scenario projections									
2020	126	243	102	228	1,738	1,188	1,134	1,817	196
Decreasing feed conversion efficiency scenario projections									
2020	141	262	149	242	1,802	1,233	1,183	1,870	202

[a]Sources: The updated IMPACT baseline projections are from Delgado et al., 1999; Rosegrant and Ringler, 1998; and Rosegrant et al., 1997.

yields attained in commercial fields approach 22,000 kg/ha (Council for Agricultural Science and Technology, 1994; Evans, 1993a). In contrast, the trend line for U.S. maize yield indicates an average grain yield of 8,200 kg/ha in 1997 (at 15.5% moisture content, equivalent to 131 bushels per acre), which is only 37% of the achievable yield potential of existing maize hybrids. It should be noted that more than 85% of the U.S. maize crop is produced in rainfed systems, while irrigation is required to achieve yields that consistently approach potential levels. Therefore, a large yield gap is indicated between actual and potential maize yields, which can be exploited by improved crop management. Large yield gaps exist for the other major cereal crops in the United States and in most other developed and developing countries. For example, average irrigated rice yield was 5.0 t/ha in 1991 on 70 million hectares (Mha) in the developing countries of Asia, which is 57% of the estimated yield potential of present rice varieties (Cassman and Harwood, 1995).

Closing these yield gaps will depend on decreasing yield reductions caused by untimely field operations; inadequate nutrient and water supply; and weed, insect, and disease pressure. It also will depend on maintenance of soil quality. Improved management practices must assure the protection of natural resources, such as ground and surface water and wildlife habitat, and more efficient use of water and energy. Population and income growth will rapidly increase demand for the land, water, and energy used in agricultural production. Future production systems therefore must provide the necessary inputs, without excess or deficiency and at the precise time and place, to sustain increases in crop yields, while maximizing input-use efficiency and minimizing potential adverse environmental effects.

Such a "precision agriculture" approach will require new knowledge of plant biology and agro-ecology and the development of advanced information technologies to improve management decisions involving a myriad of interacting factors. While considerable progress has been made to develop information technologies that facilitate a precision approach, e.g., yield monitors, global positioning systems, variable-rate applicators, remote-sensing techniques, adoption of these tools by farmers in developed countries has been hampered by inadequate knowledge of crop response to climate, soils, and pests. In developing countries, precision agriculture also will be needed to sustain yield advances and protect natural resources but at a different scale. On small farms, precision agriculture requires a "field-specific" approach (Cassman, 1999) and there is an additional challenge to extend information and new technologies to hundreds of millions of farmers with average holdings of less than 5 ha. In both developed and developing countries, farmers will require greater education and technical skills to successfully implement precision agriculture techniques.

Sustained annual increases in actual yields of 1.4% eventually will lead to average yield levels that approach the present yield potential limit. Assuming this rate of increase, average farm yields will exceed 80% of the present yield potential during the next 30 years in several major cereal-production areas. Hence, rais-

Figure 5.10. Livestock grazing systems can be developed that are compatible with or in some cases may actually benefit wildlife. Elk in western rangeland. Photograph courtesy of Martin Vavra, Oregon State University, Burns, Oregon.

Figure 5.11. Sagebrush steppe rangeland that has been ungrazed for 60 years on the right side of the fence and properly grazed on the left. Little difference in appearance and ecological condition occurs with proper grazing practices. Photograph courtesy of Martin Vavra, Oregon State University, Burns, Oregon.

ing the yield potential is crucial for sustaining both greater input-use efficiency and yield increases, because crop response to applied inputs is curvilinear and the marginal response to applied inputs decreases as yields approach the yield plateau (Council for Agricultural Science and Technology, 1994; de Witt, 1992).

Compared to premodern crop varieties, the primary factors contributing to the greater yield potential of modern crop varieties are increased harvest index, which is the proportion of total plant dry matter in grain, and modification of plant development to better fit the environment. These attributes were incorporated into the first modern varieties of rice and wheat, the “miracle” varieties that were the driving force of the green revolution of the 1960s and 1970s. For maize, there was a shift to single-cross hybrids from double-cross and open-pollinated varieties. But these factors now have been widely incorporated and refined in the varieties and hybrids released during the past 25 years. At issue are potential yield gains that can be realized from their further refinement and other innovations.

While a quantum leap in yield potential is evident when modern varieties are compared with traditional wheat and rice varieties and modern maize hybrids are compared with open-pollinated varieties, more recent trends are less apparent. Conflicting evidence exists about yield potential trends during the past 25 years. Evidence that indicates yield potential has not changed comes from studies of plant physiology, long-term experiments, and yield contests. For example, there is little evidence that breeding efforts have improved the basic metabolic and assimilatory processes that govern the rate of dry matter production (Evans, 1993a). Likewise, yields of the major cereals have remained constant or even decreased during the past 25 years in long-term experiments with irrigated tropical rice in which there has been regular replacement of older modern varieties with recent releases and crop management follows recommended practices for fertilizer inputs and pest control (Cassman et al., 1995). Lack of a yield increase with a constant crop management regime suggests that crop yield potential has changed little, if at all, during the past 25 years. More detailed analyses of yield trends clearly indicate that rice yield potential has not changed since the release of the first modern, semidwarf tropical variety (‘IR8’) in 1966, although more recent, inbred varieties have earlier maturity and greater resistance to insect pests and diseases (Khush, 1993; Kropff et al., 1994). Thus, the continued increase in average rice yields achieved by farmers reflects improved resistance to insects and diseases and better crop management.

Increased yields of maize during the past 25 years are associated with greater resistance to abiotic and biotic stresses, e.g., drought, insect, diseases, and better adaptation to both short and long seasons as well as to modern agronomic practices such as high plant density and responsiveness to applied nitrogen (Duvick, 1992; Tollenaar et al., 1994). Whether maize yield potential has increased at all during the recent past is not clear. In fact, yield increases from greater stress resistance and adaptation to modern agronomic practices, rather than an increase in genetic yield potential, is consistent with trends in the annual yield contests sponsored by the National Corn Growers Association in Nebraska, where both irrigated and rainfed maize are widely grown (Duvick and Cassman, 1999). Whereas rainfed yields have been increasing steadily, there is no detectable yield trend with irrigation (Figure 5.12). The highest yield (21,800 kg/ha) was achieved in 1986, while the contest-winning rainfed yields are steadily increasing and are rapidly approaching the irrigated yield plateau. This convergence is at odds with the more optimistic scenario of Evans (1993b) and Waggoner in the CAST publication (1994), who project that the gap between yield potential and the average yields achieved by farmers will

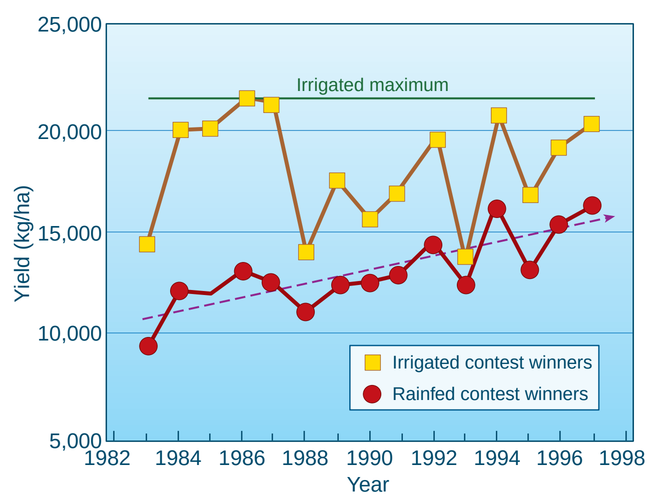

Figure 5.12. Maize yield trends in Nebraska from 1983 to 1997 as measured in the annual yield contests sponsored by the National Corn Growers Association (NCGA) for irrigated and rainfed production systems. The dashed line with an arrow represents the trend line for contest-winning rainfed yields. All yields are adjusted to 15.5% moisture content. Yields are verified by independent observers and are obtained from a combined harvest of fields with a minimum size of 4 ha (data from Duvick and Cassman, 1999)

not decrease in the foreseeable future. It should be noted, however, that their analyses were based on yield trends in the Iowa Masters contest, where maize is grown under rainfed conditions. Those yield trends are similar to the rainfed yield trends in the Nebraska contests, which are approaching the irrigated yield barrier suggested by the data in Figure 5.12.

Wheat seems to be the exception, because increasing yield trends are evident in long-term experiments in Punjab, India, and the central and northwestern United States (Cassman et al., 1995). Additional evidence of increased wheat yield potential comes from field experiments that compare yields of varieties released at different times since 1960 (Sayre et al., 1997; Waddington et al., 1986). Results from such “historical” varietal comparisons, however, must be interpreted with caution, because the older varieties are not compared in the environment for which they were selected due to changes in agronomic practices, soil quality, and disease and insect pressure. For both wheat and rice, there seems to be a yield potential gain of 10 to 20% from more widespread use of hybrid seed, because both crops are mostly grown from inbred varieties (Jordaan, 1996; Virmani et al., 1991).

Our conclusion is that gains in yields of the magnitude needed to meet projected demands for food grains and feed grains seem feasible through raising average yields closer to the biological potential of these crops and through new technological innovations. Because the rate of increase in genetic potential for crop yield seems to be declining or stagnant, sustaining grain production at these higher yield levels, while conserving natural resources and protecting environmental quality, will be a major challenge. Achieving the total increase in grain production to meet projected demand also will depend on minimizing losses of cropland to urbanization, industrialization, and soil degradation and making required investments in research and education to develop and apply relevant technologies. Although all of these actions are feasible, they will occur only with the necessary investment of funds and effort throughout the world.

Technologies to Improve Animal Production Efficiency

Animal agriculture has shared in the twentieth-century revolution in agricultural technology in many respects, although traditional production systems continue to be an important part of the global total. We document here a few examples of increases in productivity and efficiency and explore some opportunities for the future. Additional new technologies are discussed by Heap (1998).

Examples of Achieved Efficiency Increases

U.S. Milk Production

From 1960 to the 1990s, U.S. per cow milk production, based on production-recorded herds, increased approximately 65% (Bradford, 1998) and the rate of increase shows no signs of slowing. This increase is due to improved genetics, nutrition, disease control, reproduction management, and other factors; improved genetic potential seems to account for more than half the gain. This increased production requires more input per cow but the country now produces more milk from fewer than half as many cows as were present at the end of World War II. Resulting savings in labor, land requirement, and other inputs are very large. As shown in Table 4.24, overall efficiency of feed conversion is approximately twice as high in U.S. dairy herds as in several other countries.

This pattern has been duplicated in other developed countries but to only a very limited extent in developing countries, with the result that the global average production of 1,150 kg/cow/yr (Seré and Steinfeld, 1996) is only about 10% of that of the highest-producing herds. The opportunity for increases in efficiency by applying known technologies in this area seems to be especially good.

Growth and Feed Conversion in Broiler Chickens

A comparison of a modern (1991) commercial broiler strain with a random-bred control with no selection since 1957, using 1957 and 1991 diets and production practices, was carried out by Havenstein et al. (1994a, b). The 1991 strain on the 1991 diet grew three to four times faster than the 1957/1957 combination and required only 68% as much feed per unit of gain. Results of the two alternative combinations, i.e., 1957 strain with 1991 diet and vice versa, showed that strain accounted for most of the difference in growth rate and diet for the largest part of the increase in conversion rate. Carcass yield as a % of live weight and carcass fat % were highest in the 1991 strain on the 1991 diet. Animals in this group also had higher mortality (9 vs. 3%) and a higher incidence of leg problems. Thus, the very large increases in growth and feed conversion efficiency are accompanied by some negative effects, although the latter are small relative to the gains.

Global Change in Feed Conversion Rates

Apparent conversion rates of grain to meat, milk, and eggs for developing and developed countries, based on 1993 data, were given in Table 4.5. Using 1983 and 1993 data on meat production and on feed use for these regions (Table 5.1) and using the proportions of feed grains attributed to meat production calculated from the data in Table 4.5, changes in conversion rates for this period were calculated. The results are presented (Table 5.2) as both output per unit of input and as the more familiar grain per unit of meat.

It is recognized that many of the global statistics used for these calculations are estimates and that the data may not be particularly accurate. However, it seems unlikely that the relative accuracy of the estimates of meat production and feed use would have changed much during this decade. Assuming similar reliability for the two dates, the conclusion is that meat produced per unit of feed grain fed increased by about 15% in both developed and developing countries in one decade.

Increases in per Animal Production in Asia

Seré and Steinfeld (1996), in their summary of world livestock production systems, note the following: "Growth rates [of animal production] have been highest in Asia, with a 7.8% increase annually in beef and veal production, 6.3% in sheep and goat meat, 7.0% in cow milk production, 7.0% in pork, 9.6% in poultry meat, and 9.6% in poultry eggs. Comparing these growth rates with stock increases where possible (for ruminants) it shows that there is very little horizontal expansion [i.e., increase in numbers of animals] (1.2% for cattle stock, 1.8% for sheep and goats, 2.3% for cattle dairy stocks). This means that annual productivity increases of between 4% and 6% have been obtained in the decade. This is unprecedented and can only be compared to the Green Revolution in crop production in the same region during the 1960s and early 1970s." Such increases in production per animal and the resulting decrease in proportion of feed going for maintenance would be a major contributor to the increased conversion rates noted earlier.

Rosegrant et al. (1997), using FAO data, calculated annual change in meat production per animal for cattle, sheep and goats, pigs, and poultry for the periods 1967–1982 and 1982–1994. While the increases were less than values indicated for Asia, they were positive for all four classes of animals in both periods, for both developed and developing countries, confirming a global trend towards increased productivity.

These examples, based on different regions, species, products, and sources of information, indicate increases in productivity of animals, which, if continued over the period to 2020, would provide for meeting the large projected increases in demand for foods of animal origin with proportionally much smaller increases in inputs. It is encouraging that increases in productivity are occurring in both developing and developed countries and that output per unit of input, as well as output per animal, is increasing.

Potential Future Increases from Improved Technologies

Successful animal production from the technological perspective involves simultaneous attention to genetic potential, nutrition, health, management, and the production environment. Programs to improve animal productivity may, at times, need to focus on the most-limiting constraint, which may be any one of these but, in general, need to pay attention to all constraints. For example, the potential productivity of animals with superior genetics for growth, milk production, etc., will not be realized without adequate nutrition and health care; investment in increased nutritional or other inputs will not pay off with animals lacking the genetic potential to respond. Some specific technologies will be considered but it is emphasized that the interdependency of factors needs to be considered when implementing change in any one area.

Animal Genetics

Genetic potential is defined as performance when nutrition and environmental factors are not limiting. Genetic potential of domestic animals for growth, reproduction, and production of desired products varies widely on a global basis, due to both natural selection and selection by humans toward a variety of production objectives since domestication (Figures 5.13–5.21). For example, mean milk yield of cattle breeds, i.e., breeding populations with distinctive characteristics, ranges approximately from 1,000 to more than 10,000 kg per cow per year, mean litter size of pig breeds ranges from 7 to 14 and of sheep from 1 to 3, and mean mature weight and growth rate of cattle and sheep breeds varies five- to six-fold.

This between-population variation and the within-population genetic variation available for making further change provide the means for substantially improving the productive potential of domestic animals. Choice of improvement technologies varies with species, production system, and infrastructure.

With regard to breed variation, optimum genetic potential is not necessarily synonymous with maximum potential for growth rate, milk yield, etc. Breeds need to be evaluated based on lifetime productivity and, if possible, biological efficiency (output/input), under the nutritional and environmental conditions in which they will be expected to perform.

In modern industrial production systems and in mixed crop-livestock systems in favorable areas, levels of inputs and environmental conditions are under fairly complete control by the producer. Such systems generally provide the opportunity for the highest-potential breeds to express that potential. Such high-input, high-output systems also tend to be located where the most effective within-population genetic improvement programs are being applied. In less favorable environments, e.g., seasonal variation in forage quantity and quality characteristic of grazing systems, or the greater disease and parasite challenges in most tropical and subtropical regions, ability to utilize local feedstuffs and to survive and reproduce are more important than level of performance for production traits, such as growth rate or milk yield.

Figure 5.13. Beef cow with twin calves. Twinning in beef cattle is normally infrequent but can be increased by genetics. In favorable production environments, twinning is a technology that can be used to increase efficiency of production substantially. Photograph courtesy of John Dunbar, University of California, Davis.

Throughout the colonial era and still continuing in some countries, it often has been assumed that importing high genetic potential breeds is the best way to raise productivity above the low levels observed with locally available stocks. This frequently has met with disappointing results. The imported animals often suffer higher mortality and have lower fertility and poorer production because of disease or temperature stresses to which they are not adapted, or simply because the nutrients to permit them to express their genetic potential are not available.

Use of breed resources to improve productivity can, with careful selection of breed(s) and some attention to removing nutritional and other constraints, result in one-step increases in performance of 50% or more. In general, breed transfer from one temperate environment to another is fairly successful; an example is the recent extensive use of North American Holstein breeding to increase milk yield of European dairy cattle. Transfer of breeds from one tropical environment to another also can be useful. Gatenby et al. (1997) describe results of a comparison of Caribbean hair sheep crosses with a local breed in Indonesia in which two crossbred groups produced 34 and 51% more total lamb weight per ewe per year and an estimated 15 and 26% more lamb per unit of maintenance feed requirement than the local breed. However, a major limitation to improvement of tropical animal production by this method is the lack of high-production potential breeds in the tropics, compared to temperate regions. Thus, the choice of "improver" breeds from this source is limited.

Many disappointing results of breed transfer have occurred when breeds developed in temperate regions are imported to the tropics and subtropics; such transfers should be made with great caution. New germplasm should be released only after the imported stock has been shown to be superior, as a purebred or in crosses, to local breed(s), on a life-cycle basis under conditions characteristic of local farms. Such evaluations should include measurement of fertility, viability, veterinary costs, and length of productive life, as well as the production traits of primary interest. It is much easier to produce individual animals with higher growth rate or milk yield than to produce herds with higher mean productivity on a life-cycle basis. Where temperate-origin breeds have contributed to improvement of animal production in the tropics, it has most often been as contributors to a crossbred population based on local breeds.

Mention was made earlier of the large increases effected in genetic potential for milk yield in developed countries in the last three decades and of the very large differences in yield between developed (temperate) and developing (mostly tropical) countries. A major factor in the latter difference is that tropically adapted breeds have lower milk production potential. Crossing between improved temperate (*Bos taurus*) and tropically adapted (*Bos indicus*) breeds results in F_1s that are reasonably well adapted to the tropics and with much higher milk yield than the *Bos indicus* parent (Cunningham and Syrstad, 1987). However, animals with more than 50% *Bos taurus* inheritance often have lower fertility and therefore longer calving intervals (Rege, 1998) and, as the Cunningham and Syrstad review showed, F_2 and later generations of the 50:50 combination consistently are substantially inferior to the F_1. As a result, a high milk yield breed well adapted to the tropics is a goal not yet achieved, in spite of much effort in many countries over the past century. Rutledge (1997) has suggested an ingenious plan for continuous production of F_1s using embryo transfer that may be logistically and economically feasible in some tropical countries.

Availability of breed resources for effecting future genetic improvement depends on conserving existing breed variation. One unfortunate consequence of inappropriate breed importations, in addition to the risk of failure to effect genetic improvement, has been dilution or loss of indigenous stocks with valuable genetic adaptation to local environments and markets. An important global need is for systematic evaluation of indigenous breeds, assessment of relationships among them, and implementation of programs to conserve those with unique performance characteristics or that are most distinctive genetically.

Selection within populations can increase productivity 1 to 2% per year, occasionally more. Such rates often are perceived as slow but they are cumulative and permanent. The dairy cattle case described earlier represents an increase of this order consistently over three decades and, to date, there is no evidence of diminution of response. Thus, where achieved, these rates would permit maintaining or increasing global per capita availability of animal products without an increase in the numbers of breeding animals.

Selection programs to increase animal performance depend on extensive recording of performance, using the records to identify genetically superior animals, and using those animals for breeding. Effective genetic evaluations depend on sophisticated statistical methodologies and computers. Effective dissemination of superior germplasm depends, at least in some species, on widespread use of technologies such as artificial insemination (AI).

These conditions generally are met in developed countries. Dairy and beef cattle breeding is based on systematic performance recording in large numbers of herds, objective genetic evaluations carried out by governmental or large breed organizations with professional scientific staff and extensive computing capability, and provision of AI service by governmental agencies or large commercial firms. Embryo transfer, which can further increase intensity of selection, also is generally available and increasingly used.

Poultry breeding in developed countries is now done almost exclusively by a small number of large firms that maintain large breeding flocks and have their own scientific staff to supervise performance

Figure 5.14. Genetic potential matched to the production environment and markets of a region are important to efficient animal production. Jersey and Friesian cattle in the United Kingdom. Photograph courtesy of Eric Bradford, University of California, Davis.

Figure 5.15. Genetic potential matched to the production environment and markets of a region are important to efficient animal production. Red Sindhi (Zebu) cattle in India. Photograph courtesy of Eric Bradford, University of California, Davis.

recording and perform genetic evaluations. Dissemination of the improved stocks is done by providing breeding stock (hatching eggs) to franchised multiplier enterprises. The latter then produce and sell birds to commercial producers. The commercial birds are typically a three- or four-way cross involving proprietary strains of the breeding firm. This maximizes exploitation of hybrid vigor (heterosis) and also ensures that the commercial producer must continuously return to the breeding firm, rather than breeding from the commercial animals, to obtain the highest genetic potential.

Pig breeding is rapidly evolving a similar pattern to that of the poultry breeding industry. For both poultry and pigs, most breeding firms operate internationally, placing control of genetic improvement in these two species with a relatively small number of international firms. The utilization of a small number of high-performance potential stocks is facilitated by the fact that industrial poultry and pig production involves highly standardized systems, which minimize nutritional and environmental constraints characteristic of traditional systems. (Such industrial systems depend heavily on relatively low feed grain prices and global trade in feed grains.) The breeding system is very efficient in effecting and disseminating genetic improvement; however, it is generating some concern about loss of genetic diversity to meet changed needs in the future (Council for Agricultural Science and Technology, 1999).

An alternative structure to effect genetic improvement in livestock is cooperative or group breeding schemes, often referred to as nucleus programs. Developed initially for sheep improvement in New Zealand (Parker and Rae, 1982), the system involves screening a large population, comprising all of the animals in many flocks, for superior animals, which then are placed in one flock to produce breeding animals (predominantly males) for all participating flocks. In principle, the system is similar to the breeding firm/franchise hatchery system described for poultry, except that it is a cooperative venture, usually with opportunity for superior animals from participating flocks to enter the nucleus on a continuing basis (open nucleus). Properly organized, such systems can cause genetic change as rapidly as the AI/national genetic evaluation breeding plans described for cattle or the large-firm poultry- and pig-breeding structure. Such programs have been successfully implemented for sheep, cattle, and goat improvement in New Zealand, Australia, South Africa, and elsewhere.

Figure 5.16. Genetic potential matched to the production environment and markets of a region are important to efficient animal production. Zebu ∞ Friesian cow in India. Photograph courtesy of Eric Bradford, University of California, Davis.

The situation in developing countries for dairy, beef, sheep, and goat production—and also for much poultry and pig production—can be quite different from that in developed countries. Herd/flock size, farmer education levels, lack of infrastructure, and other factors limit uniform performance recording on large numbers of animals. The availability of genetic evaluation expertise and computing capability are irrelevant without performance data. Dissemination of improved genetic material may be constrained by lack of communication systems, roads, reliable vehicles, etc. needed for successful AI.

Under these circumstances, many selection programs used effectively in developed countries cannot be implemented in developing countries. Importation and use of improved breeds or other crosses with local breeds may be an effective means of improvement (McDowell, 1994) provided nutritional and health constraints can be sufficiently alleviated. In principle, successful implementation of cooperative breeding plans should be possible whenever a group of producers agree to do so but farmer education levels and lack of effective extension programs mean that few, if any, such programs have been implemented in developing countries.

As the economies of countries or regions develop and increased demand for animal products contributes to higher or at least more stable prices, producers should be able to afford increased inputs. This will permit greater use of "improved" breeds and their crosses, more effective use of indigenous breed resources, and increased investment in record keeping and selection. As this happens, at varying rates in different parts of the world, improved genetics can be used to help close the very large gaps between potential production levels and those now characteristic of many livestock populations.

Biotechnology

Biotechnology, which may be used in any of the animal science disciplines, often is listed as a potentially powerful tool for improving animal productivity and eventually may well prove to be so. To date, it has been used to improve efficiency and effectiveness of disease diagnosis and to develop vaccines for disease prevention. Monoclonal antibody techniques are being used in some 20 new diagnostic tests, including for bovine viral diarrhea (BVD), sarcocystis, chlamidia, and toxoplasma. Polymerase chain reaction (PCR) methods are being used routinely to diagnose BVD, Johne's disease, blue tongue, and mycoplasma, as well as other diseases. Genetically engineered vaccines for pseudorabies in hogs and for infectious laryngotracheitis in poultry are now available. A double recombinant vaccine for rinderpest has been developed and is being field tested in Kenya and Ethiopia (Giavedoni et al., 1991; Yilma, 1994). This vaccine not only provides protection to the vaccinated animals but, because it does not require refrigeration, veterinary services in developing countries can now carry out much more effective campaigns against rinderpest.

Another application is the use of recombinant bovine somatotropin (rBST) to increase milk production from intensively managed dairy cows.

With respect to genetic improvement of animal productivity and product quality, biotechnology has so far had relatively little impact. In the future, it seems probable that product composition may benefit more than production efficiency, for two reasons. One is that product composition, e.g., amount of fat or fatty acid composition in meat, milk, or eggs, tends to be less complex, from a genetic perspective, than traits such as growth or reproduction, and thus easier to modify genetically. Second, funding for biotechnology research is largely from private sources, so it is likely to be more feasible to patent changes in product composition than in a trait such as yield or feed conversion rate. Given the remarkable contributions of past scientific achievements to increasing animal productivity, it would be unwise to rule out any possibility. Technologies that result directly in increases in yield or efficiency may be developed, even though they are not on the immediate horizon.

One approach that could have large indirect benefits for yield and efficiency is breeding for disease and parasite resistance. To date, it has received much less attention in animal than in plant breeding but is currently receiving more emphasis by animal breeders. Its impact could be particularly important in the tropics and subtropics, where animal productivity and animal product consumption are, on average, low. This field is seen as having especially good potential for applying biotechnology to augmenting human food supply.

Cloning, i.e., making genetically identical copies of an individual, recently has been achieved using cells from adult animals (Wilmut et al., 1997). Cloning the best individuals has been a very effective tool used in crop improvement for millennia. It is not clear whether large-scale, low-cost cloning will ever be feasible in domestic animals but its availability would be an important tool for improvement of livestock production efficiency and product uniformity.

There are two types of concerns regarding biotechnology. One is that it may produce environmental or health hazards and therefore should not be used; this concern has resulted in constraints on the use of genetically engineered materials in food production in Europe (*Science*, 1998). The second is that misinformation disseminated by opponents of biotechnology, based on the first kind of concern, can lead to legislation and policies that will prevent the adoption of technologies with important potential to improve the quantity or quality of the human food supply, even for technologies thoroughly tested and proven safe (Pinstrup-Andersen et al., 1997).

Animal Health

Disease prevention and control are essential to ef-

Figure 5.17. Zebu cows typically require presence of the calf at milking time for proper milk let-down. This is not the case for specialized dairy breeds such as Friesians. Zebu cow in India. Photograph courtesy of Eric Bradford, University of California, Davis.

ficient animal production. Prevention may be effected by exclusion, accomplished through strictly enforced import restrictions, quarantine, etc., by vaccination, by elimination of disease vectors, or by use of genetically resistant animals. Good nutrition is an important tool for limiting the impact of a number of disease agents, such as internal parasites. Good management/husbandry also can play a major role in preventing infections or limiting their spread. Where infection does occur, animal health research has developed a range of tools, two particularly important ones being antibiotics and anthelminthics, to eliminate or reduce morbidity and mortality from disease.

East Coast fever (ECF) is a disease that illustrates the interaction of genetics and disease incidence as well as the range of animal health technologies required to control a disease. This usually fatal disease of cattle and the African buffalo is caused by *Theileria parva*, a protozoan parasite transmitted by the tick *Rhipicephalus appendiculatus*. Mortality resulting from infection with this organism can run as high as 90% when susceptible cattle are infected with carrier ticks. Estimates of mortality suggest that 1.1 million cattle die each year from this disease (Mukhebi et al., 1992). Thus, when animals with superior genetic makeup for productivity are imported to ECF-endemic areas, they often fall victim to the disease (Nyangito et al., 1995). This is in contrast to animals of local breeds born in endemic areas that, although often infected by the age of 6 months, have a mortality of only about 5%. It has been estimated that annual direct ECF losses to African farmers are about $170 million (Consultative Group on International Agricultural Research, 1997a; Mukhebi et al., 1992). When the additional losses due to a reduction of genetic improvement are included, the estimated loss is much higher.

Figure 5.18. The Jamunapari breed of milk goats of India has contributed to the development of breeds, such as the Etawah of Indones ia and Anglo-Nubian, popular in many countries. Photograph courtesy of Eric Bradford, University of California, Davis.

Among the methods being used to control ECF are vector or tick control, chemotherapy of infected animals, and vaccination. Using pesticides to control ticks is difficult, expensive, and adversely affects the environment (Nyangito et al., 1994). Although treatment with various chemotherapeutic agents has been successful, these agents are expensive and their use occurs in most cases only after the animals are infected and some loss of productivity already has occurred. The older method of vaccination involved direct infection of the animal while simultaneously treating with an antibiotic (infection-and-treatment immunization) (Mukhebi et al., 1990). This procedure can result in a limited immunity, risks the introduction of extraneous pathogens to the area and herd, infers a strain-specific immunity, and is costly to the farmer (Mukhebi et al., 1995). However, estimates of the benefit:cost ratio are in the range of 9 to 17:1 (Mukhebi et al., 1992). One solution would be development of a new vaccine that is efficacious, cost effective, and nonpolluting. Such a vaccine has been advanced through development of recombinant antigens to *Theileria parva* (Consultative Group on International Agricultural Research, 1997). A long-term solution would be to improve the productivity of resistant breeds through genetic selection. Even a 50% reduction in annual mortality from this disease by one or a combination of approaches would mean over 500,000 additional animals available for production of meat and milk for human use or, alternatively, fewer breeding animals to produce the same number of offspring annually, reducing pressure on the land while maintaining food production.

Improved vaccine production can save money and increase productivity. For example, it is estimated that brucellosis in U.S. cattle herds costs producers about $30 million a year. The new, genetically modified vaccines for brucellosis provide excellent protection without the complication of the old vaccines, where difficulty in distinguishing between vaccinated and naturally infected reactors have frustrated control of this disease. Pseudorabies is a disease that kills young pigs and causes reproductive failure in pregnant sows. The disease, prevalent in some areas of the country, costs pork producers about $60 million each year. The development of a genetically engineered vaccine is expected to eliminate the problem (U.S. Department of Agriculture, 1995).

Animal Nutrition and Feed Utilization

There is no doubt that science has the tools to increase production to meet the projected increase in demand for livestock products. However, not all of these tools have proved acceptable to either producers and/or consumers. Without such acceptance, their potential cannot be realized. In this section, two types of technologies will be discussed separately; first, those that enable animals to extract more nutrients from feed and, second, those that enable feed to be utilized more efficiently. Predictions of likely responses of producers and consumers are a key part of this discussion.

Nutrient Extraction by the Animal

The primary difference between the digestive tracts of ruminants and nonruminants—namely, the presence of anaerobic microbes in the rumen—is a key factor for differentiating between the approaches adopted for these two classes of livestock.

Nonruminants Digestion in pigs and poultry, the major species of nonruminant domestic livestock, is largely achieved by enzymes secreted in different parts of the digestive tract. Adding enzymes to the feed to aid digestion is already a common practice in many production systems. New genetic techniques mean that the cells in the animals' digestive tract could be manipulated to enable pigs and poultry to digest safely a wider range of feedstuffs. Introduction of an enzyme to detoxify gossypol in whole cottonseed and cottonseed meal could decrease the degree of competition between nonruminants and humans for soybean oilmeal or other protein supplements. However, consumers may not accept the use of animals whose cells have been manipulated simply to produce more meat.

Ruminants It is tempting to consider the rumen as a large vat containing many species of microbes that provides an easy mechanism for using more fibrous feeds through the introduction of a manipulated microbe that can digest cellulose more efficiently or even extract nutrients from lignin. There would be little reason for consumers to object to such a practice. However, after several decades of research by microbiologists and molecular biologists, a significant breakthrough in energetic efficiency or cellulose digestion is still elusive (although inoculation with modified microorganisms has proven successful for detoxification of substances such as mimosine and nitrate). The problem is that survival in the rumen is highly competitive for any microbial species and the attributes that scientists are trying to introduce for the benefit of the animal are not likely to contribute to the microbe's competitive abilities. Manipulation of animal cells, as described for nonruminants, thus may be a more successful route for increasing the ability of the ruminant to extract fiber from highly fibrous feeds, which are abundant.

All Species After digestion, nutrients are absorbed from the digestive tract and then metabolized. Efficient production will result from the absorption of different classes of nutrients in ratios approximate to their requirements for production. These ratios change with stage of growth and milk production, and their profile with the age of the animal and potentially among breeds. Using available biochemical- and mathematical-modeling techniques, researchers are achieving a better understanding of these profiles. Closer matching of nutrient absorption to nutrient requirements should not only improve the production efficiency of meat, milk, and eggs but also decrease the environmental costs from excess nitrogen and other nutrients being excreted in the waste from livestock-production systems.

Feed Modification for Improved Utilization

The key to successful modification of feeds for improved productivity is a sound understanding of the starting point, i.e., the nutritional value of the basic feed. Modern laboratory equipment such as near-infrared spectroscopy (NIRS) greatly facilitates the rapid analysis of large numbers of samples, although the

Figure 5.19. Buffalo cow in Egypt. Buffalos are important producers of milk for human consumption in many tropical and subtropical countries. Photograph courtesy of Eric Bradford, University of California, Davis.

system does require calibration against standard chemical analysis for each type of feed. With calibration, there is some evidence that NIRS can predict not only the content of each nutrient but also its digestibility (i.e., the extent to which the animal can utilize the nutrients). Improving the digestibility of fiber is the nutritional advance with the greatest potential to increase livestock productivity, given the worldwide abundance of fibrous feeds with digestibilities of less than 50%.

Attempts to increase the digestibility of fibrous feeds started with the use of chemicals in the 1970s. For example, ammonia treatment of rice straw has been shown to increase its feeding value for ruminants by 11 to 17% (Cann et al., 1991). However, adoption of the technology by farmers in developing countries, which are most dependent on fibrous feeds, has been slow. This constraint to adoption has been variously attributed to lack of labor or water, the price of the chemicals, or the lack of incentive to increase livestock productivity. Thus, the use of the technology has been greatest in recent years in China, where the demand for livestock products is fast growing and governmental influence greater. This provides a lesson on how and when to introduce new technologies, i.e., when a market, including the necessary infrastructure, for the products exists and national policy facilitates the adoption.

Improving the feeding value of many crop residues and by-product feeds through development of new technologies (physical or chemical treatments) is undoubtedly possible; however, research funding for this field, in the United States or elsewhere, is very limited. Reasons include geographically limited availability and relatively small contribution of individual by-products in feeding systems. For example, although by-products in total may constitute 30 to 50% of U.S. dairy cattle rations, compared to alfalfa at 50%, no single by-product may contribute more than 10%. However, changes such as an increase in the real price of feed grains could make it worthwhile to increase research in this area. Important research needs include development of economical methods to assess nutritive value of a wide variety of products, and investigations of possible toxins, naturally occurring or from the use of agricultural chemicals, including assessment of the ability of ruminant animals to detoxify such substances.

Figure 5.20. Sahelian sheep with owner in livestock market in Mali. Photograph courtesy of Eric Bradford, University of California, Davis.

Feed Grains Modifying the composition of feed grains to improve their feeding value is a possibility. However, the energy used by a plant to synthesize protein and particularly oil is substantially higher than to synthesize starch (McDermitt and Loomis, 1981; Penning de Vries et al., 1974), which explains in part why soybean yields are much lower than maize. Breeding any crop species for higher protein or oil content will involve yield tradeoffs; thus, this approach is unlikely to contribute a net increase to animal feed supply.

A number of reports have documented differences in feeding efficiency among crop varieties that were related to starch digestibility and nutritive value. In one study on sorghum, average daily weight gain of steers fed equivalent rations containing an inefficient or efficient hybrid differed by 9%, a difference related to the in vitro measures of starch digestibility rather than starch quantity (Wester et al., 1992). The maximum potential increase in feeding value from genetic improvement in starch quality is probably no more than 10% for maize and 15% for sorghum, however, which is the increase in feeding efficiency that can be derived from steam flaking or steam rolling the grain before feeding (Owens et al., 1997). This process gelatinizes the starch, reduces the particle size, and makes the starch more digestible. Eliminating the need for flaking would reduce the input costs from 5 to 10%. The above estimates apply to potential improvements in feeding value for beef cattle; the improvement may be greater for dairy cattle.

Protein quality also can be modified to increase feeding efficiency of grain by providing a better balance of required amino acids. Although it is genetically feasible to alter protein quality in grain, e.g., high-lysine maize varieties, currently, this technology has not been widely adopted because it has been more economical to supplement animal rations with amino acids derived from microbial fermentation production systems. Amino acid supplementation is widely used in commercial animal rations, particularly for poultry and pigs. Use of recombinant DNA technology has permitted increased supplies of amino acids such as lysine and methionine at greatly reduced cost. However, high yielding amino acid-enriched grains currently being developed may offer a competitive alternative in the future.

Antinutritional factors also affect digestibility and feed value. One promising technology is low phytic acid feed grains. About 80% of the phosphorus (P) found in feed maize is contained in phytic acid, a form of P unavailable to nonruminant animals such as poultry and swine. For example, only 10 to 20% of the P is assimilated by the animal; the rest is excreted. Recent research has identified genetic maize mutants with a 66% reduction in phytic acid phosphorus content in grain, although grain total P is unchanged (Raboy and Gerbasi, 1996) and seeds remain viable (Ertl et al., 1998). When fed to chicks in moderately phosphorus deficient diets, feed efficiency increased 11%, compared with normal maize. This increase was associated with greater P utilization from the low phytic acid maize and by a 40% reduction in fecal P excretion. In fact, the environmental benefits of reduced phosphorus load in swine and poultry manure are perhaps more important than the potential improvement in feeding efficiency from low phytic acid maize. Work is underway to identify the genes responsible for this trait, so it may soon be possible to produce transgenic maize and other feed grain crops with low phytic acid content.

Low phytic acid grain is but one example of potential opportunities to modify grain quality using molecular genetic approaches because many quality traits are under single-gene control. During the next decade, it is likely that a number of genetically engineered crop varieties with modified grain quality, e.g., resistance to aflatoxin and other mycotoxins, will be commercialized and will contribute to increased feeding efficiency and decreased environmental impact.

Forages Forage production can be increased by breeding for greater forage yield and quality, although considerably less research has been devoted to the genetics of pasture and range plants than to cereal crops (Vogel et al., 1989). In spite of this reduced emphasis, forage breeders have successfully developed improved varieties of several species with improved digestibility, greater yields, and better disease resistance (Casler and Vogel, 1999). Many of these improved varieties are now in commercial use and produce higher yields with greater feed value than unimproved genotypes. There remain a large number of plant traits that influence forage quality that have not been fully exploited, such as reducing the content of antinutritional factors and altering cell wall and lignin concentration and composition. Improved hybrids and hybrid seed production systems hold promise for increasing forage yields of some species. In addition to conventional breeding methods, molecular genetics and plant transformation are being used to facilitate research on forage genetics, which should accelerate forage crop improvement efforts.

Advanced Information Systems

Reference was made earlier, during the discussion of future animal feed supplies, to the potential contributions of "precision farming" to increased crop productivity and, in particular, to more efficient use of production inputs. Likewise, improved information resources and technology can contribute to higher efficiencies in livestock production. This is made possible by advances in computer hardware, including increased internal data storage and portability (CD-ROM), processing capacity, decision support software, and the World Wide Web with its incredible collection of data. On-line sensors will continue to be integrated with these tools for more automated systems. For example, in the United States, national databases by livestock species are being developed to support decision making by farmers, ranchers, and those who work with them in an educational, consultative, or service capacity. These national databases are comprehensive electronic collections of peer-reviewed and expert-selected educational materials, lists, software tools, and other decision aids. This brings useful decision support tools to farms, homes,

Figure 5.21. Javanese Thin-Tail breed ewe with quintuplets in Indonesia. Photograph courtesy of Luis Iniguez, ICARDA, Aleppo, Syria.

and offices in the smallest or most remote rural community. These collections are distributed via CD-ROM and the Internet.

The Web will continue to grow, supplying marketing information and sales opportunities, providing education and decision aids, and enabling two-way communication with active agents, the equivalent of consultants within narrow subject areas. Judging the quality of available information remains a major challenge.

Individual identification of large animals and associated databases will be developed further for improved animal selection and herd management. This already is a legal requirement in the EU and is widely used by dairy producers in many countries. Beef industry associations in the United States have called for a voluntary program to enhance food safety and management information feedback to improve product quality as well as industry profitability. With such a system, the interdependence of all segments of the industry is recognized. Hence, throughout the production system, from providers of animal genetics to sellers of consumer-ready products, all can capitalize on the information provided to help people solve complex, industry-level problems and individual producer- and firm-level problems associated with the many significant changes occurring in these industries.

In the developing world, change may occur less rapidly. However, with access to the Web and advanced information resources, there is no basic reason why lack of access to information will be the most limiting resource for livestock production.

Production Systems

Grazing Lands

Meat, milk, and fiber represent only a portion of the many goods and services provided by the 35% of the world's land grazed by livestock. Others include maintenance of wildlife populations and general biodiversity, fresh water, open space, and recreational space for a rapidly expanding human population. Walker (1995) predicted that, in the future, livestock on rangelands would be dual purpose: commodity production and vegetation manipulation. Thus, the definition of sustainability of grazing lands has shifted from a level of animal off-take that does not decay the land's ability to continue producing forage to a balance between what people collectively want, reflecting social values and economic concerns, and what is ecologically possible in the long term (Borman et al., 1994; Vavra, 1996).

When discussing impacts of grazing on rangeland natural resources, it is important to specify the particular ecosystems involved. Much attention has focussed on the more arid lands because of the very large areas involved globally and the fact that many of these areas have been grazed for many centuries. As will be discussed, controversy exists over the impacts of grazing on such lands but there is good evidence that, with proper management, their use for grazing can be sustainable and compatible with other purposes.

A more recent development is the clearing of rain forests in the Amazon to permit livestock grazing. From the perspectives of maintaining biodiversity and of global carbon dioxide production, this is an undesirable change. The primary driving force is the need for economic opportunities for a rapidly expanding human population; there are presently limited alternatives available in this region. The situation is a complex one (Faminow and Vosti, 1998) and substantial policy changes to provide alternative pathways of economic development will be required to protect the remaining rainforests.

With regard to traditionally grazed lands, grazing is perceived by some as an unsustainable use of the land. For example, in 1994, the Society for Conservation Biology called for drastic reductions in livestock grazing on public lands. Fleischner's (1994) review identified several results of livestock grazing: loss of biodiversity, lowering of population densities for a wide variety of taxa, disruption of ecosystem function, changes in community organization, and changes in the physical characteristics of terrestrial and aquatic habitats. As a result, it is widely perceived that lands grazed by livestock are steadily deteriorating in biological productivity. However, long-term monitoring of the infra-red index by National Aeronautics and Space Administration satellites (Tucker et al., 1991) and evaluation of livestock productivity by de Haan et al. (1997) have shown that the perceived wide scale degradation of rangeland resources may not be occurring. In a seven country region from Senegal to Sudan, there was a 47% increase in meat production per animal and a 93% increase in meat production per hectare over the period 1960–1991. Production did decrease temporarily during the 1970s drought, but the trend for the whole period is clearly an increase in both measures of productivity.

There is a natural expansion and contraction of the Sahara, with vegetation and livestock responding to naturally occurring climate variation. This has led to the conclusion that these types of ranges are more resilient than previously assumed. Because abiotic factors such as rainfall are the main determinants of vegetation, recognition has developed for the need to manage this type of grazing resource in a manner that makes use of the forage when it is available and then allows grazers the potential to move to different areas (see Box 7). In a very different part of the world, grazing lands in the western United States are judged to be in the best condition in a century, although much room for improvement remains (Box, 1990; Council for Agricultural Science and Technology, 1996a).

The undesirable effects described by Fleischner (1994) do, in fact, occur with improperly managed grazing, which unfortunately happens with sufficient frequency that such effects can readily be found. However, properly managed grazing can be neutral or even beneficial with regard to biodiversity and other desired environmental outcomes. Bryant's (1982) review of 214 papers on livestock influences on wildlife found more cases of positive than of negative effects. Sever-

Box 7

Stocking Rate

A frequent suggestion for increasing animal production from rangelands, while improving the sustainability of the range resource, is to reduce stocking rate, i.e., the number of animals grazing a given area, on ranges perceived to be overgrazed.

The biological principle involved in this recommendation is a simple one. If the stocking rate is at or close to the maximum number of animals that the range can maintain, (1) all or most of the available forage will be consumed except during periods of most rapid forage growth, and (2) nearly all of the nutrients in the forage will be used by the animals just to meet their maintenance needs, with little left for reproduction, lactation, growth, or fiber production. By reducing the number of animals, those remaining will each have more forage and, therefore, more nutrients for productive functions and there will be less grazing pressure on the range.

This recommendation is based on the assumptions that the goal of keeping animals is to maximize off-take rates and that removal of vegetation by livestock is the primary determinant of the plant biomass and species mix present.

The first of these assumptions is generally valid for ranching systems in developed countries but often not true for pastoral people in arid regions heavily dependent on their animals to provide their food and livelihoods. In the latter case, having extra animals to slaughter during a drought while still leaving sufficient animals to repopulate when the drought is over may be an essential risk management strategy, more important than maximizing off-take rates in normal years.

The assumption that livestock grazing is a major determinant of vegetation status tends to be true for equilibrial systems, i.e., systems with reasonably dependable rainfall from year to year where there is a direct feedback between animal numbers and vegetation states. In such systems, reduction of animal numbers from an overstocked status can increase reproduction, growth, and survival rates of the remaining animals sufficiently to produce a net increase, in some cases, quite large, in off-take rate. Areas with a high temporal and spatial variability in forage yield and quality resulting from high interseason and particularly interyear variability in rainfall are described as nonequilibrial. In such systems, livestock herders traditionally pursue opportunistic strategies, based on mobility, to optimize use of rangeland resources (Sandford, 1983). During drought years, losses of forage due to termites, decomposition, and weathering deplete the forage supply, regardless of animal numbers. In such situations—and considering the different production objectives of pastoral people compared to ranchers—conventional ideas of carrying capacity no longer apply. Policies that support traditional practices, e.g., that facilitate movement of animals and their owners out of drought areas, may be much more beneficial to both the pastoralists and the environment than confining the herds to a specific area at a predetermined stocking rate (de Haan et al., 1997 [Box 3]; Ellis and Swift, 1988). Movement of animals out of drought areas, however, assumes there are accessible areas with unused forage, which becomes progressively less likely as human population increases.

The conclusion is that reducing animal numbers on overstocked lands in equilibrial systems can both increase animal production from the land and reduce the detrimental effects of overgrazing. In nonequilibrial systems, the picture is much less clear and this intervention may have adverse consequences for both the people and the environment. Thus, it should be considered, if at all, only after a careful assessment of the goals and characteristics of the system and the probable social as well as environmental consequences of such a change.

son (1990) provides examples of a variety of species benefited by livestock grazing, including sage grouse, sharp-tailed grouse, and waterfowl. Kay and Walker (1997) reported little or no effect of a century of sheep grazing on willow communities, while elk populations had nearly eliminated willows on their range in the same region.

A recent report (Collins et al., 1998) showed that bison grazing or mowing tall grass prairie significantly increased biodiversity, compared to no grazing; while this study did not involve a domestic livestock species, it seems highly probable that a similar effect could be achieved with selective management of such animals. Elimination of cattle grazing can have adverse effects on the quality of winter range for a species such as mule deer (Urness, 1990). Schwartz and Ellis (1981) found the dietary overlap between wildlife and livestock species to be fairly limited throughout most of the year. Mwangi and Zulberti (1985) and Western and Pearl (1989) showed that a combination of livestock and wildlife management resulted in an equal or better species wealth than when these two activities were practiced individually.

A number of strategies may be used to enhance livestock production from grazed lands while maintaining or enhancing the ability of the land to meet other purposes. Multispecies grazing results in less grazing pressure on individual plant species, while maintaining or increasing meat or fiber production, compared to single-species grazing; for a recent review, see Walker (1994). Changes in stocking rate can be used to increase productivity but the impact of such changes can vary markedly, depending on the ecosystem and production system involved (see Box 7).

Grazing systems are specializations of management that define recurring periods of grazing and deferment (non-use) for two or more pastures or management units; Heitschmidt and Taylor (1991) provide an excellent discussion of grazing systems.

In the development of grazing systems compatible with wildlife, two main objectives usually are considered. The first is simply to develop a system that has minimal environmental consequences. The other has specific plant community manipulations in mind and the livestock are used to develop that plant community through the process of grazing.

The development of sustainable grazing systems usually begins with a change from continuous, season-long use to a system where livestock are moved through a given number of pastures, creating recurring periods of grazing and deferment. Most systems are designed to provide rest or deferment through the growing season in an effort to sustain plant vigor. Often, a change from continuous use to a grazing system will benefit wildlife, if stocking rates are not excessive.

On most rangelands, the landscape is such that some areas are preferred by livestock due to topography, distance to water, shade, and/or palatability of plant species. Season of use also may influence livestock distribution. The end result is that rangelands are seldom grazed to a uniform level of utilization. Areas of heavy, moderate, light, and even non-use commonly occur within one pasture (Sheehy and Vavra, 1995). Gradients of disturbance and consequent successional status should then occur across the landscape, providing an array of habitats. The key to success is a moderate level of stocking so that residual plant material remains and not all locations within all pastures are heavily grazed. Moderate levels of stocking also should provide the proper level of gain per animal and per ha, so that livestock production itself is sustainable.

In specific instances, livestock grazing systems are designed to manipulate plant communities to enhance the habitat for featured species. The development of these systems probably had its beginnings in the work of Bell (1971) and others, who observed that grazing by one species of herbivore can modify vegetation so that individual plant species or communities are improved in ways that benefit other species of herbivores. In forests of the interior northwestern United States, elk and mule deer change both feeding habitat and species composition of their diets in response to cattle grazing. On the Isle of Rhum, Scotland, Gordon (1988) found that red deer production was increased on the area of the island where cattle grazing was reintroduced. More red deer calves per 100 females were produced in the cattle-grazed area.

Severson and Urness (1994) provide an excellent description of the specific vegetation manipulations possible with livestock grazing management. Livestock of various species may be used to alter the composition of the vegetation, increase the productivity of selected plant species, increase the nutritive quality of the forage, and increase the diversity of habitat by altering its structure. Likewise, different species of livestock can be used to the same effect to improve forage conditions for other species of livestock. Even within-species enhancement is possible.

One specialized grazing system, transhumance, involves the systematic movement of livestock to take advantage of seasonal differences in forage growth, e.g., at different elevations. Such systems have been used in different parts of the world for many centuries and can be both productive and sustainable. For example, a traditional transhumant system in the Sahel was found to be as productive, in terms of animal protein per unit area, as ranching systems in comparable zones in Australia and the United States (Bremen and Uithol, 1984). However, transhumant systems are being seriously constrained by increasing human population pressures in developing countries, e.g., in the interior delta of the Niger in West Africa, by conversion of former grazing lands to crop production, and, in both developing and developed countries, by construction of highways and other barriers to livestock movement.

Technologies exist to substantially improve animal productivity from grazing lands, e.g., fertilization, fencing to permit more intensive control of grazing, and seeding with improved forage species provided care is taken to ensure that introduced species do not become weeds in the new environment. These practices may be appropriate in some cases but often are not economically justified because of the inherently low productivity potential of the lands involved. Their use also may be constrained by other considerations, such as the inhibiting effect of fences on wildlife migration.

An important goal is development of management pathways for livestock production based on ecological soundness that provide the essentials of vegetation cover, water-holding capacity, and lack of erosion to the landscape, which also support economic sustainability of livestock enterprises. Grazing treatments for specific habitat considerations can be factored in where objectives dictate.

Crop-Livestock Systems

Because mixed crop-livestock systems produce more than half the meat and most of the world's milk supply, improvements in productivity in this sector are critical to meeting the increased demand for foods of animal origin.

As discussed earlier, matching genetic potential of animals to the available nutrient level and management conditions, improving animal health, and improving yield and nutritional value of forage crops and feed grains are important means of raising animal productivity. All are important aspects of mixed crop-livestock systems. Such systems also put a special premium on management skills, not only on management of the animals but also on the integration of crop production, utilization of crop residues to meet nutritional needs, and management of manures to maintain soil fertility, into an economically and environmentally sustainable production system.

Among animal management decisions, control and improvement of reproduction is an important area. In many developing country (and in some developed country) enterprises, breeding males are left with the herd year round. While having offspring born at various seasons or throughout the year may have advantages for risk aversion in either subsistence or market systems, a frequent result is offspring, particularly of grazing animals, born at times when feed supply or weather are unfavorable for survival and growth of young. Controlling the breeding season so that young are born at the most-favorable time of year can result in much greater production per breeding animal, more efficient lactation, etc., although care must still be taken to minimize risk. Controlling the breeding season also permits more efficient use of aids to reproduction, such as estrus synchronization and AI, where these are appropriate. Other advantages include more effective delivery of animal health practices, such as vaccination and internal parasite control agents.

With regard to nutrition, successful strategies adopted in some areas include the increasing use of leaves from leguminous trees for livestock feed. Although indigenous species have been used for this purpose since time immemorial in the arid zone, until relatively recently, emphasis on pasture improvement in the wetter agro-ecological zones had been focused on the introduction of herbaceous legumes. Notable exceptions to this trend were *Leucaena leucocephala* and *Gliricidia sepium*. Now, a wide range of other genera and species are under evaluation (Gutteridge and Shelton, 1994). The responses to different combinations of species have received little attention but could have benefits both agronomically and nutritionally.

Industrial Systems

Industrial livestock production systems readily adopt and make effective use of technological advances that can reduce production costs. Least-cost ration formulation using computers, feed additives and growth promoters, AI (confinement dairies, turkey production), and implementation of product quality-assurance programs are among widely used practices, especially in developed countries. These systems are also in the best position to utilize advanced information technologies, an area where innovations are occurring very rapidly.

Stratified Systems

These systems are combinations of components of the other systems, for example, transferring animals produced on rangelands to industrial feedlots for finishing, thus utilizing technologies appropriate to the different segments at different stages. Significant improvements in overall efficiency will be facilitated by effective integration of more complete and readily accessible information on prices and markets, supplies of animals, and feed availability and feeding value. While each segment of the industry seeks to maximize net returns for that segment, use of such information by all should increase output per unit of input for the system as a whole.

Quantitative estimation of the increase in efficiency of animal production from adoption of improved technologies is difficult because of the many factors involved and interactions among them. Continuation of the estimated recent rate of improvement in feed conversion rate of 1% per year should be fairly readily achievable. With favorable economic and policy environments, the increases possible, particularly in many developing countries, are believed to be considerably greater.

Environmental Considerations

Various environmental aspects of animal agriculture have been mentioned in previous sections, particularly the section on grazing lands, where environmental and alternative-use considerations increasingly determine the management procedures and technologies that can be implemented for animal production. Because it is important to protect environmental quality and the resources involved in food production, an overview of some key environmental issues related to other production systems will be presented here.

Although mixed crop-livestock and industrial systems use less total land than grazing lands, there are very important environmental considerations related to each.

Mixed crop-livestock systems have excellent potential for beneficial effects on the environment and on sustainability of food-producing systems but can have negative impacts as well. Positive contributions include production of organic fertilizer to maintain soil fertility; consumption by animals of crop residues and by-products, providing an alternative to burning, storing in landfills, or releasing into water bodies; providing draught power and sparing fossil fuel; and providing an incentive to grow cultivated forages that reduce soil erosion and improve soil tilth. Potential negative impacts include excess nutrients such as phosphorus and nitrogen from manure contributing to soil and water pollution and overgrazing of grassland areas interspersed with cropping areas. Obviously, an important goal is to maximize the beneficial effects and minimize the negative ones.

Efficient use of manures is one important tool for achieving this goal. Manure storage to minimize nutrient losses and timely application and incorporation of manures into the soil can improve the quality and availability for uptake by crops. While providing adequate plant nutrients is the greater challenge in much of the world and one that efficient use of manures can be very helpful in meeting, avoiding excess nutrients can be an issue. In situations where chemical fertilizers are inexpensive and readily available, farmers occasionally have provided the recommended amounts of N, P, and K from chemical fertilizers, in addition to the application of manure, using the rationale that the amounts of nutrients available to plants from manure are variable and not accurately known. Clearly, this can lead to excess nutrient loading, with adverse effects on soil and water quality. Thus, it is important that recommended application rates for both chemical fertilizer and manure, based on best-available information, be followed. More rapid, accurate, and economical assessment of nutrient content of manures and soils would be helpful. Maximum plant uptake of nutrients from applied manures not only reduces the chemical fertilizer needed for optimum crop production but also minimizes potential pollution effects of these nutrients.

Industrial systems are, in general, more problematical with regard to the environment because of the concentration of large amounts of manure and urine in one location. Pollution of surface and ground water can result from improper handling of these materials; atmospheric pollution, e.g., ammonia, odors, also can occur (U.S. General Accounting Office, 1995; Tanji, 1994). Nitrate nitrogen, in particular, can infiltrate to ground water, increasing concentrations above levels consistent with public health. Phosphorus from manure and urine can be carried by runoff to streams and estuaries, where it promotes growth of aquatic plants and subsequent eutrophication.

Systems such as lagoons, manure drying facilities, etc., have been developed to deal effectively with manure and urine from large confinement facilities, i.e., to prevent pollution and obtain an economic return from these products, (Animal Agriculture Research Center/Agricultural Issues Center, 1994). The construction of such systems generally adds to the net cost of the operation and, unless such systems are mandated by enforceable regulations applied to all operations, they may not be implemented. Such regulations are used in a number of areas, e.g., northern Europe and North America, but are far from universally in place or enforced. A problem with lagoons, even when properly constructed and maintained, is that they may overflow at times of rare weather events such as hurricanes or catastrophic floods. This is a compelling reason to locate intensive livestock operations away from areas of high human population density and where the topography will minimize impacts of such overflow. Restrictions on the use of lagoons have been proposed recently based on concerns about air quality, e.g., ammonia release as well as water quality. (Technologies for environmentally sound animal waste management are covered in more detail in CAST Report 128 [1996b] and in de Haan et al., 1997.) Some examples of voluntarily implemented technologies, which prevent pollution and provide an economic return from animal manures, are described in the AARC/AIC publication (1994); one ranch in California obtains a return of $80 per ton of swine manure by producing electricity from the biogas generated. In general, an approach that treats manure as a valuable resource rather than as waste is an important first step to solving the potential pollution problems of industrial animal production.

De Haan et al. (1997) present several suggestions that would help control pollution levels. These include policy initiatives that reduce subsidies on concentrate feeds, development of incentives to improve emission control technologies, and removal of import restrictions on materials and equipment that improve feed efficiency. Important technological solutions to reduce pollution levels include introduction of multiphase feeding, which more closely matches the nutritional needs of utilization levels by the animals being fed, and improving the accuracy of determining N, P, and sodium (Na) requirements and content in feeds, as a mechanism to reduce concentrations of these elements in animal waste. With regard to the last concept, the supplementation of swine and poultry rations with synthetic amino acids, a standard practice in the formulation of commercial rations, significantly reduces the total N required in the ration and therefore excreted by the animals. Feeding low phytic acid food grains (see Chapter 5, Feed Grains) substantially reduces the P content of manures. The potential to reduce pollution through modifying animal diets is a field in the early stages of development but one that offers substantial promise of future environmental benefits.

It is important to note that industrial animal production produces more human food on less land, from less total feed input, with fewer animals and less methane production than other animal-production systems. Thus, expansion of this system has potentially important environmental benefits, if the concentrated "wastes" produced are properly managed. Another potentially positive aspect of these systems is that the manure is accumulated in one place, i.e., it is a point source, facilitating its capture, treatment, and disposal.

The use of stratified systems provides the opportunity for flexibility regarding when and how rangelands are used. The use of crop residues or cultivated pastures during times of the year when rangeland use might cause ecological degradation or when nutrient content of range vegetation is below production levels provides improved production and environmental protection.

A number of areas in which additional research is needed are indicated in the following section. Fitzhugh (1998), and other papers in the volume in which that paper appears, outline animal science research agendas in more detail.

Policy Issues

Policy decisions, within countries and internationally, can greatly impact food supplies in general and the contributions of animal agriculture to food supply in particular. Important issues include the following:

- Availability of banking and credit services to pastoralists and small-holder livestock farmers in developing countries. Livestock owners who lack access to these services tend to keep more animals than they may need in the short term or than is desirable from the perspective of sustainable carrying capacity, as a hedge against drought or other contingencies where their livestock may be their only saleable asset or food reserve. The option of selling animals when a surplus exists and having the funds available for subsequent contingencies reduce stocking and increase off-take rates.
- Policies related to resource use and environmental quality. The essential difference between natural resource and environmental consequences is that the former are borne by the animal producers and the latter are borne by others. The distinction is critical for thinking about policies to promote sustainable animal production. Where animal producers have clear, enforceable property rights to the land (and other resources) they use, they have strong incentives to avoid losses of the land's productivity or to enhance it where feasible, because they pay the costs and reap the benefits. They have no comparable incentive to reduce environmental costs or increase environmental

benefits of their operations, because to do so would impose costs on them with no offsetting benefits, at least in the short term. Two policy issues arise from this distinction: (1) how to strengthen property rights of animal producers to the resources they need for production, so that they will have incentive to protect the productivity of those resources; and (2) how to find policies and institutions that induce or require animal producers to take account of the environmental consequences of their operations. An example of the impact of government policy on resource use and environmental quality is provided by the recent report by Sneath (1998).

- Extremely important are policies that provide incentives to farmers to produce. In many countries, the political influence of urban populations leads to cheap food policies that do not provide adequate incentives for farmers to produce the food they could; this seems to be a particular problem in Africa (Pinstrup-Andersen et al., 1997), although it is not restricted to developing countries. Dyson (1996), from a detailed analysis of trends in world cereal production, suggests that "the explanation for the recent decline in per capita cereal production lies in reduced incentives for farmers in the world's more developed regions to both plant and grow cereal crops."
- Another aspect of the production incentive issue is subsidies in some developed countries that encourage overproduction and subsequent sale of food to developing countries at prices below cost of production. This not only may result in suppressing prices and therefore production in the receiving country but also can lead to excessively high densities of livestock in the country with the subsidies, with negative consequences for environmental quality, as has happened, for example, in some northern European countries. Recent trends toward reduced subsidies are contributing to alleviation of this problem.
- Policies affecting general economic development and employment opportunities. Much of the migration of people to the Amazon basin where they have cleared rainforests to produce livestock has occurred because of the lack of alternative means of making a living. Again, policies related to land tenure and to conservation are involved.
- As mentioned earlier, public support, both national and international, for agricultural production research and extension is critical to achieving needed increases in all components of the food supply.

The Future

This report indicates that it should be possible to produce an adequate global supply of human food, including desired levels of animal products, on a sustainable basis, given appropriate policies and adequate investment in research and extension. All projections are based on numerous assumptions; achievement of the projected outcomes depends on the validity of those assumptions. Undoubtedly, some will not hold true until the year 2020. Pinstrup-Andersen et al. (1997) and Waggoner (1998), among others, have speculated on possible developments that could result in major departures from current expectations. These include unforeseen consequences of global warming; scarcity of water for agriculture; major changes in human dietary habits; deviations from current population projections (in either direction); increased loss of soil or its productivity to alternative uses, erosion, and salinization; and technological breakthroughs. Several of these could contribute to less optimistic outcomes than now projected, although slower human population growth rates, technological developments, and even climate changes (in some regions) could contribute to increased per capita food supply.

As detailed in this report, increases in food supply must come primarily from increases in yield of crops and livestock, with cereal yields being a key to supply of foods of both plant and animal origin. Current productivity levels of both are greatly below biological potential, providing much opportunity for increasing food supply by raising average global production levels towards best-possible levels.

The development and application of new technologies is, of course, an area particularly difficult to predict. Although no new "green revolution" seems on the horizon (American Association for the Advancement of Science, 1997), the record of achievement of agricultural science during the twentieth century gives reason for optimism about the future. As indicated, the contributions of biotechnology are particularly uncertain, both because it is still a relatively new field and because of major uncertainties about public acceptance of the results.

Recognizing that the future for food production, as for all human activities, is uncertain, a vision of what would constitute a good future may be worth stating.

- Human population increasing no more rapidly than the most recent UN medium-variant projections, and preferably less.
- Appropriate agricultural policies and adequate public investment (national and international) in

agricultural research and extension, to facilitate farmer adoption of improved technologies that lead to (1) increases in crop yields matching or exceeding human population growth rates, and (2) increases in productivity of food-producing animals, to meet the projected increased demand for meat, milk, and eggs with minimal increases in numbers of breeding animals.

- Implementation of grazing management and animal-production practices that contribute to maintaining or enhancing agricultural productivity and environmental quality, including protection of biodiversity.
- National and international policies on income and food distribution that assure adequate nutrition for all, including some foods of animal origin for those who wish them and with special emphasis on nutritional adequacy of diets for children.

Appendix A: Abbreviations, Acronyms, and Symbols

AI	artificial insemination
ARC	Agricultural Research Council (United Kingdom)
ATNESA	African Traction Network of Eastern and Southern Africa
BSE	bovine somatotrophic encephalopathy
BVD	bovine viral diarrhea
CAST	Council for Agricultural Science and Technology
CGIAR	Coordinating Group on International Agricultural Research
CIMMYT	Centro Internacional de Mejoramiento de Maiz y Trigo
CP	crude protein
d	day
EC	European Community
ECF	East Coast Fever
EEC	European Economic Community
FAO	Food and Agriculture Organization of the United Nations
FAOSTAT	FAO database (http://apps.fao.org)
g	gram
ha	hectare
ICAR	Indian Council for Agricultural Research
IFPRI	International Food Policy Research Institute
ILRI	International Livestock Research Institute
IRRI	International Rice Research Institute
K	potassium
kg	kilogram
L	liter
ME	metabolizable energy
Mha	million hectares
MJ	mega joules
Mt	million metric tons
N	nitrogen
Na	sodium
NCRSP	Human Nutrition Collaborative Research Support Program
NIRS	near-infrared spectroscopy
NRC	National Research Council
OECD	Organization for Economic Cooperation and Development
P	phosphorus
PCR	polymerase chain reaction
t	metric ton
UN	United Nations
USDA	U.S. Department of Agriculture

Appendix B: Glossary

Biological efficiency. Ratio of output to input.

Camelids. Camels, llamas, alpacas.

Cloning. Making genetically identical copies of an individual.

Concentrates. Feed grains, milling by-products.

Conversion rate. The amount of meat, milk, or eggs per unit of input.

Crop residues. Straws, stovers.

Digestibility. The extent to which an animal can extract nutrients from a feed through its digestive processes.

Equilibrial systems. Systems with reasonably dependable rainfall from year to year where there is a direct feedback between animal numbers and vegetation states.

Equines. Horses, mules, donkeys.

Feed grains. Grains fed to animals, as opposed to grain directly consumed by humans (food grains).

Grazed forages. Rainfed or irrigated pastures.

Grazing systems. Specializations of management that define recurring periods of grazing and deferment (non-use) for two or more pastures or management units.

Harvest index. Ratio of grain to total plant; proportion of total plant dry matter in grain.

Harvested forages. Hays, silages.

Industrial livestock systems. Animals typically kept in large numbers, in barns or outdoor pens, with all feed brought to them. Feed may be grown on adjacent land or brought from a distance. Operations are usually highly mechanized.

Micronutrients. Vitamins and minerals.

Mixed crop-livestock systems. Both crops and livestock produced on the same farm. Animal feed provided by crops, crop residues, as well as grazing, and animal manures returned to the cropland. Animals are often used for traction and transport on the farm.

Nonruminants. Poultry, pigs.

Off-take. Numbers of animals slaughtered or amounts of product produced per year per census animal.

Ruminants. Includes cattle, sheep, goats, buffalo, and many nondomesticated species such as deer and antelope. Presence of anaerobic microbes in the rumen.

Stocking rate. Number of animals grazing a given area.

Stratified animal production system. A combination of two or three of the following: grazing, mixed crop-livestock, industrial systems.

Transhumance. A specialized grazing system involving the systematic, seasonal movement of animals to take advantage of seasonal differences in forage growth (e.g., at different elevations).

Literature Cited

American Association for the Advancement of Science. 1997. Reseeding the Green Revolution. Special Report: World Food Prospects. *Science* 277:1038–1043.

Animal Agriculture Research Center and Agricultural Issues Center. 1994. In R. Coppock and S. Weber (Eds.). *Animal Agriculture Impacts on Water Quality in California*. Proceedings of a conference cosponsored by the Animal Agriculture Research Center and Agricultural Issues Center, University of California, Davis.

Avery, D. T. 1996. The Environmental Necessity for Higher Yield Agriculture. *American Association for the Advancement of Science Panel on Environment and Sustainability: Limits to Agricultural Productivity*. Baltimore, Maryland, February 10, 1996.

Beaton, G. H., D. H. Calloway, and S. P. Murphy. 1992. Estimated protein intakes of toddlers: Predicted prevalence of inadequate intakes in village populations in Egypt, Kenya, and Mexico. *Am J Clin Nutrit* 55:902–911.

Beckett, J. L. and J. W. Oltjen. 1993. Estimation of the water requirement for beef production in the United States. *J Anim Sci* 71:818–826.

Bell, R. H. V. 1971. A grazing ecosystem in the Serengeti. *Sci Am* 225:86–93.

Borman, B. T., M. H. Brookes, E. D. Ford, A. R. Kiester, C. D. Oliver, and J. F. Wigand. 1994. *A Framework for Sustainable Ecosystem Management*. General Technical Report No. 331. U.S. Department of Agriculture, U.S. Forest Service, Washington, D.C.

Box, T. W. 1990. Rangelands. Pp. 101–120. In R. N. Sampson and D. Hair (Eds.). *Natural Resources for the 21st Century*. Island Press, Washington, D.C.

Bradford, G. E. 1998. Animal genetic resources in North America. *Proceedings of the Eighth World Conference on Animal Production*, Seoul, Korea, Symposium Series 1:216–228.

Bremen, H. and P. W. J. Uithol (Eds.). 1984. *The Primary Production in the Sahel Project—A Bird's Eye View*. Centre for Agrobiological Research, Wageningen, The Netherlands.

Brown, L. R. 1997. Facing the prospect of food scarcity. Pp. 23–41. In L. R. Brown, C. Flavin, and H. French (Eds.). *State of the World*. W. W. Norton and Company, New York.

Bryant, F. C. 1982. Grazing, grazing systems and wildlife. *Proceedings of the Great Plains Agricultural Council Annual Meeting*. North Platte, Nebraska, June 7–9, 1982. Technical Article T-9-297. College of Agricultural Science, Texas Tech University, Lubbock, Texas.

Bunyavejchewin, P., C. Chantalakhana, and S. Sukharomana. 1993. DAP vs. mechanisation in rural development. In Draught Animal Power in the Asian-Australasian Region. *ACIAR Proceedings No. 46*.

Bywater, A. C. and R. L. Baldwin. 1980. Alternative strategies in food animal production. Pp 1–30. In R. L. Baldwin (Ed.). *Animals, Feed, Food and People*. American Association for the Advancement of Science Selected Symposium No. 42. Westview Press, Boulder, Colorado.

Calloway, D. H., S. Murphy, J. Balderston, O. Receveur, D. Lein, and M. Hudes. 1992. Village nutrition in Egypt, Kenya and Mexico: Looking across the CRSP projects. Pp. 1–130. In *Functional Implications of Malnutrition* (Final Report). University of California, Berkeley, California.

Cann, I. K. O., Y. Kobayashi, M. Wakita, and S. Hoshimo. 1991. Digestion properties of ammoniated rice straw in the rumen and lower tract of sheep. *Anim Feed Sci Technol* 35:55–68.

Casler, M. D. and K. P. Vogel. 1999. Accomplishments and impact from breeding for increased forage nutritional value. *Crop Sci* (in press).

Cassman, K. G. 1999. Ecological intensification of cereal production systems: Yield potential, soil quality, and precision agriculture. *Proc Natl Acad Sci (USA)* 96:5952–5959.

Cassman, K. G. and R. R. Harwood. 1995. The nature of agricultural systems: Food security and environmental balance. *Food Policy* 20:439–454.

Cassman, K. G., R. Steiner, and A. E. Johnson. 1995. Long-term experiments and productivity indexes to evaluate sustainability of cropping systems. Pp. 231–244. In V. Barnett, R. Payne, and R. Steiner (Eds.). *Agricultural Sustainability in Economic, Environmental, and Statistical Terms*. John Wiley & Sons, Ltd., London, U.K.

Cleaver, K. and G. Schneiber. 1994. *The Population, Agriculture and Environmental Nexus in Sub-Saharan Africa* (revised). Agriculture and Rural Development Series No. 9. Technical Department, Africa Region, World Bank, Washington, D.C.

Cheeke, P. R. 1995. *Impacts of Livestock Production on Society, Diet/Health and the Environment*. Interstate Publishers, Danville, Illinois. 241 pp.

Cohen, J. E. 1995. *How Many People Can the Earth Support*? W. W. Norton and Co., New York.

Coley, D. A., E. Goodlife, and J. Macdiarmid. 1998. The embodied energy of food: The role of diet. *Energy Policy* 26:455–459.

Collins, S. L., A. K. Knapp, J. M. Briggs, J. M. Blair, and E. M. Steinauer. 1998. Modulation of diversity by grazing and mowing in native tall grass prairie. *Science* 280:745–749.

Consultative Group on International Agricultural Research. 1997a. *International Livestock Research Institute's Development of a Live Vaccine Delivery System for East Coast Fever*. Nairobi, Kenya.

Consultative Group on International Agricultural Research. 1997b. Twenty-five Years of Improvement, Part IV. *Livestock Research*. Nairobi, Kenya.

Council for Agricultural Science and Technology. 1994. *How Much Land Can Ten Billion People Spare for Nature?* Report No. 121. Council for Agricultural Science and Technology, Ames, Iowa.

Council for Agricultural Science and Technology. 1996a. *Grazing on Public Lands*. Report No. 129. Council for Agricultural Science and Technology, Ames, Iowa.

Council for Agricultural Science and Technology. 1996b. *Integrated Animal Waste Management*. Report No. 128. Council for Agricultural Science and Technology, Ames, Iowa.

Council for Agricultural Science and Technology. 1997a. *Contribution of Animal Products to Healthful Diets*. Report No. 131. Council for Agricultural Science and Technology, Ames, Iowa.

Council for Agricultural Science and Technology. 1997b. *The Well-Being of Agricultural Animals*. Report No. 130. Council for Agricultural Science and Technology, Ames, Iowa.

Council for Agricultural Science and Technology. 1998. *Food Safety, Sufficiency, and Security*. Special Publication No. 21. Council for Agricultural Science and Technology, Ames, Iowa.

Council for Agricultural Science and Technology. 1999. *Benefits of Biodiversity*. Report No. 134. Council for Agricultural Science and Technology, Ames, Iowa.

Cunningham E. P. and O. Syrstad. 1987. *Crossbreeding Bos indicus and Bos taurus for Milk Production in the Tropics*. Animal Production and Health Paper No. 68., Food and Agricultural Organization of the United Nations, Rome.

Dawson, J. and I. Barwell. 1993. *Roads Are Not Enough: New Perspectives on Rural Transport Planning in Developing Countries*. International Forum for Rural Transport and Development Occasional Paper IT Transport. Ardington, Oxford, U.K.

de Haan, C., H. Steinfeld, and H. W. Blackburn. 1997. *Livestock-Environment Interactions: Finding a Balance*. Report of a study coordinated by the Food and Agriculture Organization of the United Nations, the U.S. Agency for International Development, and the World Bank, Brussels. 115 pp. Available from FAO, Rome.

de Witt, C. T. 1992. Resource use efficiency in agriculture. *Agric Systems* 40:125–151.

Delgado, C. L. and McIntire, J. 1982. Constraints on oxen cultivation in the Sahel. *Am J Agr Econ* 64 (2):188–196.

Delgado, C. L., C. C. B. Courbois, and M. L. Rosegrant. 1998. Global food demand and the contribution of livestock as we enter the new millennium. In M. Gill, T. Smith, G. G. Pollott, E. Owen, and T. L. J. Lawrence (Eds.). *Food, Lands and Livelihoods: Setting Research Agendas for Animal Science*. Occasional Publication No. 21. British Society of Animal Science, Edinburgh, Scotland.

Delgado, C., M. Rosegrant, H. Steinfeld, S. Ehui, and C. Courbois. 1999. *Livestock to 2020: The Next Food Revolution*. Food, Agriculture and the Environment Discussion Paper No. 28. International Food Policy Research Institute, Washington, D.C.

Duvick, D. N. 1992. Genetic contributions to advances in yield of maize. *Maydica* 37:69–79.

Duvick, D. N. and K. G. Cassman. 1999. Post-green-revolution trends in yield potential of temperate maize in the northcentral United States. *Crop Sci* (in press).

Dyson, T. 1996. *Population and Food: Global Trend and Future Prospects*. Global Environmental Change Program. Routledge, London, U.K.

Ellis, J. E. and D. M. Swift. 1988. Stability of African pastoral ecosystems: Alternative paradigms and implications for development. *J Range Manage* 41:450–459.

Ertl, D. S., K. A. Young, and V. Raboy. 1998. Plant genetic approaches to phosphorus management in agricultural production. *J Envir Qual* 27:299–304.

Evans, L. T. 1993a. *Crop Evolution, Adaptation, and Yield*. Cambridge University Press, Cambridge, U.K.

Evans, L. T. 1993b. Processes, genes, and yield potential. Pp. 687–696. In *International Crop Science I*. Crop Science Society of America, Madison, Wisconsin.

Fadel, J. G. 1999. Quantitative analysis of selected by-product feedstuffs: A global perspective. *Anim Feed Sci Technol* 79:255–268.

Faminow, M. D. and S. A. Vosti. 1998. Livestock-deforestation links: Policy issues in the Western Brazilian Amazon. Pp 88–103. In A. J. Nele (Ed.). *Proceedings of the International Conference on Livestock and the Environment*. Wageningen, The Netherlands, June 1997.

Fitzhugh, H. A. 1998. Global agenda for livestock research. Pp. 11–17. In M. Gill, T. Smith, G. G. Pollott, E. Owen, and T. L. J. Lawrence (Eds.). *Food, Lands and Livelihoods: Setting Research Agendas for Animal Science*. Occasional Publication No. 21. British Society of Animal Science, Edinburgh, Scotland.

Fleishchner, T. L. 1994. Ecological costs of livestock grazing in western North America. *Conserv Biol* 8:629–644.

Food and Agriculture Organization of the United Nations. 1997. FAOSTAT database. http://faostat.fao.org/default.htm. Accessed September and December 1997.

Francis, P. A. 1988. Ox draught power and agricultural formation in Northern Zambia. *Ag Systems* 27:15–28.

Gatenby, R. M., M. Doloksaribu, G. E. Bradford, E. Romjali, A. Batubara, and I. Mirza. 1997. Comparison of Sumatra sheep and three hair sheep crossbreds. II. Reproductive performance of F_1 ewes. *Small Ruminant Res* 25:161–167.

Giavedoni, L., L. Jones, C. Mebus, and T. Yilma. 1991. A *Vaccinia* virus double recombinant expressing the F and H genes of rinderpest virus protects cattle against rinderpest and causes no pock lesions. *Proc Natl Acad Sci USA* 88:8011–8015.

Gordon, I. J. 1988. Facilitation of red deer grazing by cattle and its impact on red deer performance. *J Appl Ecol* 25:1–10.

Grasser, L. A., J. G. Fadel, I. Garnett, and E. J. DePeters. 1995. Quantity and economic importance of nine selected by-products used in California dairy rations. *J Dairy Sci* 78:962–971.

Gryseels, G., A. Astatke, F. M. Anderson, and G. Assemenew. 1984. The use of single oxen for crop cultivation in Ethiopia. *International Livestock Center of Africa Bulletin* 18:20–25.

Gutteridge, R. C. and H. M. Shelton (Eds.). 1994. *Forage Tree Legumes in Tropical Agriculture*. CAB International, Wallingford, U.K.

Harper, A. E. 1993. Challenge of Dietary Recommendations to Curtail Consumption of Animal Products. *Proceedings of the World Conference on Animal Production*, Vol. 1, Pp. 525–543. Edmonton, Canada.

Havenstein, G.B., P. R. Ferket, S. E. Scheideler, and B. T. Larson. 1994a. Growth, livability and feed conversion of 1957 vs. 1991 broilers when fed “typical” 1957 and 1991 broiler diets. *Poultry Sci* 73:1785–1794.

Havenstein, G. B., P. R. Ferket, S. E. Scheideler, and D. V. Rives. 1994b. Carcass composition and yield of 1991 vs. 1957 broilers when fed “typical” 1957 and 1991 broiler diets. *Poultry Sci* 73:1795–1804.

Heap, R. B. 1998. Animals and the human food chain. Pp 232-245. In J. C. Waterlow, D. G. Armstrong, L. Fowden and R. Riley (Eds.). *Feeding a World Population of More than Eight Billion People*. Oxford University Press, New York and London.

Heitschmidt, R. K. and C. A. Taylor, Jr. 1991. Livestock production. In R. K. Heitschmidt and J. W. Stuth (Eds.). *Grazing Management: An Ecological Perspective*. Timber Press, Portland, Oregon.

Hendy, C. R. C., U. Kleih, R. Grashaw, and M. Phillips. 1995. *Interaction Between Livestock Production Systems and the Environment: Concentrate Feed Demand*. Food and Agriculture Organization of the United Nations Consultancy Report for

Livestock and the Environment Study. (See de Haan et al., 1997)
Human Nutrition Collaborative Research Support Program. 1992. *Functional Implications of Malnutrition*. Human Nutrition Collaborative Research Support Program (NCRSP), Final Report. University of California, Berkeley, California.
Humphreys, L. C. 1994. *Tropical Forages. Their Role in Sustainable Agriculture*. The Longman Group, Harlow, U.K.
Ikombo, B. M. 1989. Effects of manure and fertilizers on maize in semi-arid areas of Kenya. *E African Agric Forestry J* 44:266–274.
Iniguez, L. C. and M. D. Sanchez (Eds.). 1991. *Integrated Tree Cropping and Small Ruminant Production Systems*. Proceedings of a Workshop, Medan, Indonesia, September 1990. Small Ruminant Collaborative Research Support Program, University of California, Davis, California.
Jordaan, J. P. 1996. Hybrid wheat: Advances and challenges. Pp. 66–75. In M. P. Reynolds, S. Rajaram, and A. McNab (Eds.). *Increasing Yield Potential in Wheat: Breaking the Barriers*. Centro Internacional de Mejoramiento de Maiz y Trigo (CIMMYT), Mexico City, Mexico.
Kay, C. E. and J. W. Walker. 1997. A comparison of sheep-and wildlife-grazed willow communities in the Greater Yellowstone ecosystem. *Sheep Goat Res J* 13:6–14.
Khush, G. 1993. Breeding rice for sustainable agricultural systems. Pp. 189–199. In *International Crop Science I*. Crop Science Society of America, Madison, Wisconsin.
Kropff, M. J., K. G. Cassman, S. Peng, R. B. Matthews, and T. L. Setter. 1994. Quantitative understanding of yield potential. Pp. 21–38. In K. G. Cassman (Ed.). *Breaking the Yield Barrier: Proceedings of a Workshop on Rice Yield Potential in Favorable Environments*. November 29– December 4, 1994. International Rice Research Institute, Los Banos, Philippines.
Kruit, F. 1994. Animal traction technology in Niger and some implications for Zambia. Pp. 474–480. In P. Starkey, E. Mwenya, and J. Stares (Eds.). *Improving Animal Traction Technology*. Proceedings of the First Workshop of African Traction Network of Eastern and Southern Africa (ATNESA), January 18–23, 1992, Lusaka, Zambia, Technical Centre for Agricultural and Rural Co-operation. Wageningen, The Netherlands.
Lawrence, P. R., Dijkman, J. T., and Jansen, H. G. P. 1997. The introduction of animal traction into inland valley regions. Manual labour and animal traction in the cultivation of rice and maize: a comparison. *J Agric Sci* (Cambridge) 129:65–70.
Loomis, R. L. and D. J. Connor. 1996. *Crop Ecology*. Cambridge University Press, Cambridge, U.K.
Loomis, R. L. and J. Wallinga. 1991. Alfalfa: Efficient or Inefficient User of Water? *Proceedings of the Twenty-first California Alfalfa Symposium*, Sacramento, California, December 9–10, 1991.
Malthus, T. R. 1798. An essay on the principle of population. Pp. 4–6. In G. Hardin (Ed.). *Population, Evolution and Birth Control—A Collage of Controversial Ideas*. 2nd ed. 1969. W. H. Freeman and Company, San Francisco, California.
McDermitt, D. K. and R. S. Loomis. 1981. Elemental composition of biomass and its relation to energy content, growth efficiency, and growth yield. *Ann Bot* 48:275–290.
McDowell, R. E. 1994. *Improvement of Livestock Production in Warm Climates*. W. H. Freeman and Company, San Francisco, California.
McIntire, J., Bourzat, D., and Pingali, P. 1992. *Crop-Livestock Interactions in Sub-Saharan Africa*. World Bank Washington, D.C.
Mitchell, D. O. and M. D. Ingco. 1993. *World Food Outlook*. International Economics Department, World Bank, Washington, D.C.
Mukhebi, A. W., B. D. Perry, and R. Kruska. 1992. Estimated economics of theileriosis control in Africa. *Prevent Vet Med* 12:73–85.
Mukhebi, A. W., D. P. Kariuki, E. Mussukuya, G. Mullins, P. N. Ngumi, W. Thorpe, and B. D. Perry. 1995. Assessing the economic impact of immunization against East Coast fever: A case study in Coast Province, Kenya. *The Veterinary Record* 137:17–22.
Mukhebi, A. W., S. P. Morzaria, B. D. Perry, T. T. Dolan, and R. A. I. Norval. 1990. Cost analysis of immunization for East Coast fever by the infection and treatment method. *Prevent Vet Med* 9:207–219.
Mullinax, D., D. Meyer, and I. Garnett. 1998. *The Economic Value of Animal Manure as a Source of Plant Nutrients and Energy Generation*. University of California Agricultural Issues Center Publication, Davis. 42 pp.
Murphy, S. P., D. H. Calloway, and G. H. Beaton. 1995. School children have similar predicted prevalences of inadequate intakes as toddlers in village populations in Egypt, Kenya, and Mexico. *Eur J Clin Nutrit* 49:647–657.
Mwangi, Z. J. and C. A. Zulberti. 1985. *Optimization of Wildlife and Livestock Production. Wildlife/Livestock Interfaces on Rangelands*. Inter-African Bureau of Animal Resources, Nairobi, Kenya.
National Research Council. 1980. *Toward Healthful Diets*. Food and Nutrition Board Division of Biological Sciences Assembly of Life Sciences. National Academy Press, Washington, D.C.
National Research Council. 1984. *Nutrient Requirements of Beef Cattle*. 6th ed. National Academy Press, Washington, D.C.
National Research Council. 1989. *Nutrient Requirements of Dairy Cattle*. 6th ed. National Academy Press, Washington, D.C.
National Research Council. 1992. *Grasslands and Grassland Sciences in Northern China*. A Report of the Committee on Scholarly Communication with the People's Republic of China. Office of International Affairs, National Research Council. National Academy Press, Washington, D.C.
New, M. B. 1997. Aquaculture and the capture fisheries. *World Aquaculture* (June):11–30.
Nyangito, H. O., J. W. Richardson, A. W. Mukhebi, P. Zimmel, J. Namken, and B. P. Perry. 1995. Whole farming simulation analysis of economic impacts of East Coast fever immunization strategies on mixed crop-livestock farms in Kenya. *Agric Syst* 51:1–27.
Nyangito, H. O., J. W. Richardson, A. W. Mukhebi, D. S. Mundy, P. Zimmel, J. Namken, and B. D. Perry. 1994. Whole farm economic analysis of East Coast fever immunization strategies in Kilifi District, Kenya. *Preventative Vet Med* 21:215–235.
Oltjen, J. W., M. R. George, and D. J. Drake. 1992. Dynamic allocation of multiple forage sources for beef cattle herds. Pp. 58–63. In D. G. Watson, F. S. Zazuelta, and A. B. Bottcher (Eds.). *Computers in Agricultural Extension Programs*. American Society of Agricultural Engineers, St. Joseph, Michigan.
Owens, F. N., D. S. Secrist, W. J. Hill, and D. R. Gill. 1997. The effect of grain source and grain processing on performance of feedlot cattle. A review. *J Anim Sci* 75:868–879.
Panin, A. 1987. *The use of bullock traction for crop cultivation in Northern Ghana. An empirical economic analysis*. ILCA Bulletin 29:2–8.
Parker, A. G. H. and A. L. Rae. 1982. Underlying principles of cooperative group breeding schemes. Pp. 95–101. In R. A. Bar-

ton and W. C. Smith (Eds.). *Proceedings of the World Congress on Sheep and Beef Cattle Breeding*, Vol. II. Dunmore Press, Palmerston North, New Zealand.

Penning de Vries, F. W. T., A. H. M. Brunsting, and H. H. van Laar. 1974. Products, requirements and efficiency of biosynthesis: A quantitative approach. *J Theoret Biol* 43:339–377.

Pimentel, D. 1997. Livestock production: Energy inputs and the environment. Pp. 16–26. *Proceedings of the 47th Annual Meeting, Canadian Society of Animal Production* Montreal, Quebec. July 1997.

Pimentel, D., J. Houser, E. Priess, O. White, H. Frang, L. Mesnick, T. Barsky, S. Tariche, J. Schreck, and S. Alpert. 1997. Water resources: Agriculture, the environment and society. *Bioscience* 47:97–106.

Pinstrup-Andersen, P., R. Pandya-Lorch, and M. W. Rosegrant. 1997. *The World Food Situation: Recent Developments, Emerging Issues and Long-term Prospects*. Food Policy Report, International Food Policy Research Institute, Washington, D.C.

Powell, J. M. 1986. Manure for cropping: A case study from Central Nigeria. *Exper Agric* 22(1):15–24.

Powell, J. M., R. A. Pearson, and J. C. Hopkins. 1998. Impacts of Livestock on Crop Production. In M. Gill, T. Smith, G. G. Pollott, E. Owen, and T. L. J. Lawrence (Eds.). *Food, Lands and Livelihoods: Setting Research Agendas for Animal Science*. Occasional Publication No. 21. British Society of Animal Science, Edinburgh, Scotland.

Powell, J. M., S. Fernandez-Rivera, T. O. Williams, and C. Renard (Eds.). 1995. *Livestock and Sustainable Nutrient Cycling in Mixed Farming Systems of Sub-Saharan Africa*. Vol. II. Technical Papers. Proceedings of the International Conference, Addis-Ababa, Ethiopia, November, 1993.

Preston, T. R. 1998. Animal production and use of natural resources. Pp. 450–460. In *Proceedings of the 8th World Conference on Animal Production*, Seoul, Korea, June 28–July 4, 1998.

Raboy, V. and P. Gerbasi. 1996. Genetics of myo-inositol phosphate synthesis and accumulation. Pp. 257–285. In B. B. Biswas and S. Biswas (Eds.). *Subcellular Biochemistry. Vol. 26. Myo-inositol Phosphates, Phosphoinositides, and Signal Transduction*. Plenum Press, New York, New York.

Ramaswamy, N. S. 1985. Draught animal power—socio-economic factors. In J. W. Copland (Ed.). *Draught Animal Power for Production*. ACIAR Proceedings No. 10.

Rege, J. E. O. 1998. Utilization of exotic germ plasm for milk production in the tropics. *Proceedings of the Sixth World Congress on Genetics Applied to Livestock Production*. Vol. 25:193–200. Armidale, NSW, Australia, January 1998.

Resource Inventory and Management, Ltd. 1992. *Nigerian Livestock Resources*. [Four-volume report to the Federal Government of Nigeria by Resource Inventory and Management Ltd.; Vol. I. Executive Summary and Atlas; Vol. II. National Synthesis; Vol. III. State Reports; Vol. IV. Urban Reports and Commercially Managed Livestock Survey Report.]

Romans, J. R., W. J. Castello, C. W. Carlson, M. L. Greasen, and K. W. Jones. 1994. *The Meat We Eat*. Interstate Publishers, Danville, Illinois.

Romney, D. L., P. J. Thorne, and D. Thomas. 1994. Some animal-related factors influencing the cycling of nitrogen in mixed farming systems in sub-Saharan Africa agriculture. *Ecosystems Environ* 49:163–172.

Rosegrant, M. W. and C. Ringler. 1997. World food markets in the 21st century: Environmental and resource constraints and policies. *Austral J Agric Res Econ* 41:401–428.

Rosegrant, M. W. and C. Ringler. 1998. Asian economic crisis and the long-term global food situation. Paper presented at the *International Agricultural Trade Consortium Symposium on Policy Reform, Market Stability and Food Security*, Alexandria, Virginia, June 26–27, 1998

Rosegrant, M. W., M. Agcaoili-Sombilla, and N. D. Perez. 1995. *Global Food Projections to 2020: Implications for Investment*. Food, Agriculture, and the Environment Discussion Paper No. 5. International Food Policy Research Institute, Washington, D.C.

Rosegrant, M. W., A. Sombilla, R. V. Gerpacio, and C. Ringler. 1997. Global Food Markets and U.S. Exports in the Twenty-first Century. Paper presented at the *Illinois World Food Sustainable Agriculture Program Conference*, Meeting the Demand for Food in the 21st Century: Challenges and Opportunities for Illinois Agriculture, May 28, Urbana-Champaign, Illinois.

Rutledge, J. J. 1997. Cattle breeding systems enabled by in-vitro embryo production. *Embryo Transfer Newsletter* 15:14–18.

Sandford, S. 1983. *Management of Pastoral Development in the Third World*. John Wiley and Sons, New York.

Sayre, K. D., S. Rajaram, and R. A. Fischer. 1997. Yield potential progress in short bread wheats in northwest Mexico. *Crop Sci* 37:36–42.

Schwabe, C. W. 1984. *Veterinary Medicine and Human Health*. 3rd ed. Williams and Wilkins, Baltimore, Maryland.

Schwartz, C. C. and J. E. Ellis. 1981. Feeding ecology and niche separation in some native and domestic ungulates in short grass prairie. *J Appl Ecol* 18:343–353.

Science. 1998. Agricultural biotech faces backlash in Europe. *Science* 281:768–771.

Seré, C. and H. Steinfeld. 1996. *World Livestock Production Systems*. Animal Production and Health Paper 127. Food and Agriculture Organization of the United Nations, Rome.

Severson, K. E. 1990. *Can Livestock Be Used as a Tool to Enhance Wildlife Habitat?* U.S. Forest Service Rocky Mountain Forest and Range Experiment Station General Technical Report RM-194.

Severson, K. and P. J. Urness. 1994. Livestock grazing: A tool to improve wildlife habitat. Pp. 232–249. In M. Vavra, W. A. Laycock, and R. Pieper (Eds.). *Ecological Implications of Livestock Herbivory in the West*. Society for Range Management, Denver, Colorado.

Sheehy, D. P. and M. Vavra. 1995. Ungulate foraging areas on seasonal rangeland in northeastern Oregon. *J Range Manage* 19:16–23.

Sigma, M., C. Neumann, A. A. Jansen, and N. Bwibo. 1989. Cognitive abilities of Kenyan children in relation to nutrition, family characteristics, and education. *Child Devel* 60:1463–1474.

Smaling, E. M. A., S. M. Nandwa, H. Prestele, R. Roetter, and F. N. Muchena. 1992. Yield response of maize to fertilizers and manure under various agro-ecological conditions in Kenya. *Agric Ecosystems Envir* 41:241–252.

Sneath, D. 1998. State policy and pasture degradation in inner Asia. *Science* 281:1147–1148.

Steinfeld, H., C. de Haan, and H. Blackburn. 1997. *Livestock-Environment Interactions: Issues and Options*. Report of a Study coordinated by the Food and Agriculture Organization of the United Nations, the U.S. Agency for International Development, and the World Bank, Brussels. 115 pp. Available from FAO, Rome.

Sumberg, J. and Gilbert, E. 1992. Agricultural mechanization in the Gambia: Drought, donkeys and minimum tillage. *African Livestock Res* 1:1–10.

Tanji, K. K. 1994. Impacts on human health and agricultural and natural systems. Pp 23–27. In R. Coppock and S. Weber (Eds.). *Animal Agriculture Impacts on Water Quality in California*. Proceedings of a conference cosponsored by the Animal Agriculture Research Center and Agricultural Issues Center, University of California, Davis.

Thorne, P. J. and M. Herrero. 1998. The role of livestock in natural resources management. In M. Gill, T. Smith, G. E. Pollott, E. Owen, and T. L. J. Lawrence (Eds.). *Food, Lands and Livelihoods: Setting Agendas for Animal Science*. Occasional Publication No. 21. British Society of Animal Science, Edinburgh, Scotland

Tollenaar, M., D. E. McCullough, and L. M. Dwyer. 1994. Physiological basis of the genetic improvement of corn. Pp. 183–235. In G. A. Slafer (Ed.). *Genetic Improvement of Field Crops*. Marcel Dekker, Inc., New York.

Tucker, C. J., H. E. Dregne, and W. W. Newcomb. 1991. Expansion and contraction of the Sahara desert from 1980–1990. *Science* 253–299.

Tweeten, L. 1999. Status of the world: Global change in income, food and demand for animal products. Paper presented at *FAIR 2002 Symposium*, Federation of American Societies of Food Animal Science, Baltimore, Maryland. April 1999. 16 pp.

United Nations. 1996. *World Population Prospects: The 1996 Revision*. Population Division, Department for Economic and Social Information and Policy Analysis, United Nations, New York.

Urness, P. J. 1990. Livestock as manipulators of mule deer winter habitats in northern Utah. Pp. 25–40. In K. E. Severson (Ed.). *Can Livestock Be Used as a Tool to Enhance Wildlife Habitat?* Rocky Mountain Forest and Range Experiment Station General Technical Report RM-194.

U.S. Department of Agriculture. 1975, 1979, 1990, 1992. *Agriculture Handbook 8: Composition of Foods—Raw, Processed, Prepared*. Washington, D.C.

U.S. Department of Agriculture. 1995. *Animal Health. Accomplishments Report*. Joint Council on Food and Agricultural Sciences, Animal Health and Wealth. Washington, D.C.

U.S. Department of Agriculture, Economic Research Service. 1996. *Long-term Projections for International Agriculture to 2005*. ERS Staff Paper No. 9612, August. Washington, D.C.

U.S. General Accounting Office. 1995. *Animal Agriculture: Information on Waste Management and Water Quality Issues*. GAO/RCED-95-200 BR. Washington, D.C.

Vavra, M. 1996. Sustainability of animal production systems: An ecological perspective. *J Anim Sci* 74: 1418–1423.

Virmani, S. S. J. B. Young, H. P. Moon, I. Kumar, and J. C. Flinn. 1991. *Increasing Rice Yield Through Exploitation of Heterosis*. International Rice Research Institute, Los Banos, Philippines.

Vogel, K. P. and K. J. Moore. 1991. Native North American grasses. Pp. 284–293. In J. Janick and J. E. Simon (Eds.). *New Crops*. John Wiley and Sons, Inc., New York.

Vogel, K. P., H. J. Gorz, and F. A. Haskins. 1989. Breeding grasses for the future. Pp. 105–122. In *Contributions from Breeding Forage and Turf Grasses*. Crop Science Society of America Special Publication No. 15. Madison, Wisconsin.

Waddington, S. R., J. K. Ransom, M. Osmanzai, and D. A. Saunders. 1986. Improvement in the yield potential of bread wheat adapted to northwest Mexico. *Crop Sci* 26:698–703.

Waggoner, P. E. 1998. Food, feed and land. Pp. 69–94. In D. A. Crocker and T. Linden (Eds.). *Food, Feed and Land: The Good Life, Justice and Global Stewardship*. Rowman and Littlefield Publishers, Lanham, Maryland.

Waggoner, P. E., J. E. Ausubel, and I. K. Wernick. 1996. Lightening the tread of population on the land. *Populat Devel Rev* 22:531–545.

Walker, J. W. 1994. Multispecies grazing: The ecological advantage. *Sheep Res J* (special issue) 52–64.

Walker, J. W. 1995. Viewpoint: Grazing management and research now and in the next millenium. *J Range Manage* 48:350–357.

Wester, T. J., S. M. Gramlich, R. A. Britton, and R. A. Stock. 1992. Effect of grain sorghum hybrid on in vitro rate of starch disappearance and finishing performance of ruminants. *J Anim Sci* 70:2866–2876.

Western, D. and M. C. Pearl. 1989. *Conservation for the Twenty-first Century*. Oxford University Press, New York.

Westlund, L. 1995. Apparent Historical Consumption and Future Demand for Fish and Fishery Products—Exploratory Calculations. Paper presented at the *International Conference on Sustainable Contribution of Fisheries to Food Security*, Kyoto, Japan, December 4–9.

Wheeler, R. D., G. L. Kramer, K. B. Young, and E. Ospina. 1981. *The World Livestock Product, Feedstuff and Food Grain System*. Winrock International Institute for Agricultural Development, Morrilton, Arkansas.

Wilmut, I., A. E. Schnieke, J. McWhir, A. J. Kind, and K. H. S. Campbell. 1997. Viable offspring from fetal and adult mammalian cells. *Nature* 385:810–813.

Winrock International Institute for Agricultural Development. 1992. *Assessment of Animal Agriculture in Sub-Saharan Africa*. Winrock International, Morrilton, Arkansas.

Yilma, T. 1994. Genetically engineered vaccines for animal viral disease. *J Am Vet Med Assoc* 204:1606–1615.

Zenebe, S. and Fekade, T. 1997. The role of pack donkeys in the major grain market (Yehil Bernada) of Addis Abada, Ethiopia. In *Improving Donkey Utilization and Management*. Proceedings of an African Traction Network of Eastern and Southern Africa (ATNESA) Workshop, Debre Zeit, Ethiopia, 5–7 May 1997 (in press).

Zerbini, E., B. Shapiro, C. E. S. Larsen, and A. G, Wold. 1996. *Dairy-draught cows performance and implications for adoption*. In Conference Handbook and Abstracts. All-Africa Conference on Animal Agriculture, 1–4 April 1996. South African Society of Animal Science, Pretoria, South Africa.

Index

M

N–O

P

R

S

T–U

V

W–Z